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Review of scientific, technical and economic aspects of wind energy development

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Abstract. At present, the development of renewable energy sources in the Republic of Kazakhstan is one of the strategic priorities of the state policy. Among these sources, wind energy holds particular significance as an environmentally friendly and inexhaustible form of energy. Nearly half of Kazakhstan's territory experiences an average annual wind speed of 4–6 m/s, which provides favorable conditions for the efficient placement of wind power plants (WPPs). In particular, the Dzungarian Gate and Shelek Corridor in the Almaty region, as well as areas in the Akmola and Zhambyl regions, are characterized by high wind potential. The utilization of wind energy not only addresses energy shortages but also contributes to reducing carbon emissions and enhancing energy security. This paper examines the current state of wind energy in Kazakhstan, the geographical distribution of wind resources, and the prospects for their future development.

1 Introduction

In recent years, the Republic of Kazakhstan has prioritized the transition to renewable energy sources as a key element of its national energy policy. Among these sources, **wind energy** has emerged as one of the most promising directions due to its environmental sustainability, inexhaustibility, and broad geographic availability across the country. Nearly half of Kazakhstan's territory experiences average annual wind speeds of 4–6 m/s, creating favorable conditions for the efficient deployment of wind power plants (WPPs). Regions such as the Dzungarian Gate, Shelek Corridor, and parts of the Akmola, Zhambyl, and Mangystau areas are characterized by high wind potential, providing substantial opportunities for wind energy development.

The growing demand for electricity, driven by industrial expansion and population growth, has led to an increased focus on renewable alternatives capable of ensuring energy security and environmental protection. Wind energy, in this context, represents a vital solution for reducing carbon emissions and diversifying the national energy balance. However, the efficient use of wind resources requires detailed meteorological assessment, advanced turbine technologies, and the implementation of modern control and storage systems capable of addressing the intermittency and variability of natural wind patterns. This study presents a comprehensive review of the current state, geographical distribution, and

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development prospects of wind energy in Kazakhstan. It also examines the scientific, technical, and economic aspects that influence the sustainable growth of the wind energy sector, including the optimization of wind turbine design, improvement of power grid infrastructure, and enhancement of investment mechanisms. The ultimate goal of this research is to outline strategic directions for the large-scale implementation of wind power technologies that will strengthen Kazakhstan's position in the global renewable energy landscape.

2 Overview of wind energy resources in Kazakhstan

The operation of wind power generation systems requires the presence of sufficient wind energy resources [1]. The territory of the Republic of Kazakhstan is rich in vast wind potential. Approximately 50% of the country's land area experiences average wind speeds of 4–5 m/s, while in certain specific regions, wind speeds exceed 6 m/s. Such indicators provide favorable conditions for the active development of wind energy [2]. According to expert assessments, Kazakhstan meets all the essential criteria for the successful advancement of wind power generation among the world's leading countries. The main regions with concentrated wind potential are located in the central and northern parts of the country, around the Caspian Sea, as well as in the southern and southeastern regions. Considering an average WPP power density of around 10 MW/km² and the availability of open land, it is estimated that several thousand megawatts of wind power capacity could be installed across Kazakhstan. Statistical data indicate that the total theoretical wind potential of Kazakhstan is approximately 1,820 billion kWh per yea». To accurately assess these capabilities, specialized meteorological studies are required. Such studies involve installing measurement masts ranging from 30 to 80 meters in height and conducting continuous measurements for at least one year. The collected meteorological data enable the calculation of the potential annual energy output of wind turbines. The results of these calculations are essential for the technical and economic feasibility studies (TEFS) during the design and construction stages of wind power plants.

Among all regions of Kazakhstan, the «Dzungarian Gate» area in the Almaty region is the most prominent for its exceptional wind energy potential. This mountainous corridor, approximately 20 km long and 10–15 km wide, offers ideal conditions for wind turbine installation - potentially accommodating around 11,000 wind turbines with rotor diameters of 25 meters each. During cold periods, continuous wind flow in this area may last 60–110 hours, and in some cases up to 270–320 hours. The average annual wind speed at 50 meters height reaches 9.7 m/s, making it one of the most promising sites for wind energy development. Meteorological studies conducted between 1998 and 2000 with the support of the UNDP revealed additional high-potential wind zones besides the Dzungarian Gate. These include the Zailiysky Alatau and Shelek Corridor areas in the Almaty region, where the average annual wind speed at 50 meters is about 7.8 m/s, as well as the Erementau area in the Akmola region, the Fort-Shevchenko area near the Caspian coast, and the Kordai district in the Zhambyl region. In total, 13 promising wind energy zones have been identified across Kazakhstan (see Figure 1) [3].

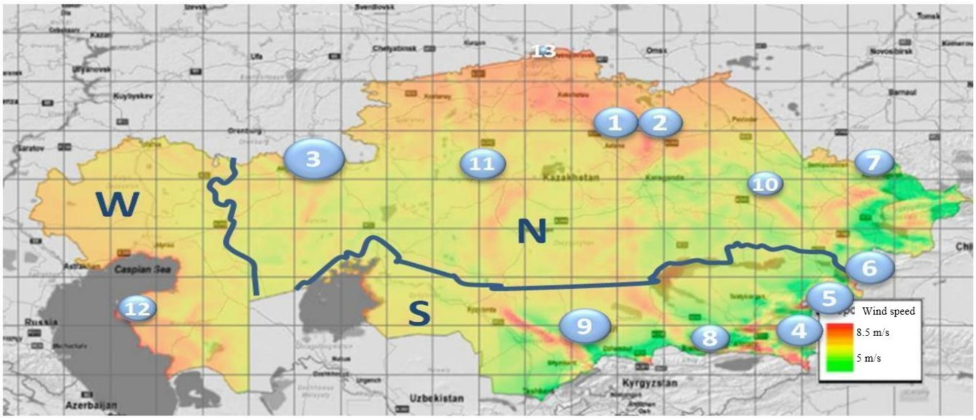

Fig. 1. Regions suitable for the future construction of wind power plants.

As shown in Figure 1, the locations of wind power plants across the territory of the Republic of Kazakhstan are indicated by numbers, which are explained in more detail in Table 1 [4].

Table 1. Sites proposed for the future construction of wind power plants.

№	Name of the Wind Power Plant	Region	Power (MW)
1	WPP near Erementau	Akmola	45
2	WPP near Erementau (duplicate site)	Akmola	30-50
3	WPPs in Badamsha and Kargaly	Aktobe	300
4	WPP in the Shelek Corridor	Almaty	51
5	WPP in Shelek	Almaty	60
6	WPP in the Dzungarian Gate	Almaty	72
7	WPP at the Ulan Mountain Pass	East Kazakhstan	24
8	WPP in Kordai	Zhambyl	21
9	WPP in Sarysu near Zhanatas	Zhambyl	100
10	WPP in Karaganda	Karaganda	15
11	WPP near the city of Arkalyk	Kostanay	48
12	WPP in Fort-Shevchenko	Mangystau	19,5
13	WPP in Novonikolskoe, Kyzylzhar	North Kazakhstan	1,5

Most of the above-mentioned windy regions are located in areas that experience electricity shortages, which increases the necessity for constructing wind power plants in these locations-particularly in regions such as the Dzungarian Gate and the Shelek Corridor, among others

3 Intensity of electricity consumption

According to data from the system operator, in 2018, the total electricity consumption in Kazakhstan amounted to 103,288.3 million kWh, which represents a 5% increase compared to 2017 (see Figure 2). The growth in electricity consumption was observed across all energy regions of the country: by 5% in the Northern, 7% in the Southern, and 8% in the Western energy regions. This overall increase was mainly driven by a 4.1% rise in industrial production across 14 regions of Kazakhstan. Between 2014 and 2018, the Northern energy region accounted for the highest share of electricity consumption, totaling 6.99 billion kWh. During this period, a decline in electricity consumption was observed only in the Kostanay region, primarily due to reduced energy use at the Sokolov–Sarbai Mining and Processing

Association (SSGPO), where electricity consumption fell by 541 million kWh. This reduction resulted from a 25–29% decrease in iron ore production, caused by the completion of major construction projects in western China, which had been the main consumer of SSGPO's output. Between 2014 and 2018, the highest growth in electricity consumption (see Figure 2) was recorded in the Aktobe and Atyrau regions, largely due to the expansion of industrial activities in these areas. In particular, consumption increased by 1,588 million kWh at JSC "TNK Kazchrome" (Aktobe Ferroalloy Plant) and by 976 million kWh due to the growth of oil production at the Kashagan field.

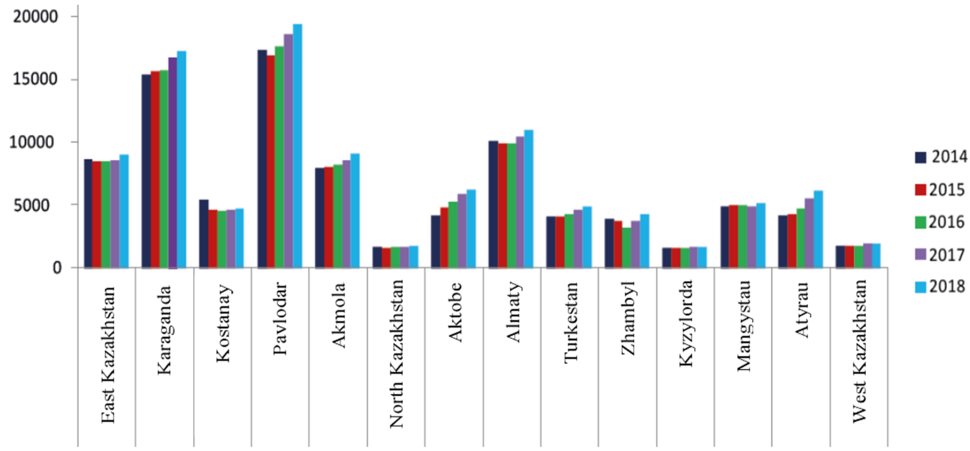

Fig. 2. Changes in electricity consumption between 2014 and 2018.

During the observed period, electricity consumption at JSC "TNK Kazchrome" (Aktobe Ferroalloy Plant) doubled due to the increased global demand and rising prices for chromium, as well as the high quality of chromium produced in Kazakhstan. The rise in electricity consumption in the Karaganda and Pavlodar regions was driven by the growth of aluminum and other metallurgical production, as well as by the expansion of operations at the Pavlodar Oil Chemistry Refinery (PNHZ) [5].

In Kazakhstan, approximately one-third of the total electricity produced is consumed by large industrial enterprises (see Figure 3).

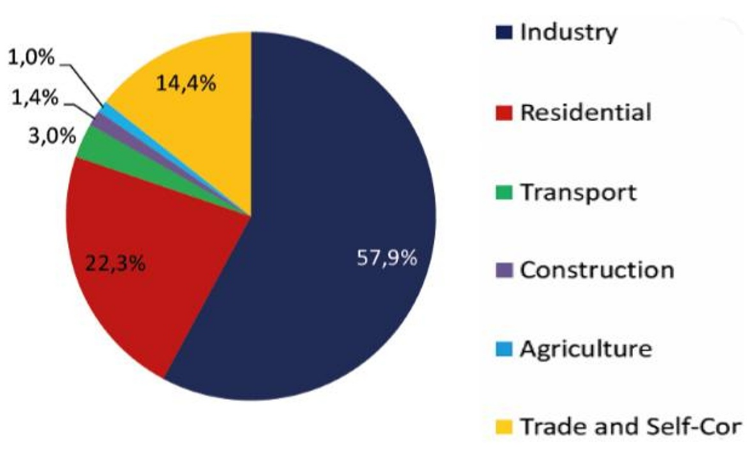

Fig. 3. Structure of electricity consumption in Kazakhstan.

To reduce electricity losses during transmission, it is necessary to optimize the operating modes of power grid equipment and to modernize and upgrade transmission infrastructure. These measures can significantly decrease energy losses in the grid; however, under Kazakhstan's current conditions, it is impossible to reduce transmission losses below a certain threshold (see Figure 4) [5, 6].

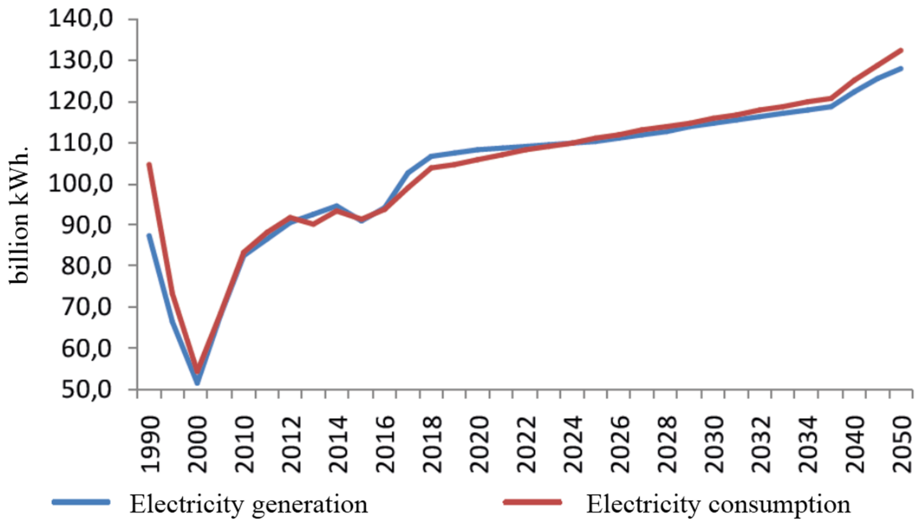

Fig. 4. Forecast of electricity production and consumption in Kazakhstan until 2050 (billion kWh).

The dominant factor influencing Kazakhstan's electricity consumption is the activity level of export-oriented industries, whose demand largely depends on the situation in global metal markets as well as on oil production and transportation volumes. In the housing and utilities sector, the gradual and steady growth of the population will lead to an increase in electricity demand. However, this growing demand can be effectively managed through the implementation of energy-saving measures, ensuring that the needs of the population are met efficiently. According to IHS Markit's electricity consumption forecast, there is no significant need to increase Kazakhstan's base generation capacity until 2030. Nonetheless, considering the projected commissioning of up to 2.5 GW of wind and solar power plants, the country will need to introduce additional maneuverable (flexible) capacities to maintain grid stability. The primary function of a wind power plant is to convert the kinetic energy of the wind into electrical energy. At first glance, this appears to be a highly convenient and sustainable energy source, offering seemingly "free" electricity from the wind. However, despite the well-understood principles of kinetic-to-electric energy conversion, controlling the natural behavior of wind remains a complex challenge. Since every region on Earth experiences different wind patterns, variability in wind speed, direction, and consistency poses significant challenges. There are periods when the wind is completely absent, followed by times of extremely strong gusts or storms. Due to these natural fluctuations in wind characteristics, the process of converting wind's kinetic energy into stable electrical energy cannot be achieved easily or continuously [7–11].

4 Conclusion

The conducted analysis demonstrates that Kazakhstan possesses a vast potential for the development of wind energy, supported by favorable climatic conditions and extensive territories suitable for wind farm construction. The regions of the Dzungarian Gate, the

Shelek Corridor, and parts of the Akmola, Zhambyl, and Mangystau regions exhibit particularly high wind potential, providing a solid foundation for the deployment of large-scale wind power plants. The steady growth in electricity consumption, driven by industrial expansion and population increase, highlights the urgent need to diversify the country's energy mix and reduce dependence on fossil fuels. Wind energy represents one of the most promising directions for achieving sustainable energy development, reducing greenhouse gas emissions, and ensuring national energy security. However, the further advancement of wind energy in Kazakhstan requires addressing several scientific, technical, and economic challenges. These include the need for detailed meteorological assessments, optimization of turbine design for local conditions, integration of smart grid technologies, and improvement of storage and balancing systems to compensate for the natural intermittency of wind.From an economic standpoint, the long-term competitiveness of wind energy depends on state support mechanisms, such as preferential tariffs, tax incentives, and investment in local production of wind turbine components. Establishing a strong scientific and industrial base will enable Kazakhstan to become a regional leader in renewable energy technologies.

In conclusion, the development of wind energy in Kazakhstan is not only an environmental necessity but also a strategic priority that can drive technological innovation, attract foreign investment, and contribute to the sustainable growth of the national economy.

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