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# Renewable Energy and Sustainable Development in a Resource-Abundant Country: Challenges of Wind Power Generation in Kazakhstan

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**Abstract:** In recent years, the environmental effects of energy production have increasingly entered into the foreground of the sustainable development agenda. Hydrocarbon-abundant countries are blamed to become the largest emitters of greenhouse gases, trace metals, and other pollutants due to extensive use of oil, gas, and coal in energy production. Combustion of fossil fuels for heat and power generation is reported to be among the major reasons for progressing climate change globally. The United Nations and other international actors have called on national governments to substantially increase the share of renewable energy, but the main point is how to incentivize the resource-rich countries to shift to greener technologies. For the example of Kazakhstan, whose energy sector is centered on coal, this paper discusses the challenges and prospects of wind power as both an environmentally friendly and efficient option to support a transition of a resource-rich country to a green economy and a sustainable energy future. Forty-two locations across the country have been assessed on the parameters of average annual wind speed, wind availability, and four types of potential for wind power production: gross, technical, economic, and emissions reduction. Some of the key findings are that at the height below 50 m above ground level, wind power production is economically viable in electricity-deficientt southern territories, particularly, in Djungar, Saryzhas, Zhuzimdyk, and Taraz. In western, central, and northern parts of Kazakhstan, at a height above 50 m, the most promising areas for wind power production are Caspian, Northwestern, Central, and Tarbagatay corridors. The paper identifies the areas with the highest emission reduction potential and elaborates the policies to encourage the selection of wind farm locations based on their “economic potential-environmental effect” ratio. The approach allows assessing the opportunities, which decentralized wind energy systems offer to transition away from a dependence on fossil fuels and to enable sustainable economic growth.

**Keywords:** electricity; environment; fossil fuel; greenhouse gases; Kazakhstan; renewable energy; sustainable development; wind power

## 1. Introduction

Global energy resources are split into three major categories: fossil fuels, nuclear resources, and renewable resources, often called alternative sources of energy [1]. Among the three, the fossil fuel sector dominates as the major generator of power and electricity worldwide. At the same time, fossil fuel combustion contributes the most to atmospheric pollution with greenhouse gases, such as carbon dioxide and methane, and other air contaminants, such as nitrogen oxides [2]. The largest contribution to the greenhouse effect stems from the emissions of carbon dioxide, 75% of which, in turn, result from the combustion of fossil fuels for the generation of energy, in particular, by coal-fired thermal power plants [3]. In 2017, the amount of carbon dioxide in the atmosphere surpassed a record high—406.5 parts per million [4]. Depending on the fuel used, power plants can also release trace metals, such as mercury [2].

There is growing concern about the effects of conventional coal-fired power production on the global environment. Excessive consumption of coal and other fossil fuels for power generation has a significant adverse impact on the environment, resulting in increased health risks and the threat of global climate change [5]. The year 2016 became the hottest year since 1880 [6]. In 2017, a combined land surface, air, and sea-surface water temperature (NASA Index) was 0.9 °C higher compared to the 1951–1980s [6]. The United Nations (UN) estimates that, in the absence of a significant reduction in emissions, global temperatures could rise by 4 °C by 2050 and 6 °C by 2100 [7]. The effects of growing emission of greenhouse gases (GHG) have become central to the discussion of sustainable development. In its Sustainable Development Goals (SDGs), the UN encourages national governments to integrate climate change measures into their policies and planning and substantially increase the share of renewable energy in the energy mix [8]. A Global Initiative on Sustainable Energy for All aims at providing universal access to modern energy services; doubling the global rate of improvement in energy efficiency; doubling the share of renewable energy in the global energy mix by 2030 [7]. A reduction of coal-fired power generation, particularly, in developing countries was one of the goals of the Paris Agreement under the UN Framework Convention on Climate Change (UNFCCC) [9]. The projects that have already been implemented under the UNFCCC framework allowed avoiding 1.8 Gt of carbon dioxide emissions in 2017 [4].

Amid the progressing climate change and growing efforts on the reduction of GHG emission, there have recently been increasingly important shifts in power-generating sector [10]. The global community has started focusing on renewable energy as an important part of the energy portfolio [11], a method of effective waste minimization and sustainable production [12], and a mechanism for achieving sustainable development [13]. Jonaitis et al. [14] report that in order to mitigate the effects of human activities on the environment, governments worldwide have promoted the use of renewable energy sources which can be used to generate power permanently [15], i.e., solar, wind, biomass, hydro and geothermal energy, ocean wave energy, and biofuels [16–18]. The developing technologies that are becoming cheaper allow wider renewable energy development [14]. In a decade, the proportion of world electricity generated by renewable sources increased to 12.1% in 2017, a record, up from 5.2% in 2007 [4]. The major rationale for growth and development of renewable energy sector have been the following:

- renewable energy sources emit significantly less GHG, particularly, carbon dioxide and other pollutants [19], and actually contribute to significant reductions in GHG emissions [20];
- generation of renewable energy has minimal impact on physical and natural environment [21], flexible to various landscapes, and has lower requirements to infrastructure, compared to coal-fired power plants;
- production of renewable energy in decentralized manner helps meeting the rural and small-scale energy needs in remote and sparsely populated areas, including desert and mountain zones, natural reserves, and specially protected territories, in a reliable and environmentally sustainable way [22];
- implementation of renewable energy projects has social and territorial development effects, particularly, in rural areas, where it can create job opportunities and bring other economic benefits [23];
- renewable energy generating facilities require less maintenance costs compared to traditional energy generators [24].

One of the most environmentally benign sources of renewable energy is wind power [25]. As of Gagliano et al. [26], among the renewable resources of energy, wind power constitutes a feasible alternative to conventional energy supply systems. For wind energy, no pollutants are emitted during electricity production, adverse health effects have not been registered, disturbing impacts from noise are very low, impacts on birds and animals are negligible [27]. In 20 years, an exploitation of wind power turbine (1 MW average capacity) saves approximately 29,000 tons of coal or 92,000 barrels of oil, thus avoiding emissions of 1800 tons of carbon dioxide, nine tons of sulfur dioxide, and four tons of nitrogen oxide [4]. Wind energy for electricity production is widely used in many countries, primarily, China, the USA, Germany, and India [28]. The sector of wind-powered electricity generation reached a global capacity of 539 GW in 2017, a 69.3% growth since 2013 [29]. Wind turbines which have been installed worldwide by 2018 can cover over 5% of the global electricity demand [29] and thus help avoiding many million tons of carbon dioxide and other emissions [11,30].

The growth of wind power generation has been driven by not only environmental considerations and international commitments of the governments, but also energy security, particularly in resource-poor countries. For such countries as Denmark, Germany, Ireland, Portugal, and Spain, wind power has become a pillar in their strategies to phase out fossil energy [29]. Continued investments in wind power are considered as a means of reducing dependency on imported fossil fuel and improving national energy security [31]. Renewable energy sources supplement the traditional power production and, thus, diversify the energy mix of a country [32]. Gagliano et al. [26] suggested that wind turbines represent a possible way to realize distributed power generation. Diversification is crucial for stable development of energy sector in the countries short of fossil fuel reserves, where wind power generating facilities can be installed and transmitted very rapidly, even in remote and inaccessible areas [33].

For resource-abundant countries, however, the main drawback is that renewable energy is commercially uncompetitive compared to cheap and readily available fossil fuel reserves. For most of the resource-abundant countries, electricity production sector is not only an important component of national economy, but also a substantial export earner. Wind energy sources have small capacity compared with traditional fossil fuel generators [34], which prevents them from producing energy in large amounts. In the fossil fuel-abundant countries, therefore, renewable energy generation is considered as too expensive compared to the conventional one [35], unsustainable in the long term [36], and only possible owing to state support [24,37].

In this paper, a possibility of a shift to wind energy for an economy centered on fossil fuels has been studied in the case of Kazakhstan, a country located in the center of the Asian continental landmass between the Caspian Sea in the west and Tien Shan and Pamir mountains in the east [38]. Kazakhstan has a coal resource of approximately 40 billion tons and over 40 billion barrels of proven oil reserves, the third-largest outside of the Organization of the Petroleum Exporting Countries (OPEC) [39]. The specifics of energy consumption in Kazakhstan is determined by the continental climate, i.e., intensive heating during harsh winters and air conditioning during hot summers [40]. In recent decades, the economic growth and industrial development of Kazakhstan have driven increased demand for energy, which is forecasted to reach 180 TW by 2030 [41]. Approximately 85% of electricity is produced in the industrial north, primarily in Pavlodar and Karaganda regions, by thermal power plants located near coal mines (Table 1).

**Table 1.** Electricity balances in the administrative regions of Kazakhstan in 2017, TW.

| Zone/Region | Output | Domestic Consumption | Balance |
|---|---|---|---|
| **Western zone, total** | **23.562** | **24.574** | **−1.012** |
| West Kazakhstan Region | 9.931 | 10.157 | −0.226 |
| Atyrau Region | 4.557 | 4.995 | −0.438 |
| Aktobe Region | 3.791 | 5.294 | −1.503 |
| Mangystau Region | 5.283 | 4.128 | +1.155 |
| **Northern zone, total** | **63.581** | **46.132** | **+17.449** |
| Kostanay Region | 1.300 | 5.143 | −3.843 |
| North Kazakhstan Region | 3.229 | 2.978 | +0.251 |
| Akmola Region | 0.884 | 3.127 | −2.243 |
| Pavlodar Region | 34.205 | 14.124 | +20.081 |
| Karaganda Region | 14.033 | 11.473 | +2.560 |
| East Kazakhstan Region | 9.930 | 9.287 | +0.643 |
| **Southern zone, total** | **9.733** | **16.851** | **−7.118** |
| Kyzylorda Region | 1.557 | 2.598 | −1.041 |
| South Kazakhstan Region | 0.990 | 4.744 | −3.754 |
| Zhambyl Region | 2.895 | 4.512 | −1.617 |
| Almaty Region | 4.291 | 4.997 | −0.706 |

Source: authors' development based on [42].

There is a pronounced specialization of power plants on particular types of fuel, i.e., natural gas in the western regions around the Caspian Sea with large deposits of gas and coal in the northern regions around Ekibaztuz coal basin (Table 2). Old coal-fired power plants, particularly those located in Pavlodar and Karaganda, are very high emitters of carbon dioxide and other GHG pollutants. Kazakhstan coal is predominantly high ash (primarily Ekibastuz coal with ash content of 35–53% [43]) and polluting since thermal power plants are not routinely fitted with sulfur and nitrogen oxide flue gas scrubbers [44].

**Table 2.** Intensity of GHG emission from electricity generation.

| Zone/Region | Breakdown of Power Generation Sources in Electricity Production, % of Total | | | | Intensity of GHG Emission, g$CO_2$ eq/kWh |
|---|---|---|---|---|---|
| | **Coal** | **Natural Gas** | **Crude Oil** | **Oil Products** | |
| **Western zone** | | | | | **419.2** |
| West Kazakhstan Region | 0.3 | 96.2 | 0.4 | 3.1 | 426.8 |
| Atyrau Region | 0.2 | 95.7 | 0.5 | 3.6 | 409.3 |
| Aktobe Region | 0.4 | 64.5 | 26.7 | 8.4 | 342.9 |
| Mangystau Region | 0.1 | 97.8 | 0.3 | 1.8 | 497.6 |
| **Northern zone** | | | | | **828.4** |
| Kostanay Region | 96.8 | 2.1 | 0.3 | 0.8 | 723.8 |
| North Kazakhstan Region | 98.3 | 0.3 | 0.2 | 1.2 | 902.4 |
| Akmola Region | 98.7 | 0.2 | 0.2 | 0.9 | 706.9 |
| Pavlodar Region | 98.9 | 0.1 | 0.2 | 0.8 | 966.3 |
| Karaganda Region | 96.0 | 0.3 | 1.3 | 2.4 | 1129.7 |
| East Kazakhstan Region | 99.1 | 0.1 | 0.1 | 0.7 | 541.2 |
| **Southern zone** | | | | | **630.1** |
| Kyzylorda Region | 0.3 | 0.1 | 88.4 | 11.2 | 799.6 |
| South Kazakhstan Region | 3.1 | 59.4 | 0.1 | 37.4 | 511.7 |
| Zhambyl Region | 0.2 | 52.6 | 0.4 | 46.8 | 594.3 |
| Almaty Region | 92.5 | 3.7 | 0.3 | 3.5 | 614.8 |

Source: authors' development.

According to Jonaitis et al. [14], major problems which must be solved to support the development of wind energy are the ensurance of power transmission capacity of the electricity network, balancing the energy generated by wind power plants related to the error control of forecasting, and transition of the energy system from conventional to renewable generation. The electricity transmission networks across Kazakhstan are inefficient with losses during transmission and distribution estimated at approximately 15% of energy produced. In winter, electricity supply is sometimes unable to meet demand, leading to electricity shortages and adverse effects on regional economic development [45].

Kazakhstan's power-generating sector has, thus, faced two major challenges: (1) reliability of the power supply of densely populated central and, primarily, southern territories of the country; and (2) the decrease of adverse impact or power-generating facilities on the environment in the northern territories and throughout the country. The challenges are urgent for Kazakhstan, which recent industrial development has driven increased demand for power thus making the expansion of generating facilities necessary for enabling economic growth, but increasingly destructive for the environment [37,41].

In order to decrease emissions and meet the electricity demand, a decentralized, efficient, and environmentally friendly energy supply system is needed. In this context, renewable energy resources are becoming an attractive option to help bridge the gap between economic growth, environmental considerations, and sustainable growth. Among the countries rich in hydrocarbon and fossil fuel resources, Kazakhstan is one of the best suited for the development of alternative renewable energy, particularly wind power. The country is located along the wind belt of the northern hemisphere, where winds are strong (annual average wind speed is above 6 m/s, which is suitable for energy generation [45]) and stable (primarily northeast and southwest) [46]. For the period of 2013–2017, the generation of wind energy in Kazakhstan has skyrocketed. In 2017, wind power facilities generated over 300 MWh, 100 times more compared to 2013. As of 2018, three wind power plants (67.6 MW total capacity) have been launched in Zhambyl and Akmola regions [47]. By 2020, the government plans to launch new windmills with a total capacity of 793 MW [24] and increase the total share of renewable power generation to 11% by 2030 [48].

Despite such ambitious plans, however, renewable sources of energy currently contribute less than 1% of Kazakhstan's energy mix. Extensive wind potential (around 1.8 TW [49]) has not been sustainably captured and deployed due to a range of economic, technical, and institutional barriers. At the same time, Kazakhstan's power generation is responsible for increasing carbon dioxide emissions of 275 Mt with 80% derived from thermal power plants due to the low efficiency of power generation and outdated facilities [50]. Therefore, fundamental work in, first, understanding the potential of wind power energy and, second, outlining the policy challenges is required in order to assess the opportunities which decentralized wind energy systems offer to transition away from a dependence on fossil fuels and to enable sustainable economic growth.

The existing studies have not agreed on the estimation of Kazakhstan's potential in terms of wind power generation and have almost neglected a link between wind speed conditions and GHG emissions reduction potential in various parts of the country. Aghbalou et al. [51], however, demonstrated that the impact of the random behavior of the wind speed could have a significant consequence in terms of annual energy production and then the profitability of a wind power plant. The method developed by Aghbalou et al. [51] is based on the assessment of structural reliability in wind energy and allows selecting the wind farm locations taking into account the uncertainties derived from the random behavior of wind speed. Hetzer et al. [52] attempted to measure wind power uncertainty with involvement of the factors related with both underestimation and overestimation of available wind power. Lee et al. [53] proposed to select the optimal location for the construction of a wind farm based on the cost of energy and annual net profit, while Albadi and El-Saadany [54] used the capacity factor. Technical characteristics of wind turbines were addressed in the turbine cost index and the integrated matching index by Dong et al. [55], and created a normalized turbine performance index by

Chang et al. [56]. Wang et al. [57] proposed a wind power penetration model to minimize opposite objectives of wind speed uncertainty, including operational cost and security factors.

None of those approaches, however, can simultaneously focus on wind speed characteristics of a location and GHG emissions reduction effect. Jin et al. [58] attempted to link wind power uncertainty with carbon prices in purpose to quantitatively describe investment attitudes according to the specific carbon price and obtain a balanced carbon power dispatching strategy. In that model, economic and environmental dimensions addressed neither the economic potential of wind power production nor GHG emissions reduction. In a resource-abundant country, however, the assessment of a combined effects of those two factors on sustainable development is certainly important for balancing low-carbon power strategy.

## 2. Materials and Methods

Based on the specifics of electricity generation in various parts of Kazakhstan, for the purposes of this study, the territory of the country has been divided into three major power generation zones (Figure 1). The territories within Zone I depend on large reserves of oil and natural gas, which are primarily used in electricity generation in the region. Coal-burning power plants located in Zone II are the major producers of electricity in the country. Zone III lacks energy sources and imports the power shortfall from energy-abundant Zone II.

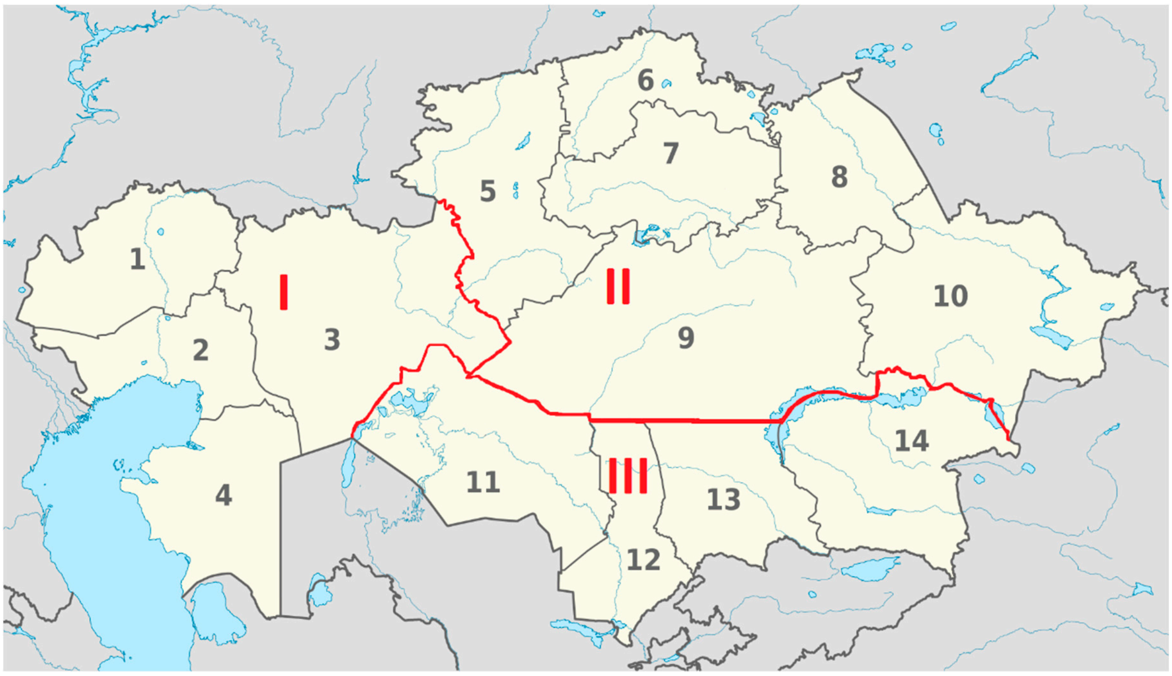


**Figure 1.** Power generation zones in Kazakhstan. Source: authors' development. Note: I (Western Zone): 1—West Kazakhstan Region; 2—Atyrau Region; 3—Aktobe Region; 4—Mangystau Region; II (Northern Zone): 5—Kostanay Region; 6—North Kazakhstan Region; 7—Akmola Region; 8—Pavlodar Region; 9—Karagandy Region; 10—East Kazakhstan Region; III (Southern Zone): 11—Kyzylorda Region; 12—South Kazakhstan Region; 13—Zhambyl Region; 14—Almaty Region.

The assumption is that the establishment of new wind farms allows (1) in Zone II, decreasing the share of coal in fuel mix and thus decreasing GHG emissions; (2) in Zone II, making wind power generation cost-effective compared to the coal-fired industry; (3) in Zone I, making wind power generation cost-effective compared to the gas-fired industry; and (4) in Zones I and III, diversifying power generation sources and decreasing the dependence of the territories on electricity imports.

To address the above-mentioned issues, the possibility of establishment of potential wind farm sites has been studied for the power generation zones I–III. Wind speed ($V$) is a basic parameter to decide on the location of a wind farm, however, the simulation of the wind speed in the long run is difficult due to the fluctuating direction, energy, and density of wind flow [59]. Wind power generators are commonly established at heights of 50 m to 100 m above ground level [60]. Therefore, in each of the zones, the selection of potential sites has been made based on the wind conditions at the two heights, specifically, in the areas where average annual wind speed is above 7.5 m/s. The annual average wind speed data of various locations obtained from Renewable Energy Atlas of Kazakhstan [61]. Further, the selected potential sites have been assessed on the criteria described below.

### *2.1. Wind Availability*

For the purpose of stable power generation, wind speed has been assessed in conjunction with its probability to be within the operational threshold. This parameter has been called wind availability, or a percentage of time within a year when the wind speed actually allows operating a wind farm. According to Akhmetov [62], normally, the majority of power generating facilities operate at the wind speed between 3.5 m/s and 25 m/s.

To assess wind availability, the authors have employed the Weibull distribution, a statistical distribution most commonly used for analyzing wind density and stability data. Among probability functions used in the wind data studies by Carta et al. [63], Fadare [64], Akdag et al. [65], Darwish and Sayigh [66], and Aghbalou et al. [51] Weibull distribution demonstrated the best agreement with the data obtained during field experiments and wind speed measurements.

The following equation of two-parameter Weibull distribution has been employed:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \quad (1)$$

where:

- $f(V)$—probability of achieving wind speed $V$;
- $V$—average annual wind speed, m/s;
- $k$—frequency distribution (Weibull dimensionless shape factor), $k = 1.6 \div 3.0$; and
- $c$—dimension speed (scale factor), $c \approx 2\overline{V}\sqrt{\pi}$.

Weibull factors $k$ and $c$ demonstrate the distribution of the winds for a particular location [67]. The following scale is implemented to measure the degree of wind availability: good—$f(V) \geq 0.90$; average—$0.75 \leq f(V) < 0.90$; and low—$f(V) < 0.75$.

### *2.2. Gross Potential of Wind Power Engineering*

The calculation of the gross potential ($GP$) has been made for each location based on the approach of Barinova and Lanshina [10]:

$$GP = \sum PW \times SA \times t \quad (2)$$

where:

- $GP$—gross potential of wind power engineering, kWh;
- $PW$—power-weight ratio of wind flow;
- $SA$—swept area of a windmill, m$^2$; and
- $t$—period of time;

Power-weight ratio of wind flow is calculated as follows:

$$PW = \frac{1}{2} d \sum_{i=1}^{n} V_i^3 p_i \quad (3)$$

where:

- $PW$—power-weight ratio of wind flow;
- $d$—average air density, kg/m$^3$;
- $V_i$—average wind speed within the range $i$, m/s; and
- $p_i$—wind speed probability within the range $i$.

### 2.3. Technical Potential of Wind Power Engineering

Technical potential ($TP$) of a particular wind farm location is calculated based on the obtained $GP$ values, share of the territories within location appropriate for wind power generation and wind energy efficiency:

$$TP = GP \times L \times E_c \quad (4)$$

where:

- $TP$—technical potential of wind power engineering, kWh;
- $GP$—gross potential of wind power engineering, kWh;
- $L$—share of the territories within location appropriate for wind power generation; and
- $E_c$—wind energy efficiency coefficient.

The $L$ parameter has been determined based on the data obtained from the Ministry of National Economy of the Republic of Kazakhstan [42]. For the purpose of this study, the $E_c$ parameter is 0.4, an average value for modern wind power generation facilities according to the Royal Academy of Engineering [68], Verma et al. [69], and Zhang [70].

### 2.4. Economic Potential of Wind Power Engineering

To assess the economic potential ($EP$) of wind power engineering, levelized cost of wind-generated electricity ($LCOE$) has been compared to the average weighted tariffs for electricity applied to industrial consumers. Residential tariffs applied to personal consumers have not been considered due the multiplicity of tariff schemes depending on the type of personal consumption (households with and without electric stoves), volume of consumption (three levels), and diversity of tariff rates in various administrative regions of the country (central and regional subsidies).

The following equation has been used:

$$LCOE = \frac{CE + \sum_{n=1}^{N} \frac{OE_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+r)^n}} \quad (5)$$

where:

- $LCOE$—levelised cost of electricity, $;
- $CE$—capital expenditures, $;
- $OE_n$—operational expenditures in year $n$, $;
- $r$—discount rate, %;
- $N$—operating life of power generating facilities, years; and
- $E_n$—electric power output in year $n$, kWh.

If $LCOE$ does not exceed a tariff, $EP$ of a territory in terms of wind power generation is taken to be equal to the $TP$ of a wind farm.

Data on capital and operational expenditures and operating life of power generating facilities have been obtained from the Ministry of National Economy of the Republic of Kazakhstan [42] and

UNDP reports [71,72], particularly, *CE*—$1250 per 1 kW of installed capacity, *OE*—$35 per 1 kW of installed capacity per year, *N*—20 years, *r*—10%.

### 2.5. GHG Emission Reduction Potential

The authors' approach to the evaluation of emissions reduction potential (*ERP*) has been based on the methodology developed by Kazakh Research Institute for Ecology and Climate [73] and the studies of Gassan-zade [74] and Akhmetov [62]. The intensity of emissions of three gases (carbon dioxide, methane, and nitrogen oxide) has been calculated based on fuel consumption data [42] and country-specific emission factors [62,75].

Carbon dioxide ($CO_2$) emissions:

$$V_{CO_2} = F \times Ox \times NCV \times Ce \times \frac{44}{12} \quad (6)$$

where:

- $Vco_2$—volume of $CO_2$ emission, g/kWh;
- *F*—volume of fuel required to generate 1 kWh;
- *Ox*—oxidation coefficient (a fraction of carbon oxidized during combustion);
- *NCV*—country-specific net caloric of fuel, TJ/natural unit;
- *Ce*—carbon emission coefficient, tC/TJ; and
- 44/12—conversion ratio of C to $CO_2$.

Methane ($CH_4$) emissions:

$$V_{CH_4} = F \times NCV \times Me \quad (7)$$

where:

- $Vc_{H4}$—volume of $CH_4$ emission, g/kWh;
- *F*—volume of fuel required to generate 1 kWh;
- *NCV*—country-specific net caloric of fuel, TJ/natural unit; and
- *Me*—methane emission coefficient, tC/TJ.

Nitrogen oxide ($N_2O$) emissions:

$$V_{N_4O} = F \times NCV \times NOe \quad (8)$$

where:

- $V_{N2O}$—volume of $N_2O$ emission, g/kWh;
- *F*—volume of fuel required to generate 1 kWh;
- *NCV*—country-specific net caloric of fuel, TJ/natural unit; and
- *NOe*—nitrous oxide emission coefficient, tC/TJ.

In order to allow a comparison between the intensity of emissions of carbon dioxide, methane, and nitrogen oxide, GHG emission has been expressed in grams of $CO_2$ equivalent emitted per 1 kWh of generated power ($gCO_2eq$/kWh), the most commonly used measure in various sources [76–79]. Total reduction potential of each location has been further measured in tons of $CO_2$ equivalent ($tCO_2eq$).

## 3. Results

Seasonal fluctuations and annual average wind speed at the heights of 50 m and 100 m have been studied for 42 locations in the three power generation zones (Table 3). According to the UNDP and the experts, at wind speed 7.5–8.0 m/s, the cost of power generation goes down to that in coal-fired power industry and at the wind speed 8.5–9.0 m/s—to that in gas-fired generation [24,49,71,80]. In light of this estimation, in most of the potential locations in Kazakhstan, wind power may compete with fossil fuel only in case of the construction of big generating facilities over 50 m high.

**Table 3.** Average wind speed across the power generation zones, m/s.

| Zone/Location | Winter | | Spring | | Summer | | Autumn | | Average Annual (V) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 m | 100 m | 50 m | 100 m | 50 m | 100 m | 50 m | 100 m | 50 m | 100 m |
| **Zone I** | | | | | | | | | | |
| Aktau | 6.5 | 8.5 | 6.5 | 8.5 | 5.5 | 8.0 | 6.5 | 8.0 | 6.25 | 8.25 |
| Aktobe | 6.0 | 9.0 | 6.5 | 8.5 | 5.0 | 7.5 | 5.5 | 8.5 | 5.75 | 8.38 |
| Atyrau | 6.0 | 8.0 | 6.0 | 8.0 | 6.0 | 8.0 | 6.5 | 8.5 | 6.13 | 8.13 |
| Emba | 5.5 | 8.0 | 6.0 | 8.0 | 5.0 | 7.5 | 5.5 | 8.0 | 5.50 | 8.00 |
| Fort Shevchenko | 6.5 | 9.5 | 6.0 | 8.5 | 5.0 | 7.5 | 6.5 | 8.5 | 6.00 | 8.50 |
| Kandyagash | 6.0 | 9.0 | 6.0 | 8.5 | 5.0 | 7.0 | 5.5 | 8.5 | 5.63 | 8.25 |
| Karabatan | 5.0 | 8.0 | 5.5 | 7.5 | 5.0 | 7.5 | 6.0 | 7.5 | 5.38 | 7.63 |
| Kulsary | 5.0 | 7.0 | 5.5 | 7.5 | 5.0 | 7.0 | 5.0 | 7.0 | 5.13 | 7.13 |
| Makat | 5.0 | 7.0 | 5.5 | 7.0 | 5.0 | 7.5 | 5.0 | 7.0 | 5.13 | 7.13 |
| Shalkar | 5.0 | 7.0 | 5.5 | 7.5 | 5.0 | 7.5 | 5.5 | 7.5 | 5.25 | 7.38 |
| Uralsk | 5.5 | 8.0 | 5.5 | 7.5 | 4.5 | 6.0 | 5.0 | 7.0 | 5.13 | 7.13 |
| Zhanaozen | 6.0 | 7.5 | 6.5 | 8.0 | 6.0 | 8.0 | 6.5 | 8.0 | 6.25 | 7.88 |
| **Zone II** | | | | | | | | | | |
| Arkalyk | 6.0 | 8.0 | 6.0 | 7.5 | 5.5 | 7.0 | 6.0 | 8.0 | 5.88 | 7.63 |
| Astana | 6.5 | 8.5 | 6.5 | 8.0 | 5.5 | 7.0 | 6.0 | 8.0 | 6.13 | 7.88 |
| Atbasar | 5.5 | 7.5 | 5.5 | 8.0 | 4.5 | 6.0 | 5.0 | 7.5 | 5.13 | 7.25 |
| Ekibastuz | 5.5 | 7.5 | 5.0 | 7.0 | 4.5 | 6.5 | 5.5 | 7.5 | 5.13 | 7.13 |
| Erementau | 6.0 | 8.5 | 6.0 | 7.5 | 5.5 | 7.0 | 6.0 | 8.0 | 5.88 | 7.75 |
| Karaganda | 5.5 | 7.5 | 5.0 | 7.5 | 4.5 | 6.5 | 5.5 | 7.5 | 5.13 | 7.25 |
| Karkaralinsk | 6.0 | 8.0 | 5.5 | 7.5 | 5.0 | 7.5 | 6.0 | 8.0 | 5.63 | 7.75 |
| Kokshetau | 5.5 | 7.5 | 5.5 | 8.0 | 4.5 | 6.0 | 5.0 | 7.5 | 5.13 | 7.25 |
| Kostanay | 6.0 | 8.5 | 6.0 | 8.5 | 5.0 | 6.5 | 6.0 | 7.5 | 5.75 | 7.75 |
| Pavlodar | 5.0 | 7.5 | 5.0 | 7.0 | 4.5 | 6.0 | 5.0 | 7.0 | 4.88 | 6.88 |
| Petropavlovsk | 4.5 | 6.0 | 4.5 | 6.0 | 4.0 | 5.5 | 4.5 | 6.0 | 4.38 | 5.88 |
| Schuchinsk | 5.5 | 7.0 | 5.5 | 7.5 | 4.5 | 6.0 | 5.0 | 6.5 | 5.13 | 6.75 |
| Stepnogorsk | 5.5 | 7.5 | 5.5 | 7.0 | 4.5 | 6.0 | 5.0 | 7.0 | 5.13 | 6.88 |
| Urzhar | 6.5 | 7.5 | 6.0 | 8.0 | 5.5 | 7.5 | 6.5 | 8.5 | 6.13 | 7.88 |
| Zhezkazgan | 5.5 | 8.0 | 5.0 | 7.5 | 5.0 | 7.5 | 5.0 | 7.5 | 5.13 | 7.63 |
| **Zone III** | | | | | | | | | | |
| Akbakay | 6.0 | 8.0 | 6.0 | 7.5 | 5.5 | 7.5 | 6.0 | 7.5 | 5.88 | 7.63 |
| Aralsk | 5.0 | 6.5 | 6.0 | 7.5 | 5.5 | 7.5 | 5.0 | 7.0 | 5.38 | 7.13 |
| Chilik | 6.0 | 8.5 | 6.0 | 9.0 | 5.0 | 8.0 | 6.0 | 9.0 | 5.75 | 8.63 |
| Djungar | 8.0 | 9.5 | 7.5 | 8.0 | 7.0 | 8.0 | 8.0 | 9.0 | 7.63 | 8.63 |
| Kapshagay | 6.0 | 7.5 | 5.0 | 7.5 | 5.0 | 7.0 | 5.5 | 7.5 | 5.38 | 7.38 |
| Karakur | 7.0 | 8.0 | 6.5 | 7.5 | 6.0 | 7.5 | 7.0 | 7.5 | 6.63 | 7.63 |
| Kordai | 7.0 | 9.0 | 6.0 | 8.0 | 5.5 | 7.5 | 6.5 | 9.0 | 6.25 | 8.38 |
| Kyzylorda | 5.0 | 6.5 | 5.5 | 7.0 | 5.0 | 7.0 | 5.0 | 7.0 | 5.13 | 6.88 |
| Mirny | 5.5 | 7.0 | 5.0 | 7.0 | 5.0 | 6.5 | 5.5 | 7.0 | 5.25 | 6.88 |
| Sarkand | 6.0 | 7.5 | 5.0 | 7.0 | 5.0 | 7.0 | 5.5 | 7.5 | 5.38 | 7.25 |
| Saryzhas | 7.5 | 8.0 | 6.5 | 8.0 | 6.5 | 8.0 | 7.0 | 8.5 | 6.88 | 8.13 |
| Taldykorgan | 6.0 | 8.0 | 5.0 | 7.0 | 5.0 | 7.0 | 5.5 | 7.5 | 5.38 | 7.38 |
| Taraz | 7.0 | 9.0 | 6.0 | 7.5 | 6.5 | 8.0 | 7.0 | 8.5 | 6.63 | 8.25 |
| Zharkent | 7.5 | 10.0 | 6.0 | 8.0 | 5.5 | 7.5 | 8.0 | 9.5 | 6.75 | 8.75 |
| Zhuzimdyk | 8.0 | 8.5 | 7.5 | 8.5 | 7.5 | 8.5 | 7.5 | 9.0 | 7.63 | 8.63 |

Source: authors' development based on [61].

In Zone I, wind power generation may be cost-effective compared to the gas-fired industry (average annual wind speed over 8.5 m/s) in Fort Shevchenko only, however, several other sites (Aktau, Aktobe, Atyrau, Emba, Kandyagash, Karabatan, and Zhanaozen) also have high potential.

In Zone II, the winds are weaker than those along the coast of the Caspian Sea, but in many locations (Arkalyk, Astana, Erementau, Karkaralinsk, Kostanay, Urzhar, and Zhezkazgan) their speed still allows generating electricity at potentially lower costs compared to traditional coal-burning technology.

Zone III is predominantly mountainous, with strong winds during winter and autumn seasons. In this zone, the most prospective sites are located (Akbakay, Chilik, Djungar, Kordai, Saryzhas, Taraz, Zharkent, and Zhuzimdyk). In Djungar Gate and Zhuzimdyk, wind conditions allow operating power generators at the height below 50 m, which may reduce the costs substantially.

The selected locations have been further assessed on the wind availability parameter (Table 4). Out of 24 locations, the most stable winds ($f(V) \geq 0.90$) are in Djungar, Fort Shevchenko, Chilik, Atyrau, and Erementau. For some locations, $f(V)$ is high at the height 50 m, however, $V$ is rather low (Aktau, Arkalyk, Fort Shevchenko, Karkaralinsk, and Urzhar). Seven locations have been excluded from the study due to low wind availability (in Zone I, Kandyagash and Zhanaozen; in Zone II, Arkalyk and Karkaralinsk; in Zone III, Karakur, Kordai, and Zharkent).

**Table 4.** Wind availability in potential wind farm locations.

| Zone/Location | *V* | | *k* | | *c* | | *f(V)* | |
|---|---|---|---|---|---|---|---|---|
| | **50 m** | **100 m** | **50 m** | **100 m** | **50 m** | **100 m** | **50 m** | **100 m** |
| **Zone I** | | | | | | | | |
| Aktau | 6.25 | 8.25 | 2.45 | 2.18 | 7.74 | 8.02 | 0.92 | 0.85 |
| Aktobe | 5.75 | 8.38 | 1.68 | 1.97 | 8.03 | 8.14 | 0.79 | 0.83 |
| Atyrau | 6.13 | 8.13 | 1.97 | 2.03 | 7.98 | 7.65 | 0.85 | 0.90 |
| Emba | 5.50 | 8.00 | 1.80 | 1.88 | 6.61 | 6.83 | 0.51 | 0.88 |
| Fort Shevchenko | 6.00 | 8.50 | 2.43 | 2.21 | 7.88 | 8.11 | 0.94 | 0.92 |
| Kandyagash | 5.63 | 8.25 | 1.83 | 1.97 | 7.92 | 7.75 | 0.63 | 0.72 |
| Karabatan | 5.38 | 7.63 | 2.59 | 2.92 | 7.21 | 7.80 | 0.68 | 0.89 |
| Zhanaozen | 6.25 | 7.88 | 2.05 | 2.14 | 6.23 | 6.09 | 0.82 | 0.73 |
| **Zone II** | | | | | | | | |
| Arkalyk | 5.88 | 7.63 | 1.88 | 2.11 | 7.89 | 7.12 | 0.93 | 0.72 |
| Astana | 6.13 | 7.88 | 1.74 | 2.16 | 6.60 | 7.02 | 0.74 | 0.86 |
| Erementau | 5.88 | 7.75 | 1.66 | 1.86 | 8.03 | 8.82 | 0.87 | 0.90 |
| Karkaralinsk | 5.63 | 7.75 | 1.69 | 1.65 | 6.14 | 6.08 | 0.91 | 0.70 |
| Kostanay | 5.75 | 7.75 | 1.70 | 1.68 | 6.62 | 6.15 | 0.74 | 0.79 |
| Urzhar | 6.13 | 7.88 | 2.48 | 2.59 | 6.07 | 6.42 | 0.91 | 0.85 |
| Zhezkazgan | 5.13 | 7.63 | 2.06 | 2.18 | 6.22 | 6.84 | 0.88 | 0.83 |
| **Zone III** | | | | | | | | |
| Akbakay | 5.88 | 7.63 | 2.02 | 1.95 | 7.23 | 7.04 | 0.66 | 0.79 |
| Chilik | 5.75 | 8.63 | 2.74 | 2.87 | 8.32 | 8.50 | 0.70 | 0.92 |
| Djungar | 7.63 | 8.63 | 2.55 | 2.96 | 8.59 | 8.97 | 0.89 | 0.93 |
| Karakur | 6.63 | 7.63 | 1.63 | 1.78 | 7.66 | 7.94 | 0.61 | 0.74 |
| Kordai | 6.25 | 8.38 | 1.87 | 1.69 | 6.95 | 6.47 | 0.87 | 0.67 |
| Saryzhas | 6.88 | 8.13 | 1.70 | 1.82 | 7.34 | 7.22 | 0.84 | 0.82 |
| Taraz | 6.63 | 8.25 | 1.99 | 2.03 | 7.96 | 7.67 | 0.71 | 0.85 |
| Zharkent | 6.75 | 8.75 | 2.09 | 2.26 | 7.55 | 7.90 | 0.62 | 0.73 |
| Zhuzimdyk | 7.63 | 8.63 | 1.89 | 1.71 | 7.87 | 7.94 | 0.88 | 0.81 |

Source: authors' development based on [61].

For the remaining 17 locations, three types of potential have been assessed separately for the heights 50 m and 100 m (Table 5).

**Table 5.** Annual gross, technical, and economic potentials of selected wind farm locations, GWh.

| Zone/Location | *GP* | | *TP* | | *EP* | |
|---|---|---|---|---|---|---|
| | **50 m** | **100 m** | **50 m** | **100 m** | **50 m** | **100 m** |
| **Zone I** | | | | | | |
| Aktau | 745 | 1932 | 287 | 429 | 42 | 125 |
| Aktobe | 288 | 415 | 62 | 84 | 4 | 23 |
| Atyrau | 412 | 899 | 76 | 102 | 15 | 39 |
| Emba | 659 | 1528 | 308 | 497 | 22 | 152 |
| Fort Shevchenko | 1496 | 2145 | 499 | 636 | 46 | 181 |
| Karabatan | 128 | 483 | 66 | 95 | 10 | 19 |
| **Zone II** | | | | | | |
| Astana | 412 | 590 | 108 | 144 | 22 | 55 |
| Erementau | 995 | 1847 | 501 | 783 | 49 | 246 |
| Kostanay | 250 | 572 | 54 | 86 | 3 | 20 |
| Urzhar | 1266 | 2070 | 337 | 522 | 33 | 176 |
| Zhezkazgan | 157 | 336 | 60 | 97 | 6 | 22 |
| **Zone III** | | | | | | |
| Akbakay | 202 | 378 | 72 | 121 | 8 | 26 |
| Chilik | 259 | 501 | 108 | 166 | 17 | 49 |
| Djungar | 1996 | 2587 | 832 | 954 | 208 | 283 |
| Saryzhas | 1211 | 1806 | 403 | 512 | 50 | 197 |
| Taraz | 985 | 1458 | 315 | 489 | 61 | 142 |
| Zhuzimdyk | 1018 | 1671 | 507 | 554 | 129 | 156 |

Source: authors' development based on [10,42,71,72].

It has been confirmed, that at the height below 50 m above ground level, wind power production is economically viable in Zone III only, particularly in Alakol (Djungar) and Southern (Saryzhas–Zhuzimdyk–Taraz) corridors. In these areas, low-altitude winds are strong and stable enough to make the cost of electricity generation competitive compared to the expenditures involved in the import of power shortfall. In Zone I and Zone II, to be able to compete with gas and coal, respectively, wind power facilities over 50 m high should be established along the four identified corridors: Caspian (Atyrau–Fort Shevchenko–Aktau), Northwestern (Emba), Central (Astana–Erementau), and Tarbagatay (Urzhar) (Figure 2).

Due to the differences in the fuel mix between the zones and large variations of GHG emissions intensities from electricity generation (Table 2), the GHG emission reduction potential of the locations varies substantially (Figure 3).

Djungar is the most attractive place to develop wind power engineering, Strong winds, high wind availability, and the highest economic and GHG reduction potentials make this site the most prospective location to establish wind generating facilities at various altitudes. Other locations in Zone III also allow reducing GHG emissions due to stable winds along the mountainous valleys in Saryzhas, Zhuzimdyk, and Taraz. In Zone I, only Fort Shevchenko has high GHG emissions reduction potential due to high $V$ and $f(V)$. Other Zone I locations have moderate potential due to the moderate regional emissions intensity. Central corridor (Astana–Erementau) has an aggregated GHG emission reduction potential of over 830,000 $tCO_2eq$ because of the very high regional emissions intensity in Zone II, particularly in Karaganda and Akmola regions.

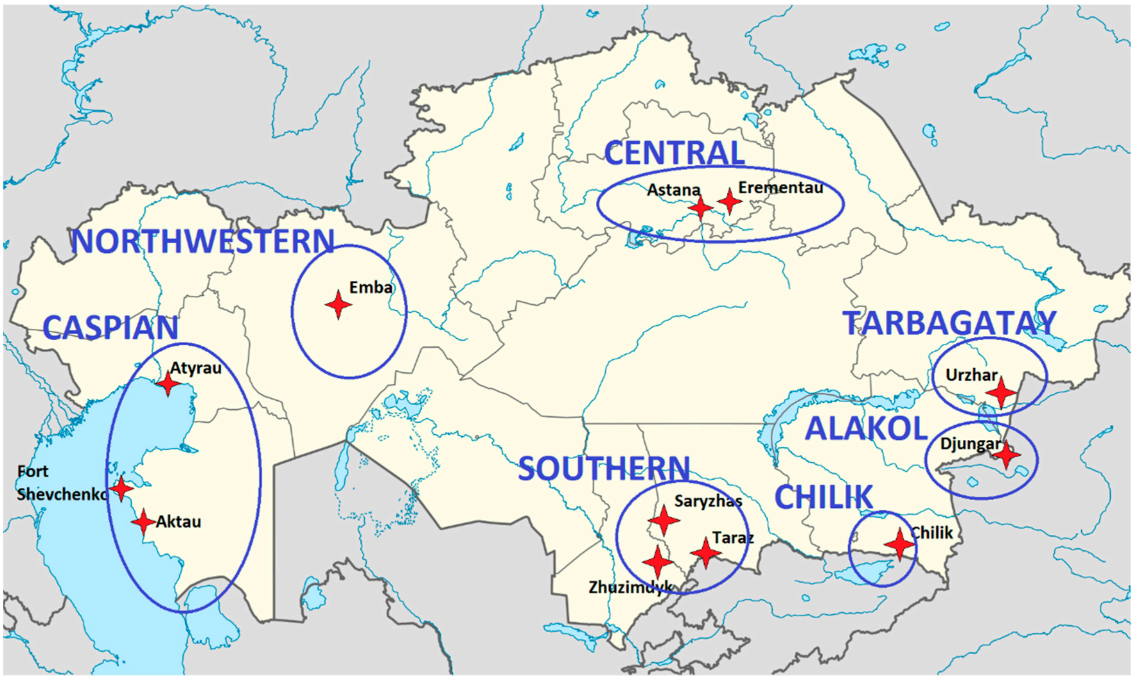


**Figure 2.** Potential wind power producing corridors. Source: authors' development.

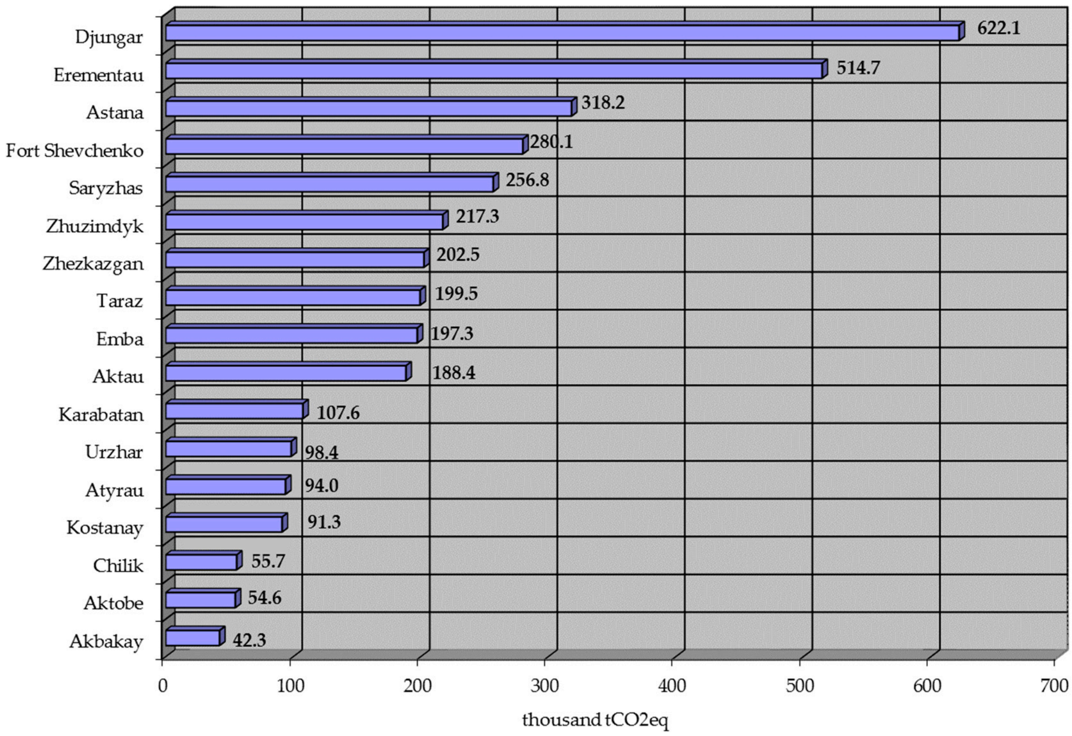


**Figure 3.** GHG emission reduction potential of selected wind farm locations, thousand $tCO_2eq$. Source: authors' development.

## 4. Discussion

Among the countries of Central Asia, Kazakhstan was the first to begin its transition to carbon-free energy. Since the early 2000s, there have been several initiatives (e.g., the Wind Power Market Development Initiative), programs (e.g., the Kazakhstan Climate Change Mitigation Program), and numerous studies that aimed to reduce the country's GHG emissions by developing the production and distribution of wind power [45]. Until now, however, an agreement on the potential sites for the establishment of wind farms and their environmental effects has not been reached.

United Nations Development Programme (UNDP) identified eight potential wind farm sites in Kazakhstan, particularly, Atyrau and Fort Shevchenko in Zone I, Arkalyk, Astana, Ermentau, and Karkaralinsk in Zone II, and Kordai in Zone III [71]. Such a configuration plan, however, does not address the critical problems of Kazakhstan's power engineering sector, namely, unequal distribution of electricity generating facilities across the territory of the country, dependence of densely populated western and southern territories on imports of electricity from the northern industrialized districts and other countries of Central Asia, and increasingly high GHG emissions in Zone II due to the dominance of coal in the energy mix. This study, first, increases the number of potential locations, particularly, in Zones I and III, and, second, demonstrates that the UNDP's Arkalyk, Karkaralinsk, and Kordai largely unfit for the purpose of wind power production due to their lower wind availability. The latter supports the findings of Akhmetov [62], who recognized Arkalyk, Karkaralinsk, and Kordai to be suitable for the installation of smaller power turbines due to lower wind characteristics of the locations.

Karatayev and Clarke [48] expanded the UNDP list by the inclusion of Djungar and Chilik and estimated that the two locations had power production potentials of 4400 kWh/MW and 3200 kWh/MW, respectively. A potential of the two sites for the production of electricity by wind turbines was also reported by Vakhguelt [81], Cochran [82], and Petersen [83]. Our assessment confirmed the highest gross and technical potentials of Djungar which may be converted into over 280 GW of economic potential of wind power production. In Chilik, however, despite high wind availability, the economic potential of wind power production is expected to be moderate. In Zone III, the Saryzhas–Zhuzimdyk–Taraz corridor should be preferred over Chilik due to its aggregate *EP* of 495 GWh and GHG emission reduction potential of over 670 thousand $tCO_2eq$. In this context, the findings of the study interfere with Doroshin [80] and Babazhanova et al. [24], who evaluated *TP* only and considered the territories along the Chilik Corridor the most promising ones in Southern Kazakhstan on that parameter.

Two sites not addressed in previous studies have demonstrated high economic and environmental potentials, namely, Emba in Zone I and Urzhar in Zone II.

In Zone I, the attention has been traditionally focused on the Caspian Corridor [24,48,80], primarily, on Fort Shevchenko [62,71]. High exploitability of this territory in terms of wind power has been confirmed, however, with not that promising economic potential of Atyrau. In most of the existing studies, the Aktobe Region has been overlooked completely due to the fact that the winds around Aktobe City are strong, but inconstant, with wide seasonal fluctuations and wind swings. According to Lee et al. [53], wind speed uncertainties may decrease the net annual profit by increasing the initial capital cost of installation and the operation and maintenance cost which may result due to the failure caused by excessive wind speed. In continuation of the UNDP [71] and other assessments [46,62], the entire Northwestern Kazakhstan, except Emba, has been found unsuitable for sustainable wind power production. Emba is located in the periphery of Aktobe wind convergence zone where winds are more stable, lower, but still strong enough to ensure cost-effective power generation.

In Eastern Kazakhstan, the government officials [84] and scholars [24,48] have been concentrating on the areas to the south of the Alakol nature reserve, primarily on Djungar Gate. However, the territories to the north of Alakol, in a valley between Urzhar and Tarbagatay Ridge, have also recorded a promising *EP*, second highest in Zone II after Erementau.

The aggregate economic potential of wind power production in prime twelve locations exceeds 1.8 TWh at the height 100 m above ground level (exactly coinciding with an estimation made by Kashkinbekov [49]). It appears substantially below the upbeat assessments of gross potential for wind energy declared by Kazakhstan's officials (920 TW, ten times the amount of electricity Kazakhstan consumes, according to Kanat Bozumbayev, Minister of Energy of Kazakhstan [85]), but definitely sufficient to fulfill the government's plan of the development of renewable energy sources that are expected to account for 3% of the total energy mix by 2020 [84]. Assisted by the United Nations

Development Program, the European Bank for Reconstruction and Development, and the Asian Development Bank, among others, Kazakhstan has adopted a range of public measures to support development of renewable energy [72]. However, to raise the share of renewable energy from current 1% to 3% within only a couple of years and further to 30% by 2030 and 50% by 2050 (as the Kazakhstan's National Concept for Transition to a Green Economy up to 2050 calls [45]), transformative actions have to be introduced. Albeit certain performance achieved in adopting new legal frameworks to encourage the transition of the energy sector towards renewable sources, there still exist significant barriers which do not allow establishing and maintaining an open dialogue on effective energy policies, environmental security, and sustainable development [48,86].

According to the EBRD [45], in Kazakhstan, the critical bars to wind power development are related to market, investment, policies, and awareness.

In terms of market, the major challenge has always been related to the efficiency of wind energy. Many scholars [37,82,87] have agreed that cheap coal and gas still prevent resource-rich Kazakhstan to move from a fossil fuel-driven energy production to alternative sources. This study, however, in support of the previous findings of Babazhanova et al. [24] and Karatayev and Clarke [48], has revealed the economic potential of wind power generation in not only electricity-deficient southern region, but also several locations in western and central parts of the country, where wind conditions allow competing with gas and coal-fired plants, respectively.

Efficiency of generation is largely discounted by low price of electricity in the country and uncertainties with the long-term power purchasing tariffs [48]. In 2013, the Renewable Energy Law established a renewable energy development framework and contributed significantly to encouraging national and international investments by a land plot allocation for the construction of wind farms, introduction of fixed tariffs, guaranteed purchase of wind energy at a fixed tariff over fifteen years, and exemption of payment for the transportation of electricity produced at wind farms [45]. The experts, however, call for even more incentives to attract foreign investment in wind energy and improve the access to credit for both consumers and investors [48,72,88]. Particularly, increased governmental support is required to overcome high initial financial and capital requirements, investment disincentives, and technological and logistical challenges in those locations, which have lower potential for wind power production. Among the identified promising wind power producing cites, Djungar, Urzhar, Saryzhas, and Chilik, are located in the highlands, far from the electricity-demanding populated areas, where infrastructure is underdeveloped. Transporting large-scale wind towers and equipment, their installation in the mountains, as well as electric power transmission from those areas substantially increase the cost of wind power [45]. Under such conditions, the investors tend to choose the projects, which are less effective, but supported by the government. One of the recent examples of a triumph of support over effectiveness is the Aktobe wind power plant whose construction started in 2017. The location, in which wind conditions are moderate ($f(V)$ = 0.83 at 100 m and 0.79 at 50 m, according to the present study) and economic potential of wind power production is low ($EP$ = 23 GWh at 100 m and only 4 GWh at 50 m), is still preferred by the investors because it is considered one of the easiest places to do business in Kazakhstan [85] and has reliable electricity, transportation, and communication infrastructure.

To ensure the attractiveness of wind power projects to investors, Kazakhstan should not only improve the energy-related infrastructure but also integrate renewable energy into the agenda. Despite the extensive public information campaign, the awareness of the opportunities associated with wind energy remains rather low, particularly, when it comes to potential environmental effects. Until now, those few studies which addressed the reduction of air emission from thermal power plants due to the development of alternative energy have actually assessed the overall effect for the entire country, not particular locations. As a consequence of this, the estimations are rather diverse and not commonly considered. Actually, none of the investors makes the investment decision on the grounds of the expected reduction of carbon emissions. An aggressive standard should be set that, first, requires a significant percentage of electricity to be generated from wind power [82] and, second, encourages the construction of wind farms in the locations where the GHG emissions reduction potential is the highest. Additionally, a long-term concept for the provision of sustainable energy services [89] should be developed in order to diversify power generation sources, correct the existing regional imbalances in energy sector, reduce the share of fossil fuel in the energy mix, decrease mortality from air pollution [32], and eventually support the transition of Kazakhstan, one of the resource-richest countries worldwide, to a green economy and sustainable energy future by 2050.

## 5. Conclusions

Having a very large, but sparsely populated, territory, Kazakhstan has enormous potential for renewable energy production, particularly, from wind. Due to the high speed of wind and relative stability of wind currents, most of the territory has been recognized as one of the best places in the world to produce wind energy [7]. At the same time, however, some of the world's largest proved oil, coal, and natural gas reserves have resulted in a negligible share of renewable sources in total energy production, a major portion of which is provided by high-polluting coal-fired plants.

Kazakhstan is a part of the Kyoto Protocol and Paris Agreement and, thus, tends to reduce greenhouse effect and increase the generation of energy from alternative sources. So far, one of the major impediments to scaling up the wind power sector has been lower economic viability of wind farms compared to thermal power plants. In recent years, however, a variety of wind power technologies have been improving and becoming increasingly cost-competitive with traditional fossil fuel-based sources, particularly against the background of erosion of current capital cost advantage of retiring old coal-fired generators. Gagliano et al. [26] acknowledged that wind turbines represent a possible way to produce renewable energy and reduce GHG emissions in case an adequate methodology to accurately predict wind energy production for a specific site was available. The approach employed in this study has allowed demonstrating that wind farms can generate attractive returns and bring along reduction of GHG emissions even in the areas where coal and gas dominate in the energy mix (northern and western Kazakhstan, respectively). Out of 42 locations across the country, twelve have been acknowledged as the most promising ones to launch wind power production in the context of both economic efficiency and expected environmental effect. Particularly, seven corridors have been identified whose aggregated *EP* is estimated to reach 497 GWh (100 m height) in Zone I, 477 GWh in Zone II, and 827 GWh in Zone III. Therefore, wind energy may contribute substantially to the diversification of power generation sources, decrease in the dependence of the southern territories on electricity imports, and improvement of energy security of the country. Due to the large size of Kazakhstan and the low population density, wind power generation represents an economically viable alternative to remote areas, even regardless of the abundance of the fossil fuel reserves. In this respect, this study contributes to the existing literature by developing an approach to the assessment of wind farm location based on wind conditions (speed and availability), economic potential, and GHG emissions reduction potential. This trilateral link has been almost neglected by international scholars (Jin et al. [58], Aghbalou et al. [51], Albadi and El-Saadany [54], among others) and those experts who investigated the wind power potential in Kazakhstan (Karatayev and Clarke [48], Babazhanova et al. [24], and Doroshin [80], among others).

Despite its economic potential, in the resource-abundant Kazakhstan, wind power still faces hurdles due to the long-established orientation of energy sector on fossil fuels, lock-in of conventional energies, substantial institutional and financial barriers to the development of wind power production, and low interest of investors in the environmental effects of green energy. Furthermore, as found by Jonaitis et al. [14], the increasing capacity of wind power affects the electric power system of a country. In case of Kazakhstan's power distribution system focused on the transference of electricity surplus from the northern regions to the south, the increase of wind power in electricity generation and distribution will inevitably change the directions in the electricity transmission network. Therefore, the development of the wind power sector should be coordinated with the development of the entire electric power system, since the infrastructure of the electricity network limits the installation of wind power plants in certain places [14]. To fulfill its international obligations and increase the share of renewables in the energy mix, the government should develop electricity and transportation infrastructure and support those investors who construct wind farms in the locations where the GHG emissions reduction potential is the highest. The study has estimated the aggregated GHG emission reduction potential of the twelve locations over 3.0 million $tCO_2eq$, including over 0.9 million $tCO_2eq$ in the northern districts, where the intensity of GHG emission from electricity generation is the highest. In this respect, the study complemented the existing approaches developed by Akhmetov [62], Gassan-zade [74], Barinova and Lanshina [10], Kalyuzhnova and Pomfret [41], Vakhguelt [81], Cochran [82], and Petersen [83], among others, by considering the intensity of emissions of three gases (carbon dioxide, methane, and nitrogen oxide) based on fuel consumption data and country-specific emission factors.

The "economic potential-environmental effect" approach employed in the paper may be generalized for the use in the countries, where fossil fuels prevail in the energy mix, as it allows explicitly pointing out the GHG emission reduction potential of particular locations depending on the availability of wind, economic potential of wind power production, and fossil fuel replaced by it, and in such a manner offers an opportunity to transition to a greener economy and to enable sustainable growth.

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