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INVESTIGATION OF THE PARAMETERS OF A HYBRID WIND–SOLAR POWER PLANT FOR ENERGY SUPPLY OF REMOTE AUTONOMOUS CONSUMERS

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Abstract. This study investigates the operating parameters of a hybrid wind–solar power plant for autonomous electricity supply in the sharply continental climate of central Kazakhstan. The plant consisted of a 600 W wind turbine, four 200 W photovoltaic panels, a 12 V battery and a charge controller, the load being separated between alternating-current and direct-current circuits. Field measurements were carried out continuously during 2025 near Karaganda. The measured generation varied seasonally from 4.0 to 6.7 kWh/day, giving an annual output of 1993 kWh, the winter minimum falling to the level of the winter load. The monthly photovoltaic and wind outputs proved strongly anti-correlated, the Pearson coefficient being -0.81 , which quantifies the seasonal complementarity of the two resources. A sizing criterion based on the coefficient of variation of the monthly generation and on a seasonal reserve factor is proposed. Raising the wind capacity to 1000 W while reducing the array to two 200 W panels lowers the coefficient of variation from 16.4 to 6.3 % and raises the December output from 4.0 to 5.5 kWh/day. Direct supply of the direct-current loads without inversion saves 25.8 % of the energy delivered to them and 18.9 % at plant level.

Keywords: solar energy, hybrid power system, photovoltaic panels, autonomous power supply, seasonal generation, renewable energy, seasonal complementarity, direct-current distribution

1. Introduction

Currently, renewable energy sources are developing actively in Kazakhstan: their share of electricity generation exceeded 7 % in 2025 against less than 1 % ten years earlier [1, 2]. The country ranks ninth in the world by territory and has a low population density among 20.5 million inhabitants [3]. One of the directions of development of its energy sector is the creation of decentralised supply systems for remote consumers of ultra-low power, without which the development of agriculture, of new lands and of small business in such areas is impossible [4]. Due to the long distances of power transmission lines, considerable energy losses arise, and the construction of new lines is costly and, in some cases, may not pay for itself even after 25 years [5]. Developing renewable sources at the point of consumption removes this obstacle and makes it possible to use remote farmland and pastures [6]. According to open sources, the average duration of sunshine in Kazakhstan is 2200 to 3000 hours per year and the annual solar radiation per unit area is 1100 to 1900 kWh/m², the mean incident power on the Earth's surface being 110 to 190 W/m² and the radiation increasing from north to south from 4100 to 5300 MJ/m² [7].

The climate of the country is sharply continental almost everywhere. In the south there are many clear days in summer, high air temperatures and little precipitation through the year; in central and northern Kazakhstan there are fewer sunny days in winter, the winds are strong and the peak temperatures fall to -40°C for short periods. In the west the Caspian Sea moderates the frosts although the winter winds are strong, and in the east the climate is more humid with winters as cold as in the north. The Kyzylorda region has the greatest solar potential, with 3100 hours of sunshine and about 2000 kWh/m^2 per year, while the potential of the country as a whole is estimated at up to 2.5 billion kWh [8].

Photovoltaic capacity of up to 50 000 MW per year is planned or already under construction [9]. Whereas solar panels are more promising for the southern regions, hybrid plants combining wind turbines with solar panels can be implemented in central Kazakhstan, where such a combination operates more efficiently in a sharply continental climate and exploits the wind potential during the winter season [10]. Northern and central Kazakhstan contain a significant amount of land suitable for agriculture. About 50 % of the territory has wind speeds of 4 to 5 m/s at a height of 30 m, the highest potential being in the Caspian region and in northern and southern Kazakhstan [11]. In central Kazakhstan the annual mean wind speed is 4 to 6 m/s, which is not always sufficient for high-capacity industrial turbines [12]. There are nevertheless several dozen locations with steady winds; at Osakarovka a wind plant of 150 MW consisting of 21 turbines of 7.7 MW each is under construction [13]. The highest wind speeds occur in January and February, in summer the mean speed decreases by half, and gusty and occasionally hurricane-force winds are characteristic of the region.

In addition to large wind turbines, low-capacity wind generators can be used in combination with solar panels. A mobile version can also be used for private livestock farms. This article presents the results of research on a hybrid wind–solar power plant (HWSPP) for energy supply to remote autonomous consumers, which is planned to be used in rural areas in the future.

Published studies of hybrid wind–solar systems in Kazakhstan are predominantly resource or policy assessments made at the level of national and regional energy balances [4]. Experimental data for installations of ultra-low rated power operated continuously for a full year under a sharply continental climate remain scarce [13]. Design recommendations are usually formulated as an approximately equal distribution of wind and photovoltaic capacities, without an explicit criterion linking the capacity ratio to the seasonal uniformity of generation [14]. The present work reports a full year of field measurements, quantifies the seasonal complementarity of the resources at the site, and formulates such a criterion.

2. Methods of research

Figure 1 shows a photograph of the hybrid wind–solar power plant designed to supply energy to remote autonomous consumers. The plant was installed on a 40-foot shipping container used as a utility and storage facility by the emergency service of the Fedorov Reservoir, Karaganda. The solar panels were mounted on a frame of shaped metal profiles and oriented to the south, with no tilt adjustment and no sun-tracking system throughout the research period. The wind generator was mounted on a mast of steel pipe at a height of 9 m above the ground and is equipped with a tail vane for orientation into the wind flow.

The panels were kept in a fixed position throughout the study period in order to ensure consistent measurement conditions. The effect of a manually adjustable tilt, corrected twice a year for the winter and summer positions, is evaluated quantitatively in Section 3, and a slotted bracket allowing this adjustment has been included in the design of the next prototype.

Figure 2 presents a schematic diagram of the configuration of the plant. It consists of a high-speed three-blade wind turbine with a synchronous electrical generator 1 and silicon solar panels 2, all connected in parallel at the same nominal voltage of 12 V. The generator 1 and the panels 2 are connected to a charge controller 3 and thence to a battery 4. The three-phase alternating current of the generator is converted to direct current by a full-wave rectifier with six diodes. All generated energy was stored in the battery (4) and supplied to consumers located inside the 40-foot shipping container via two 12 V direct current lines. The charge controller (3), battery (4), and inverter (5) were also placed inside the container. The distance from the power source to the most remote consumer inside the container did not exceed 10 m. In close proximity to the container, there is a caretaker's house (an insulated container), where two people reside year-round.

To simplify the plant and reduce the overall electrical energy losses, 12 V direct-current lines were adopted, which eliminated the need for a common voltage inversion and for an alternating-current network with unnecessary conversions. A 200 Ah lead-acid battery from a truck served as the storage unit, and a 2 kW inverter was switched on only for appliances operating solely on alternating current, such as a microwave oven,

a low-power welding inverter, a drill and an angle grinder. Consumers able to work on 12 V direct current, including a water heater, lighting lamps, a laptop and charging units for various devices, were connected through DC/DC converters. Separating the load by current type and connecting the direct-current consumers directly to the line reduced energy losses by up to 30 % [14].



Fig. 1. Photograph of the experimental hybrid wind-solar power plant

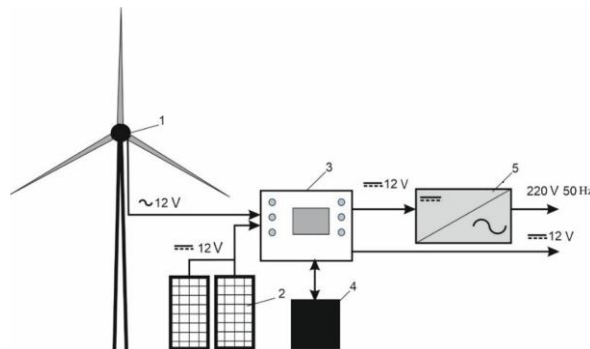


Fig. 2. Schematic diagram of the experimental hybrid wind-solar power plant

The experiment ran continuously throughout 2025 at an average annual load of 3 kWh/day, reaching 4 kWh/day in autumn and winter and falling to 2 kWh/day in summer and spring. The plant comprises four 200 W solar panels and one 600 W wind turbine, both manufactured in China; Table 1 gives the number of energy sources and the average electrical load by season. A conventional automotive-type lead-acid battery was selected primarily for its low cost and local availability. Under the regular deep-discharge cycles and the low ambient temperatures, down to -40°C , typical of the region, the usable capacity and service life of such a battery are considerably lower than the manufacturer-rated values obtained under standard conditions. Alternatives that are more resistant to temperature and to cycling, namely valve-regulated gel and lithium iron phosphate cells, are compared with it in Table 7 of Section 3.

Table 1. Information on the number of energy sources and the average electrical load by season

Season	Wind Turbine Type Turbines (600 W each)	Number of Wind Turbines (600 W each)	Solar Panel Type/Power	Number of Solar Panels (200 W each)	Average Electrical Load by Season, kWh/day
Spring, summer	HY – 600	1	Solar panels type HH-POLY – 200 W	4	2
Autumn, winter	HY – 600	1	Solar panels type HH-POLY -200 W	4	4

Table 2 presents the characteristics of the solar panels used in the field experiments. The delivery package does not include a mounting frame, a DC 12 V to AC 220 V / 50 Hz inverter, or a battery. Table 3 presents the characteristics of the wind generator used in the field experiments. The delivery package does not include a mast, a 24–220 V inverter, or a battery.

Table 2. Characteristics of the HH-POLY – 200 W solar panel

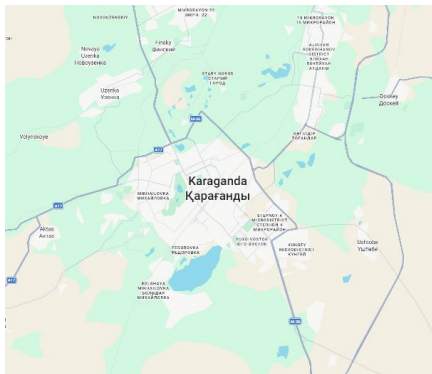
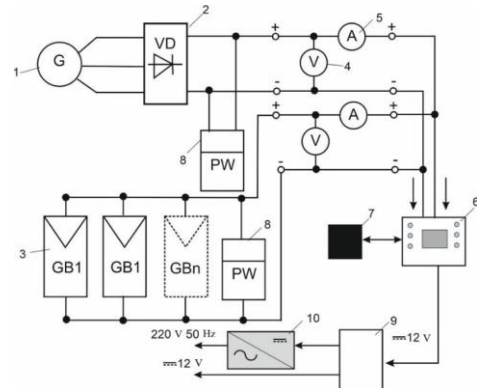
Parameter	Units	Value and Description
Rated power	W	200
Nominal voltage	V	12
Material		Polycrystalline silicon
Declared efficiency (according to the datasheet)	%	18 at cell level; 16.8 at module level, calculated from the overall dimensions
Number of cells	pcs	64
Overall dimensions	mm	1530*780*30
Weight	kg	14
Country of manufacture		China

Table 3. Characteristics of the HY–600 wind generator

Parameter	Units	Value and Description
Number of blades	pcs	3
Rotor diameter	m	2,5
Maximum peak power of the wind generator	W	700
Rated power of the wind generator	W	600
Installation height	m	9 (standard delivery mast 6 m; a 9 m mast was used in the experiment)
Number of phases of the permanent magnet synchronous generator	pcs	3
Output voltage	V	12\24
Starting wind speed	m/s	2,5
Wind speed at which the wind generator reaches 100% power	m/s	8
Wind generation range	m/s	3 - 25
Operating rotor rotational speed	rpm	450
Service life	years	15
Axis of rotation		Horizontal
Wind orientation		Mechanical
Transmission of generated current to the controller		Via slip rings
Country of manufacture		China

The research was carried out under the climatic conditions of Karaganda in central Kazakhstan, a zone with a sharply continental climate and significant temperature fluctuations, where hot summers and cold winters create a number of difficulties for the operation of renewable sources [15]. The geographical coordinates are 49°48' N and 73°07' E, and the field experiments were performed at a test site in the area of the Fedorov Reservoir. Figure 3 shows a map indicating the settlements and the location of the city. The annual number of sunshine hours is about 2300 and the average solar radiation intensity about 1300 kWh/m² per year. The panels were installed in a fixed position without a tracking system and oriented to the south, at a zenith angle of 50° and an azimuth of 180°, the total surface area being 4.8 m². A single lead-acid battery of 200 Ah and 12 V served as the storage system, capable of autonomous operation for 14 hours in summer and 7 hours in winter.

Figure 4 presents a schematic electrical diagram of the HWSPP. In addition to the main equipment previously described in Figure 2, it also shows the measuring and control instruments that were used to obtain experimental data. The sources of electrical energy are a three-phase synchronous generator 1 with a rectifier 2, whose maximum peak power is 700 W and nominal power 600 W, the output voltage being selectable between 12 and 24 V, with 12 V chosen. The energy source also includes four solar panels 3, whose number remained unchanged throughout the experiment. All sources are connected through two 12 V direct-current lines to a charge controller 6. Each line carries a combined digital voltmeter 4 and ammeter 5 in a single housing with an LED display, used for real-time monitoring of the source parameters without data storage.

**Fig. 3.** Map indicating settlements and the location of the city**Fig. 4.** Schematic electrical diagram of the HWSPP.

Electrical energy from sources 1 and 3 is supplied to the charge controller 6 and stored in the battery 7, from which it is delivered to consumers through a 12 V direct-current line. To record the generated energy, digital ATORCH DC power detectors 8 were used, capable of storing data and transmitting them over the internet to a server; each source had its own detector, so that the energy of the wind turbine and of the panels was measured separately. The energy then passes to a distribution unit 9 dividing it into two 12 V lines, one feeding an inverter 10 for loads with inductive characteristics and the other delivering direct current directly. The measuring instruments used are listed in Table 4.

Table 4. Measuring instruments

Name	Parameters	Resolution	Accuracy	Country of manufacture
Digital combined voltmeter and ammeter	Measurement of current and voltage. DC 0–100 V with a 100 A shunt and a 0.28-inch LED display	0.01 A; 0.01 V	±2%	China
Laser non-contact tachometer Victor DM6234P	Measurement of wind turbine rotational speed in the range of 2.5–99999 rpm	0.1 rpm	±(0.5% + 1)	China
Infrared pyrometer ADA TemPro 650 Hygro A00658	Temperature measurement in the range from –50 to +650 °C	0.1 °C	±1.5%	China

To measure current, voltage and power and to account for the generated electrical energy, a digital ATORCH DT3010 DC power detector made in China was used, with a measurement accuracy of ±1 %, a voltage range of 0 to 300 V DC and a current range of 0 to 100 A at resolutions of 0.05 V and 0.05 A, an energy range of 0 to 10 kWh at a resolution of 0.01 Wh and a temperature range of –10 to 99 °C at a resolution of 1 °C.



Fig. 5. ATORCH DT3010 wattmeter: (a) front view; (b) rear view with connection diagram

The appearance of the detector is shown in Figure 5: a monochrome liquid-crystal display and a control button on the front side, and the connection diagram to the electrical network with three terminals on the back of the housing. The seasonal uniformity of generation was evaluated by two dimensionless indicators calculated from the twelve-monthly mean values of daily generation E_i . The first is the coefficient of seasonal non-uniformity

$$k_s = E_{max} / E_{min} , \quad (1)$$

and the second is the coefficient of variation of the monthly series

$$CV = \sigma^E / \bar{E} , \quad (2)$$

where σ^E is the standard deviation of the twelve monthly means and $\bar{E}$ is their arithmetic mean. The reliability of supply was characterised by the seasonal reserve factor

$$k_r = E_{min} / L_v , \quad (3)$$

where L_v is the average daily load in the autumn and winter period.

A configuration was considered acceptable when k_r was not lower than 1.2, which leaves a margin for the consecutive calm and overcast days that monthly means do not resolve.

The extent to which the two resources compensate each other over the year was quantified by the Pearson linear correlation coefficient between the monthly series of photovoltaic and wind generation

$$r_{pv} = \Sigma (E_{pv,i} - \bar{E}_{pv})(E_{v,i} - \bar{E}_v) / [\Sigma (E_{pv,i} - \bar{E}_{pv})^2 \cdot \Sigma (E_{v,i} - \bar{E}_v)^2]^{1/2}, \quad (4)$$

a negative value of which indicates seasonal complementarity of the resources. This indicator is widely used in the joint planning of wind and photovoltaic capacities and permits a direct comparison of the results obtained at the test site with published data for other regions [19].

The saving obtained by supplying the direct-current loads without inversion was determined by comparing the energy withdrawn from the battery in two supply schemes for the same useful load. In the conventional scheme the whole load passes through the inverter and the direct-current appliances are then fed through mains adapters, so that the energy withdrawn per day is

$$W_{aS} = E_{aS} / (\eta_{inv} \cdot \eta_{aa}) + E_{aS} / \eta_{inv} + P_0 \tau, \quad (5)$$

whereas in the scheme adopted in this work the direct-current appliances are fed from the 12 V line through a DC/DC converter and the energy withdrawn is

$$W_{aS} = E_{aS} / (\eta_{aS} \cdot \eta_i) + E_{aS} / \eta_{inv} + P_0 \tau_{on}, \quad (6)$$

where E_{aS} and E_{aS} are the daily energy demands of the direct-current and alternating-current appliances, η_{inv} , η_{aa} and η_{aS} are the efficiencies of the inverter, of the mains adapters and of the DC/DC converter, η_i accounts for the ohmic loss in the 12 V line, P_0 is the no-load power of the inverter and τ is the time during which the inverter remains energised.

The loss factor of the line was calculated as $\eta_i = 1 - I^2 R / P$ with $R = 2lp/S$ the loop resistance of a copper cable of length $l = 10$ m and cross-section $S = 4$ mm². The efficiencies were taken as $\eta_{inv} = 0.78$ at the part load characteristic of this plant, $\eta_{aa} = 0.85$ and $\eta_{aS} = 0.92$, and the no-load power of the inverter as 8 W, these values being consistent with the measured data for low-voltage direct-current distribution reported in [20]. The expected generation of the proposed configuration, shown in Figure 9, was obtained by applying the measured monthly wind resource to the power curve of a 1000 W wind generator with a rotor diameter of 3.2 m against 2.5 m for the machine tested, the swept area being 1.64 times larger at the same cut-in speed of 2.5 m/s, and by scaling the measured photovoltaic generation in proportion to the installed capacity. The result exceeds by 8 to 14 % the value given by proportional scaling of the rated power, which is reported below as a conservative bound.

3. Results and Discussion

Figure 6 shows the average values of the electrical energy generated by the solar panels, kWh/day, against the month of the year. The values are averaged over the 30 or 31 days of each month: every day was recorded on the server as a separate value of the energy generated over 24 hours, and the values were summed and divided by the number of days automatically by the server software. Depending on the weather, the daily deviations ranged from 0.1 to 2 kWh/day. The graph in Figure 6 reflects only the energy generated by the four HH-POLY 200 W solar panels. Figure 7 presents, by the same processing method, the average daily generation of the HY-600 wind turbine over the twelve months of continuous operation; some days of each month were nearly windless and others had high generation, but the averaged value was used throughout.

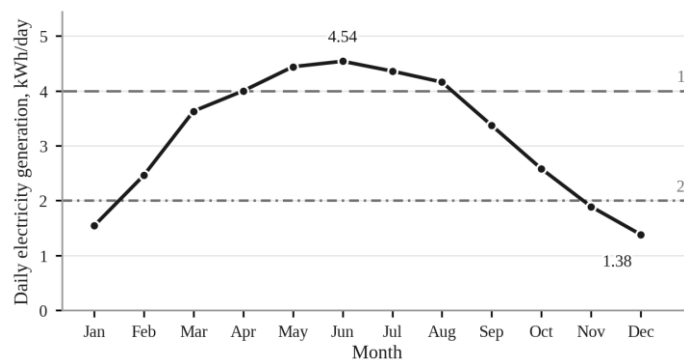


Fig. 6. Graph of the obtained average values of the electrical energy generated by solar panels, kWh/day.
1 – Average electrical load in winter and autumn, kWh/day; 2 – Average electrical load in summer and spring, kWh/day.

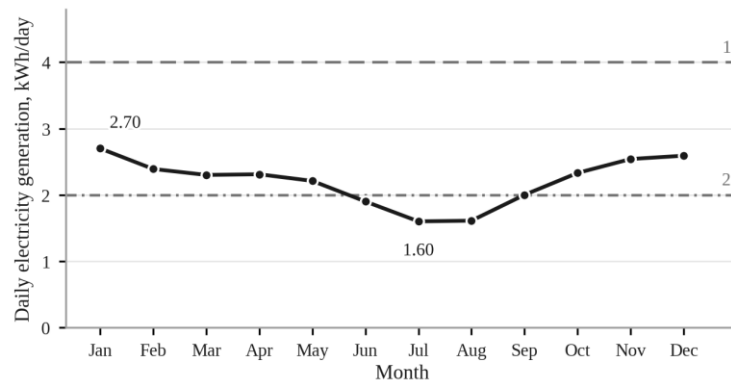


Fig. 7. Graph of the obtained average values of the electrical energy generated by the wind turbine, kWh/day. Average electrical load: 1 – in winter and autumn; 2 – in summer and spring.

Comparison of Figures 6 and 7 shows that the resources are in seasonal opposition: photovoltaic generation peaks at 4.54 kWh/day in June and falls to 1.38 kWh/day in December, whereas wind generation peaks at 2.70 kWh/day in January and falls to 1.60 kWh/day in July. The Pearson coefficient between the two monthly series, from equation 4, is -0.81 , which indicates a strong seasonal complementarity at the test site and is more negative than the range from -0.3 to -0.6 usually reported for continental sites of the middle latitudes [19]. The coefficient of variation is 35.2 % for the photovoltaic component and 15.6 % for the wind component, so the wind resource is the more uniform of the two over the year.

Figure 8 shows the total electrical energy generated by the plant over the year by the wind turbine and the solar panels together. The proposed configuration converts solar radiation more efficiently during the summer period, while in the winter season more energy is supplied by the wind turbine. In the summer months the plant operates with a surplus, the generation exceeding the consumer demand by more than 4 kWh/day.

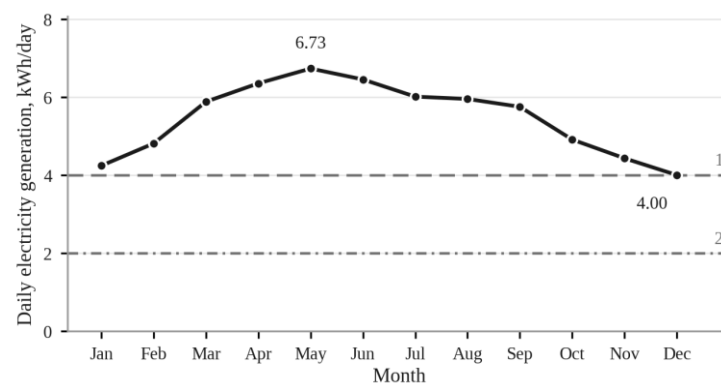


Fig. 8. Graph of the total amount of electrical energy generated by the HWSPP over the year, kWh/day. 1 – Average electrical load in winter and autumn, kWh/day; 2 – Average electrical load in summer and spring, kWh/day.

Integration of the measured monthly means over the year gives 1167.7 kWh for the photovoltaic array and 805.0 kWh for the wind generator, that is 1993.4 kWh for the plant, or 5.46 kWh/day on average. The specific yield of the array is 1460 kWh per kilowatt and the capacity factor of the wind generator is 15.3 %. The photovoltaic share of the annual output is 58.6 %, but it falls to 40.9 % in the three winter months and rises to 70.9 % in the three summer months, which follows directly from the fixed tilt. The coefficient of seasonal non-uniformity from equation 1 is 1.683 and the coefficient of variation from equation 2 is 16.4 %. The lowest monthly value, 4.00 kWh/day in December, coincides with the winter load of 4 kWh/day, so that the reserve factor from equation 3 falls to 1.00: the plant covers the load in the monthly mean but retains no margin for consecutive calm and overcast days and no surplus for restoring the battery.

The excess energy can be used for water heating, for various equipment and electric tools, for repair work with a small welding inverter, or for driving an electric pump to irrigate crops grown close to the source [16]. In the winter months the monthly mean generation falls to the level of the winter load itself, so that the seasonal reserve factor drops to unity; the plant does not enter a deficit in the monthly balance, but any sequence of calm and overcast days immediately leads to an emergency operating mode in which part of the consumers

has to be disconnected, and the battery cannot be brought back to a full state of charge [17]. For central Kazakhstan the most rational solution for remote autonomous consumers of low power is therefore a hybrid plant in which the capacities are matched to the seasonal structure of the resources rather than distributed equally.

The experiment showed that with one 600 W wind turbine and four 200 W solar panels a relatively balanced operation of the plant cannot be achieved. With this configuration the summer load can be raised to 5 or 6 kWh/day, but in December and January there is a risk of an emergency operating mode [18]. After theoretical calculation and analytical forecasting, it is proposed to use a 1000 W wind turbine, or two units of 500 W, together with two 200 W solar panels. Figure 9 presents the results of the numerical modelling of the expected generation. To place the results with respect to published work, the measured indicators were compared with those reported for hybrid installations of comparable and of larger rated power, as shown in Table 5. The capacity factor of 15.3 % obtained at a hub height of 9 m is consistent with the 12 to 18 % reported for small wind machines at continental sites with mean wind speeds of 4 to 6 m/s [16]. The specific photovoltaic yield of 1460 kWh per kilowatt exceeds the values normally quoted for northern Kazakhstan, which is explained by the high proportion of clear days in the cold season and by the low module temperature. The essential difference from published configurations concerns the wind share of the installed capacity: in [13] and [15] the capacities are distributed approximately equally, whereas at a site with a complementarity coefficient of -0.81 the uniformity of generation is governed by a wind share close to 70 %.

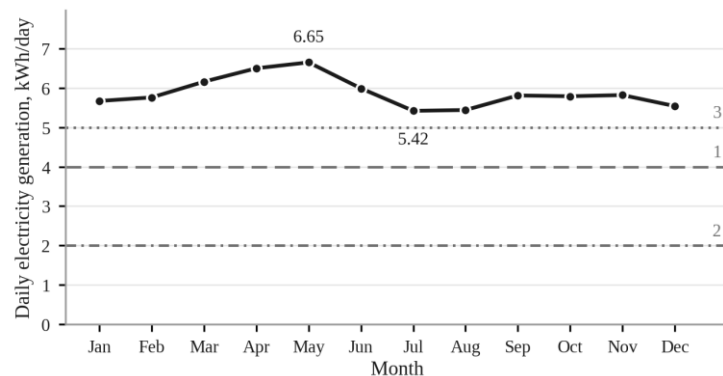


Fig. 9. Results of numerical modeling of the analytical forecast of the expected volume of electrical energy generation. 1 – Average electrical load in winter and autumn, kWh/day; 2 – Average electrical load in summer and spring, kWh/day; 3 – Total load regardless of the season, kWh/day.

Table 5. Comparison of the results obtained with published data on hybrid wind–solar systems

Source	Object and rated power	Wind share of installed capacity, %	Type of data	Key reported indicator
[13]	Hybrid wind–solar complex	≈ 50	Calculation	Equal distribution of capacities recommended
[14]	Wind–solar plant with diesel generators	40–60	Optimisation	Composition governed by the diesel share
[15]	Principles of construction of hybrid plants	≈ 50	Analytical	Equal distribution of capacities recommended
[16]	Review of hybrid wind–solar systems	various	Review	No site-specific sizing criterion
This work, tested	600 W wind + 800 W PV	43	Field measurement, 12 months	CV 16.4 %; December output 4.00 kWh/day; reserve factor 1.00
This work, proposed	1000 W wind + 400 W PV	71	Forecast from the measured series	CV 6.3 %; December output 5.54 kWh/day; reserve factor 1.39

The recommendation to provide a seasonally adjustable tilt was examined quantitatively. For the latitude of 49.8° N the biannual optimum angles are about 65° for the cold season and 35° for the warm one, against the fixed 50° used. Raising the tilt from 50 to 65° in December increases the beam component at solar noon by 7.7 % and the ground view factor from 0.125 to 0.202 at a snow albedo of 0.7, while the sky view factor falls from 0.821 to 0.711; an isotropic-sky calculation at a diffuse fraction of 0.5 gives a net gain of 6.8 % in the plane-of-array irradiation, raising the December output of the array from 1.38 to 1.47 kWh/day, the annual gain of 3 to 4 % agreeing with data for European sites at the same latitude [22]. At plant level the effect is small: since the array supplies only 34.5 % of the December output, the monthly minimum rises from 4.00 to 4.06 kWh/day, by 1.6 %, whereas rebalancing the capacities raises it to 5.54

kWh/day, by 38.5 %. Seasonal adjustment is therefore an inexpensive measure requiring a slotted bracket and two operations per year, but it cannot by itself remove the seasonal imbalance.

The saving obtained by supplying the direct-current loads at 12 V without inversion was evaluated from equations 5 and 6 for the measured load composition, in which appliances able to operate directly on direct current account for about 70 % of the annual consumption. For the same useful load the conventional scheme withdraws 4.415 kWh/day from the battery against 3.276 kWh/day for the scheme adopted here, a saving of 25.8 % of the energy delivered to those appliances and of 18.9 % at plant level; the value of 30 % quoted earlier is an upper bound reached only when the inverter works below 10 % of its rated power and stays energised around the clock. The transition to a low distribution voltage also has an unfavourable side: at a mean current of 9.72 A the ohmic loss in a copper cable of 4 mm² cross-section over a 10 m run reaches 8.27 W, that is 7.1 % of the transmitted power against less than 0.1 % at 220 V, so the admissible length of the line here does not exceed 15 m, beyond which 24 or 48 V becomes preferable [20]. The advantage of direct-current distribution as such, one to two percentage points of overall efficiency, is far smaller, since the saving arises mainly from the elimination of two conversion stages [21].

The technical indicators of the two configurations are collected in Table 6. The uniform year-round load that the tested configuration can carry is limited by its December output to 4 kWh/day, whereas the proposed configuration carries 5 kWh/day while retaining a seasonal reserve factor of 1.39, and its annual generation is 7.7 % higher, 2146 against 1993 kWh, despite the photovoltaic array being halved. The gain therefore comes not from an increase in the installed capacity but from matching the capacity ratio to the seasonal structure of the resources at the site.

The choice of the storage unit was reconsidered in the light of the operating conditions. The starter lead-acid battery is not intended for cyclic duty: under regular discharge to 50 % of capacity and at the winter temperatures inside the container, corrosion of the positive grid, sulphation and stratification of the electrolyte develop rapidly, and the service life predicted by weighted ampere-hour throughput models falls to two or three years against five to twelve for stationary OPzS cells [23]. Three options are compared in Table 7. Lithium iron phosphate cells give a usable depth of discharge of 80 % against 50 % and a cycle life about ten times longer, but must not be charged below 0 °C without an integrated heater, which in central Kazakhstan requires a management system with self-heating. Valve-regulated gel cells tolerate cyclic duty and temperatures down to –30 °C far better than starter batteries, need no maintenance and extend the replacement interval to five or six years; for an unheated container the gel battery is therefore recommended as the base option, and lithium iron phosphate with a heated management system where maintenance visits are difficult.

Table 6. Technical indicators of the configurations examined

Indicator	Unit	Tested 600 W + 800 W	Proposed 1000 W + 400 W
Annual generation	kWh	1993	2146
Minimum monthly mean generation	kWh/day	4.00	5.42
Coefficient of seasonal non-uniformity k_s	–	1.683	1.227
Coefficient of variation of monthly generation	%	16.4	6.3
Seasonal reserve factor in December k_r	–	1.00	1.39
Uniform year-round load supplied reliably	kWh/day	4.0	5.0

Table 7. Comparison of storage options for the proposed configuration

Indicator	Starter lead-acid	Valve-regulated gel	Lithium iron phosphate
Nominal capacity at 12 V, Ah	200	200	150
Usable depth of discharge, %	50	50	80
Usable energy, kWh	1.20	1.20	1.54
Cycle life at the stated depth of discharge	300–400	600–800	3000–4000
Minimum charging temperature, °C	–20	–30	0 without an integrated heater
Expected replacement interval, years	2–3	5–6	10

The measurements cover a single calendar year, which is the principal limitation of this work. The representativeness of 2025 was assessed against the long-term climatic characteristics of the site: the annual sunshine duration of about 2300 hours and the mean wind speed of 4 to 6 m/s at a height of 30 m correspond to the long-term normals for central Kazakhstan [12], and the measured capacity factor and specific yield lie within the expected ranges. With an interannual variability of wind energy production whose normalised interquartile range has a median of about 3.4 % and reaches 13.5 % at the least favourable sites [24], and a variability of the annual solar irradiation of 4 to 6 %, the December output lies between 3.5 and 4.5 kWh/day for the tested configuration and between 4.8 and 6.3 kWh/day for the proposed one, so the conclusion on the winter reserve holds over the whole interval. The conservative estimate by proportional scaling gives 4.76 kWh/day and a coefficient of variation of 6.7 %. Monitoring will continue for at least three further years with hourly recording of the load profile.

4. Conclusions

The scientific novelty of the study lies in the following:

- a circuit solution has been developed and tested in the field in which the load of an autonomous plant is separated between an alternating-current circuit and a direct-current circuit, the appliances able to operate on direct current being fed from the 12 V bus without inversion, and the annual dependences of the electrical parameters of the plant operating under this solution have been obtained from continuous measurements and are presented in Figures 6 to 8; the saving has been quantified as 25.8 % of the energy delivered to the direct-current appliances and 18.9 % at plant level, while the ohmic loss of the 12 V line, 7.1 % over a 10 m run, bounds the admissible length of that line at 15 m and defines the field of application of the solution;

- for the first time for the conditions of central Kazakhstan, the Karaganda region, the seasonal complementarity of the wind and solar resources has been quantified from a continuous year of field measurements, the Pearson correlation coefficient between the monthly photovoltaic and wind outputs being -0.81 , which is markedly more negative than the values from -0.3 to -0.6 usually reported for continental sites of the middle latitudes;

- a reproducible criterion for selecting the ratio of the installed wind and photovoltaic capacities has been formulated, in which the ratio is chosen so as to minimise the coefficient of variation of the monthly generation subject to a seasonal reserve factor of not less than 1.2; applied to the measured series, this criterion gives a wind share of about 70 % of the installed capacity, whereas the approximately equal distribution of capacities recommended in earlier work gives a coefficient of variation 2.6 times higher, 16.4 % against 6.3 %;

- the effect of a seasonal adjustment of the tilt of the photovoltaic panels has been evaluated quantitatively against the rebalancing of the installed capacities, and it has been shown that for a plant with this capacity ratio the adjustment raises the December output by only 1.6 % against 38.5 % obtained by rebalancing, which establishes the order in which the two measures should be applied.

The practical significance of the work lies in the fact that the proposed configuration, a 1000 W wind turbine or two 500 W units together with two 200 W solar panels, allows:

- raising the minimum monthly mean generation in December from 4.00 to 5.54 kWh/day and the seasonal reserve factor from 1.00 to 1.39, and reducing the coefficient of variation of the monthly generation from 16.4 to 6.3 %;

- raising the uniform year-round load that can be supplied reliably from 4 to 5 kWh/day;

- halving the number of photovoltaic modules and the area of the mounting frame, which lowers the snow and wind load on the supporting structure and the labour of clearing snow from the array, while the generation in the winter months nevertheless increases.

Thus, the results of the study confirm the feasibility of widespread application of hybrid wind–solar systems of ultra-small and small capacity for decentralized power supply in rural and remote areas of central and northern Kazakhstan. Optimization of the ratio between wind and solar generation, taking into account regional climatic characteristics, can significantly improve the uniformity of generation and the reliability of supply of such systems, contributing to the development of agriculture, small business, and the development of new lands.

The principal limitation is the duration of the observations, one calendar year; its representativeness has been verified against the long-term climatic normals of the site and the published interannual variability of the resources, and the conclusions hold over the resulting interval. Monitoring is to be continued for at least three further years with hourly recording of the load profile. For an unheated container a valve-regulated gel battery is recommended instead of the starter battery used, since it extends the replacement interval from two or three to five or six years.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

Kuatova A.S.: research, writing — original draft; **Alkina A.D.:** conceptualization, writing — review and editing; **Mekhtiyev A.D.:** research, writing — review and editing; **Bainiyazov B.A.:** research, formal analysis; **Yurchenko A.V.:** visualization, writing — review and editing. The final manuscript was read and approved by all authors.

Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article

Data Availability Statement

The data that support the findings of this article are openly available.

References

- 1 Karatayev, M., Hall, S., Kalyuzhnova, Y., & Clarke, M.L. (2016). Renewable energy technology uptake in Kazakhstan: Policy drivers and barriers in a transitional economy. *Renewable and Sustainable Energy Reviews*, 66, 120–136. <https://doi.org/10.1016/j.rser.2016.07.057>
- 2 KAZENERGY. (2019). *The National Energy Report 2019*. Astana, Kazakhstan. Available at: https://www.kazenergy.com/upload/document/energy-report/NationalReport19_en.pdf
- 3 Xenarios, S., Darke, W., & Bekturganov, N. (2024). Clean energy challenges and innovation opportunities in Kazakhstan. *Environmental Research Communications*, 6(8), 085005. <https://doi.org/10.1088/2515-7620/ad87b5>
- 4 Karatayev, M., & Clarke, M. L. (2016). A review of current energy systems and green energy potential in Kazakhstan. *Renewable and Sustainable Energy Reviews*, 55, 491–504. <https://doi.org/10.1016/j.rser.2015.10.078>
- 5 Zhakiyev, N., Burkhanova, D., Nurkanat, A., Zhussipkaliyeva, S., Sospanova, A., & Khamzina, A. (2025). Green energy in grey areas: The financial and policy challenges of Kazakhstan's energy transition. *Energy Research & Social Science*, 124, 104046. <https://doi.org/10.1016/j.erss.2025.104046>
- 6 Temirgaliyeva, N., & Junussova, M. (2020). Renewable Electricity Production and Sustainability of the National and Regional Power Systems of Kazakhstan. *International Journal of Energy Economics and Policy*, 10(3), 58–67. <https://doi.org/10.32479/ijeep.9150>
- 7 Koshim, A., Karaca, F., & Clarke, M. L. (2015). Current Energy Resources in Kazakhstan and the Future Potential of Renewables: A Review. *Energy Procedia*, 59, 97–104. <https://doi.org/10.1016/j.egypro.2014.10.354>
- 8 Akbulut, A., Seker, O., Ozcan, S., & Beycioğlu, G. (2025). Energy, exergy and enviro-economic analysis of a hybrid energy plant utilizing biogas and solar technologies in the Almaty region, Republic of Kazakhstan. *Energy Strategy Reviews*, 11, 101118. <https://doi.org/10.1016/j.cscee.2025.101118>
- 9 Darke, W., Xenarios, S., & Zhakiyev, N. (2025). From fossil fuels to renewables: Analysing efficacy and impact of auctions to attract investment in resource-rich Kazakhstan. *Energy Strategy Reviews*, 53, 101470. <https://doi.org/10.1016/j.esr.2025.101470>
- 10 Zereshkian, S., & Mansoury, D. (2023). Solar-wind hybrid energy system to supply electricity for offshore oil and gas platforms in the Caspian Sea: A case study. *The Journal of Engineering*, 2023(6), e12239. <https://doi.org/10.1049/tje2.12239>
- 11 Xu, J., Assenova, A., & Erokhin, V. (2018). Renewable Energy and Sustainable Development in a Resource-Abundant Country: Challenges of Wind Power Generation in Kazakhstan. *Sustainability*, 10(9), 3315. <https://doi.org/10.3390/su10093315>
- 12 Karatayev, M., & Hall, S. (2020). Establishing and comparing energy security trends in resource-rich exporting nations (Russia and the Caspian Sea region). *Resources Policy*, 68, 101746. <https://doi.org/10.1016/j.resourpol.2020.101746>
- 13 Aliev, A. K., Dyusenov, K. M., Sednin, A. V., & Baimukhamedov, M. F. (2024). Development of a Hybrid Wind-Solar Energy Complex. *Proceedings of the University*, 1(94), 436–443. https://doi.org/10.52209/1609-1825_2024_1_436 [in Russian]
- 14 Lavrik, A. Yu., Zhukovsky, Yu. L., Lavrik, A., & Buldysko, A. D. (2020). Features of the optimal composition of a wind-solar power plant with diesel generators. *Power Engineering: Research, Equipment, Technology*, 22(1), 10–17. <https://doi.org/10.30724/1998-9903-2020-22-1-10-17> [in Russian]
- 15 Dzendzerskii, V. A., Zhitnik, N. E., Plaksin, S. V., Pogorelaya, L. M., & Burak, I. I. (2007). Principles of Designing Hybrid Wind-Solar Power Systems. *Elektrotehnika ta elektroenergetika*, (1), 67-72. [in Russian]
- 16 Roy, P., He, J., Zhao, T., & Singh, Y. V. (2022). Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation: A Review. *IEEE Open Journal of the Industrial Electronics Society*, 3, 81–104. <https://doi.org/10.1109/OJIES.2022.3144093>
- 17 Boute, A. (2020). Regulatory stability and renewable energy investment: The case of Kazakhstan. *Renewable and Sustainable Energy Reviews*, 121, 1009673. <https://doi.org/10.1016/j.rser.2019.109673>
- 18 Kumar, R. (2025). Renewable Energy Future: Can Large-Scale Solar and Wind Energy Projects in Kazakhstan and Uzbekistan Reduce Dependence on Fossil Fuels and Alter the Region's Energy Geography? *International Journal of Research Studies on Environment, Earth, and Allied Sciences*, 2(4), 14–17. <https://doi.org/10.5281/zenodo.17590177>
- 19 Han, S., Zhang, L., Liu, Y., Zhang, H., Yan, J., Li, L., Lei, X., & Wang, X. (2019). Quantitative evaluation method for the complementarity of wind-solar-hydro power and optimization of wind-solar ratio. *Applied Energy*, 236, 973–984. <https://doi.org/10.1016/j.apenergy.2018.12.059>

- 20 Khan, H. A., & Siraj, K. (2020). DC distribution for residential power networks – A framework to analyze the impact of voltage levels on energy efficiency. *Energy Reports*, 6, 944–951. <https://doi.org/10.1016/j.egy.2020.04.018>
- 21 Haroon, A., Gelani, H. E., Tahir, H., & Manzoor, H. U. (2025). DC vs. AC distribution: Revealing the efficiency advantage of DC in today's energy landscape. *PLOS ONE*, 20(5), e0318444. <https://doi.org/10.1371/journal.pone.0318444>
- 22 Machidon, D., & Istrate, M. (2023). Tilt angle adjustment for incident solar energy increase: A case study for Europe. *Sustainability*, 15(8), 7015. <https://doi.org/10.3390/su15087015>
- 23 Dufo-López, R., Cortés-Arcos, T., Artal-Sevil, J. S., & Bernal-Agustín, J. L. (2021). Comparison of lead-acid and Li-ion batteries lifetime prediction models in stand-alone photovoltaic systems. *Applied Sciences*, 11(3), 1099. <https://doi.org/10.3390/app11031099>
- 24 Pryor, S. C., Shepherd, T. J., & Barthelmie, R. J. (2018). Interannual variability of wind climates and wind turbine annual energy production. *Wind Energy Science*, 3(2), 651–665. <https://doi.org/10.5194/wes-3-651-2018>

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