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An Assessment of Wind Power Potential in Astana: A Wind Power Plant Feasibility Study for Akmola Region, Kazakhstan

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Abstract : Kazakhstan has a huge capacity of natural resources such as coal, oil, natural gas, uranium and great renewable energy potential from solar, wind, hydro-power and biomass. However, the country is still dependent upon fossil fuel for energy generation and 75% of total produced energy comes from coal-fired power plants, which contributes to greenhouse gas emission and environmental problems [1]. The development of power plants based on renewable energy is still on small scale since the upfront investment is very high, while the internal rate of return is low. While dynamic growth of Astana city has driven increased demand for energy supply, the existing power plants in Central and Northern Kazakhstan have been already overused and are old. Therefore, construction of new wind farms near Astana is an attractive solution, which can boost energy capacity of region and gradually decrease CO_2 emissions. The aim of this research is to assess the wind energy potential of Akmola region along with the investigation on the development of energy and cost-efficient wind power plant. In particular, the wind energy potential of this region with the specific site characteristics has been analyzed. The design of wind farm is presented with appropriate layout and power conditioning and utilization schemes. Simulations in MatLab/SIMULINK software are conducted to reveal energy efficiency of the proposed wind farm. Finally, a financial analysis with environmental impacts is discussed. In conclusion, the feasibleness analysis of wind farm construction is revealed as a model procedure.

Keywords: *Kazakhsta, MatLab/SIMULINK*

I. INTRODUCTION

Kazakhstan is the world's ninth largest country, which was founded after the dissolution of the Soviet Union in 1991, with more than 2.7 million km^2 land area and 17.4 million unevenly spread population, where 47% of people living in rural terrains [2]. The Republic of Kazakhstan is a Central Asian country with continental land mass, where a steppe grassland and pastureland dominates in the North regions, desert and semi-desert are characteristic to the Central regions, the Southern part of country are covered by mountains such as Tien Shan and Pamir, and Western regions consists of catchments of Caspian and Aral Seas. The total land for agricultural sector is 76.5 million hectares, where the share of permanent pastures is 64%, while the 32% are arable lands for various grain production [3]. This country is characterized by the continental climate, where the winters are cold with average temperature of -18.5°C in North regions and -1.8°C in South regions in January, and summers are hot with average temperature of 28.4°C in south and 19.4°C in north in July [4]. The continental type of climate requires space heating in cold winter periods and air conditioning in hot summer times, which contributes to the increasing demand on energy supply.

The largest contribution to the economy of Kazakhstan comes from its natural resources such as oil&gas and uranium, heavy industry such as production of ferrous and non-ferrous metals and agricultural segment. The mining and petroleum industries accounted for 42% of GDP in 2016 and 85% of country exports [5]. Generally, GDP of Kazakhstan increased from 19.5 billion USD in 1991 to about 184.39 billion USD in 2017 with the highest 236.6 billion USD rate in 2001. The annual GDP rate has varied between -11.1% to 16.9% since the foundation of Republic of Kazakhstan as illustrated in Fig.1. The positive and significant increase in GDP and per capita income has resulted to the reduction of poverty in the country from 47% in 2001 to approximately 5% in 2014. However, the rapid economic growth has led to the huge increase in energy demand, particularly in winters. According to UNDP [6], the energy consumption of Kazakhstan (in metric tons of oil equivalent) has increased from 25.93 mtoe in 2000 to 92.3 mtoe in 2016, whereas the total power production has raised from 46 TWh in 2000 to about 94 TWh in 2016. Currently, the total capacity of energy production is 20.1 GW where only about 16 GW is usable and losses occur due to poor maintenance, grid connection and equipment aging [7]. The 78.44% of produced power generated from thermal power plants, 7.86% comes from gas power stations and 7.86% produced from hydropower stations. Unfortunately, the percentage of power generation from renewable energy sources such as solar, wind, biomass accounts for only 0.4% of total energy production [8]. However, Kazakhstan has a huge potential to generate electricity from the renewable resources and government expects to increase renewable energy production by 11% in 2020.

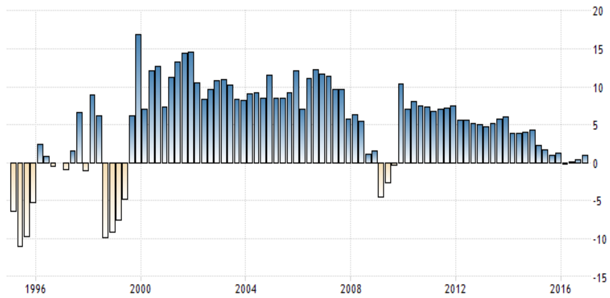

Figure 1. Kazakhstan's GDP annual growth rate [5]

Mainly, the total production of carbon dioxide emissions in Kazakhstan is 235 MtCO2 in 2016 and 80% of it has resulted from the heat and electricity generation plants [9].

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Therefore, it is crucial to increase the total share of energy production from environmentally friendly and efficient renewable energy sources in order to achieve sustainable development and meet the rising energy demand of the country. In addition, Kazakhstan has signed the United Nations Framework Convention on Climate Change and is going to accept Kyoto Protocol, which states improving energy quality for the environment protection along with the sustainable economic development [4].

Global Environmental Facility along with United Nations Development Program (UNDP) and government of Kazakhstan are investigating on the discovery and development of wind power implementation opportunities in Kazakhstan [10]. In fact, the attraction of investors from several international companies and organizations to the development of wind power generation is not only due to the intention to decrease greenhouse gas (GHG) emissions but also there is an excellent chance to develop a profitable business in this sector. According to GEF-UNDP wind resource assessments, Kazakhstan has an exceptional potential of wind resources. Particularly, observations have revealed that almost a half of Kazakhstan’s territory has a wind with 4-5 m/s average speed at a height of 35m [11]. The windiest sites of country are western regions near the Caspian and Aral seas, central regions as well as some south regions. It is estimated that the annual production of power from wind turbines could reach an 8-10 TWh. Hence, the construction of wind farms will fulfill the expanding energy shortages of the country as well as contribute to less environmental pollution and impact on population health.

This feasibility report investigates on the assessment of wind farm implementation in Astana city. In section II, a case study of Astana city with detailed description of climatic conditions is reported. Moreover, this section includes the recent trends on energy production and energy demand of Astana city along with the grid connection possibilities. Then, section III proposes the layout of wind farm by describing and selecting the most efficient wind turbines and energy storage system. Section IV provides economic analysis as well as assess possible impacts caused by wind farm. At the end, conclusion is given by suggesting whether it is feasible to build a wind farm in Astana city or not.

II. Site Description

The proposed location for wind farm construction is situated within of 5 km of the edge of the city with 51°08’ latitude and 71°28’ longitude. The area of selected site is about 8x10 km2 with the capacity for further wind farm expansion. It is estimated that this land is capable to produce up to 50 MW power.

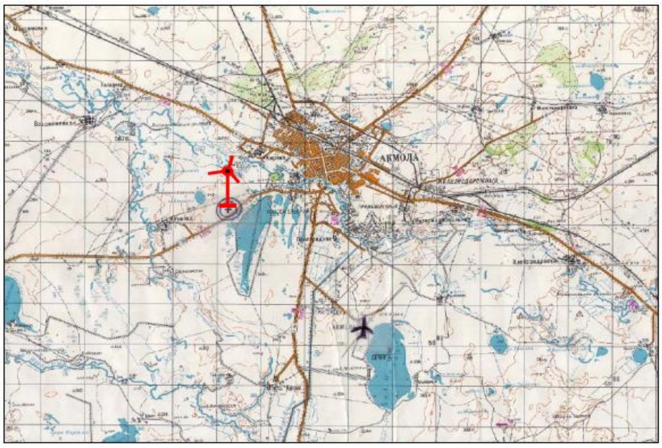

Figure 2. The wind farm location in Astana city

The selected site lies in south part of Astana city and 1.5 km apart from the southward residential villages, as shown in Fig.2. The proposed area for wind farm construction is in close proximity to highway road line, which is beneficial for the transportation of wind turbines to the site and fast response to maintenance works. Moreover, the city’s airport station is located 16 km apart from the proposed site, and the flight path is in SW-NE direction which will not disturb the function of wind farm. In addition, the 110-kV high voltage transmission line is adjacent to the wind farm location and also there is a large power substation within 1 km distance apart.

A. *Climate features of Astana*

As mentioned above, Astana is characterized by sharp continental climate with extremely cold winters and dry warm summers. The main feature of continental climate is the significant changes of air temperature, dry air and a small amount of precipitation. The annual average temperature is -3.2°C and the average rainfall is 307 mm [5]. The duration of cold time is on average 165-170 days with a daily air temperature below 0°C. The hottest period is in July with an average air temperature of 20.9°C, whereas the coldest period in January with an average air temperature of 15.2°C. Figure 3 illustrates the average air temperature and the average rainfall in each month of Astana.

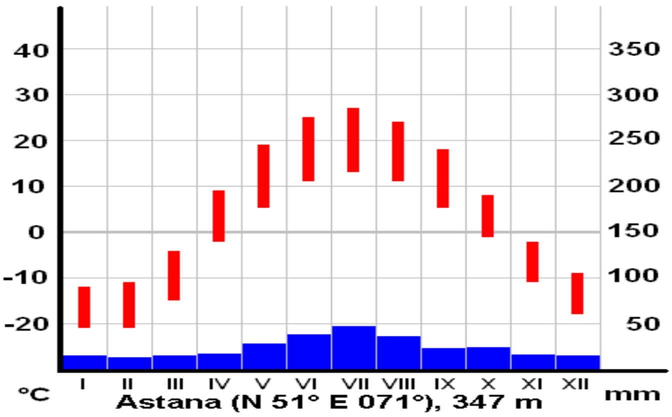

Figure 3. The average air temperature and rainfall of Astana [5]

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B. *Assessment of wind resource*

The lack of protection from the penetration of various air masses and relatively flat terrain results to the favorable wind speed. The strong wind speeds are typical for spring and summer periods. The average monthly wind speed for Astana varies between 4.0 m/sec to 6.3 m/sec [11]. The days with strong winds up to 15 m/sec ranges from 10 to 50 days per year, while the windless days varies between 50 to 70 annually. The direction of wind in winter periods are to the south and in summer periods to the north. The table 1 lists the average monthly wind speeds of Astana.

TABLE I. Average monthly wind speeds in Astana [11]

Month	Wind Speed (m/sec)		Month	Wind Speed (m/sec)
January	5.2		July	4.1
February	5.1		August	4.0
March	5.4		September	4.1
April	5.2		October	5.1
May	5.0		November	5.3
June	4.4		December	5.1
July	4.1		Annual	5.8

In 2013 the UNDP [6] have conducted a research toward the identification of wind power potential in Astana city. The average wind speeds at heights of 80 m, 51 m, 49 m and 22 m above the ground level were monitored by using a tubular tower with installed anemometers. In this research, the data taken from these measurements have been used for the feasibility analysis of wind farm in Astana. Table 2 provides the results of measurements conducted by UNDP.

TABLE II. Wind speed measurements at height of 80 m, 51 m, 49 m and 22 m [6]

Measurements	Level 1 (80 m)	Level 2 (51 m)	Level 3 (49 m)	Level 4 (22 m)
Minimum wind speed (m/s)	0.2	0.2	0.2	0.2
Maximum wind speed (m/s)	27.5	26.6	26.7	24.3
Average wind speed (m/s)	7.25	6.51	6.48	5.39

Astana is characterized by the repeatability of high wind speeds and in cold periods of year the wind is caused by western spur of the Asian anticyclone [4]. Therefore, the direction of wind in Astana predominantly is south-west, as demonstrated in energy rose map (Fig. 4). As a result, the majority of wind power initiated from the south-west direction.

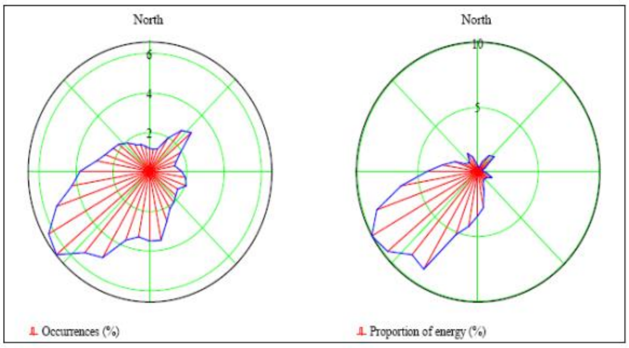

Figure 4. The wind direction and wind energy distribution for Astana [4]

Moreover, the efficiency of generated wind power is also influenced by the number of atmospheric phenomena such as thunderstorms, hails, blizzards, snowstorms and dust storms. The storms are more frequent in summer and less frequent in fall and spring. The annual average number of days with thunderstorm is 23, the average frequency of snow storms is about 38 days per year. The occurrence of days with blizzard varies between 20 to 50 on average per year, whereas the days with dust storms meet 60 times on average per year.

C. *Energy production and consumption*

Currently, the total power production from the installed plants in Kazakhstan is 18.992 TW. The percentage of electricity production from thermal power plant is 87.7% and the rest 12.2% comes from the hydroelectric power plant. About 70% of energy is produced by burning a coal, 14.6% energy generation from hydro resources, 10.6 % from gas, 4.9% from oil, whereas only 0.4% comes from the solar and wind resources [1]. The huge percent of generated power is consumed by the industry, which is about 68.7%. The domestic energy consumption is 9.3%, the agricultural sector consumes 1.2%, the transportation system uses 5.6% from total production. The leaders of energy production are Pavlodar and Karaganda cities, which are located near the coal mines [14]. Figure 5 demonstrates the distribution of electricity production level among all regions and cities of Kazakhstan.

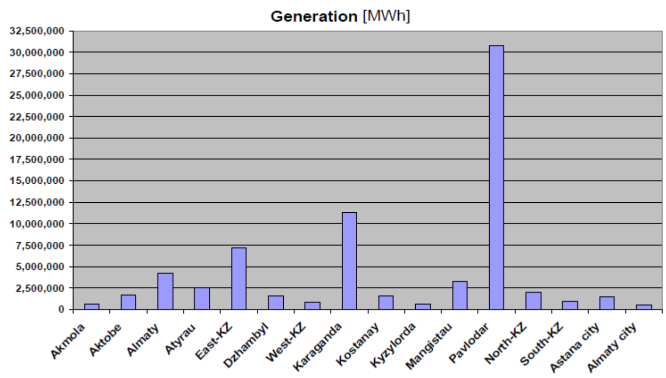

Figure 5. The total generation of electricity by regions [14]

The energy consumption differs among cities of Kazakhstan. As Karaganda, Pavlodar, East Kazakhstan cities have industrial factories, they consume the most part of

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produced power. Akmola region along with Astana city consumes approximately 5 200 000 MWh energy.

There are two working combined heat and power plants in Astana (CHP-1 and CHP-2), which produce 22 MW and 360 MW of power respectively. However, this produced amount of energy is insufficient for the total demand of fastest growing capital of Kazakhstan. Therefore, the huge amount of electricity comes from Pavlodar and Karaganda in order to fulfill the energy requirements of Astana. The seasonal energy consumption of Astana is shown in figure 7, where the most electricity is consumed during winter periods [12].

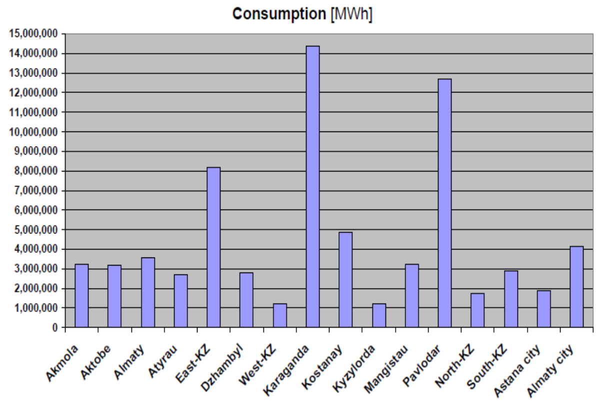

Figure 6. The energy consumption by regions [15]

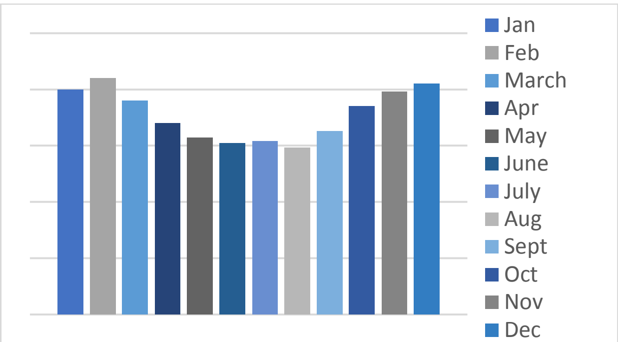

Figure 7. The monthly power consumption of Astana [12]

The electricity tariffs in Kazakhstan varies in different cities depending on the transmission distance, the percentage of occurred losses, operation and maintenance cost of region. The electricity price in Astana is 12.99 KZT/kWh for the domestic consumption and 18.1 KZT/kWh for other purposes [15].

The total length of high voltage electrical lines is more than 5500 km for 500 kV, more than 20 200 km for 220 kV, 44 500 km for 110 kV, 62 000 km for 35 kV and approximately 204 000 km for small 6-10 kV lines [13]. The power loss during the transmission and distribution accounts for 21.5 %, which is significantly. Particularly, the Akmola region has 4300 km total length of high voltage grid lines, 10 substations with the total grid capacity of 7800 MVA.

III. DESIGN OF WIND FARM

A. *Wind turbines*

A wind turbine is a mechanical machine that converts the kinetic energy of the wind into mechanical by induced rotation of rotors blade [16]. After that, generators convert produced mechanical energy into desired electrical energy for further consumption [16]. As the wind turbines form the basis of wind farm, the proper selection of them is a major concern.

Generally, there are two types of wind turbines used for power production based on axis of the turbine rotation: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) (see Fig. 8).

1. *Horizontal axis wind turbine*

The horizontal axis wind turbine uses axis parallel to the ground for a rotation. The structure of horizontal axis turbine consists of a rotor, blades, gearbox, generator located at the top of a turbine tower, and the blades faced towards the wind [16]. The shaft of a turbine starts rotating when wind hits the blades, and then gearbox attached to the end of the shaft turns a slow rotation of blades into faster rotation to drive generator [16]. Horizontal axis wind turbines are more popular compared to vertical axis wind turbines. Table III provides advantages and disadvantages of HAWT.

TABLE III. Advantages/Disadvantages of HAWT [16]

Advantages	**Disadvantages**
High efficiency	Hazards for low height crafts
Installation is self-starting	Difficult maintenance
High stability	Difficult transportation
Rotor blades can be pitched	Turbulence may cause fatigue
Variable blade pitch	Bad aesthetic view

2. *Vertical axis wind turbine*

The vertical wind turbines use axis perpendicular to the ground for rotation. The main difference of this type is that this type of wind turbine does not need to be faced towards the wind, and its efficiency does not been affected by change of the wind flow direction [16]. Moreover, all components, such as gearbox, generator, and transformer are placed near the ground. However, due to low efficiency, VAWT is mostly applied in small wind projects, while HAWT is mainly implemented in large wind farms [16]. The following table (Table IV) provides the advantages and disadvantages of VAWT.

TABLE IV. Advantages/Disadvantages of VAWT [16]

Advantages	**Disadvantages**
Ease of maintenance	Only low heights
Better aerodynamics	Low efficiency
Ease of transp. and install.	Additional energy to start rotation
The efficiency is stable	Causes drag
No need of yaw device	Flat surface is required

So, from tables (Table III & IV), it can be seen that HAWT is more suitable and preferable than VAWT, for producing large amount of energy. HAWT has higher efficiency, it is more stable, and provides more warranty.

B. *Choosing wind turbine type*

It was stated above, that chosen location has potential of producing about 50 MW of energy. So, in order to achieve that, it is necessary to choose the wind turbine which will fulfill requirements of location, such as wind speed, air density, and so on. Average wind speed is given in Table I, it is important to choose the wind turbine, which will be able to operate at low wind speed, and which will have low cut-out

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speed to prevent damage of turbine during the strong winds. After some evaluations, Vestas V112 – 3.3 MW horizontal axis wind turbine was chosen. Its specifications are provided in Table V.

TABLE V. V112-3.3 MW description [17]

Operating Data	
Rated power	3.3 MW
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s

Table V shows that Vestas V112 is able to operate at minimum wind speed 3 m/s, and if wind speed will be higher than 25 m/s, it will stop operate. Since one wind turbine is going to produce about 3.3 MW of energy, it is required to use 15 of them to generate 50 MW of energy.

C. Wind farm layout

In order to get higher profitability from the wind system, it is important to adequately design wind farm layout. The careful and detailed optimization of layout contributes to maximum wind power capture. Here is the cost of energy calculation equation:

$$CoE = \frac{C_1 * FCR + C_r}{AEP} + C_{q\&m} \qquad (1)$$

Where, C_1 is initial capital cost of wind farm, FCR is fixed charge rate, C_r is replacement cost, $C_{q\&m}$ is cost of maintenance and operation, AEP is annual energy production.

From the equation 1, it can be seen, if the annual energy production is increased, the total cost of energy will be minimized.

One of the main problems that cause the wind power capture reduction is a phenomenon known as a wake loss. When incoming wind encounters a wind turbine, a linearly expanding wake occurs behind the turbine [16]. Thus, the speed of free stream wind is lowered. The phenomenon is illustrated in Figure 8. The effect of wake loss on several turbines is illustrated in Figure 9. Therefore, it is apparent that the problem of design optimization is mainly concerned with locating wind turbines so that they are not affected by wake loss.

So, there are different computer software which provide an algorithm for the layout design. The algorithm uses different parameters, such as number of turbines, planned area, height of the turbine, average wind speed, temperature of the air, grid connections, loads, and etc., to get maximum annual energy production from the wind farm.

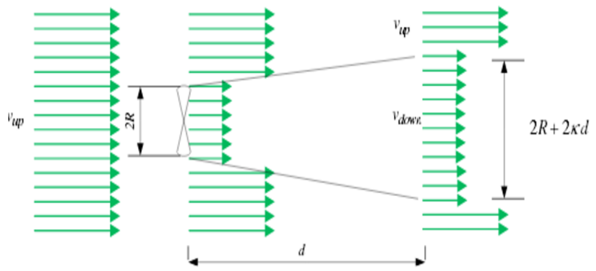

Figure 8. Wake loss [16]

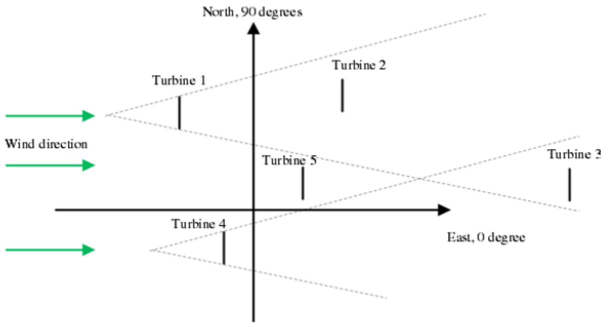

Figure 9. The effect of wake loss on wind turbines [16]

By using Homer PRO software, the optimal wind farm layout was found (see Fig. 10).

D. Grid connection

It is important to connect each wind generator to the grid. Therefore, availability of the grid close to the wind power plant site has to be considered during selection of the location for power plant.

However, it is not enough to build a wind farm, and just connect to the grid. The power plant has to fully comply with grid requirements. As the wind power is not stable during the year and occurrences of power loss, it may bring a risk to the reliability and stability of the entire power system. Therefore, before implementation of wind farm set of rules must be met and accomplished such as frequency, reactive power, power factor controls, voltage, and transient fault behaviors. Moreover, people responsible for developing wind farm should contact local Transmission System Operators. In case of meeting all set of requirements Electricity Grid Company (TSO) will provide with necessary documents for Power Purchase [18].

E. Matlab/Simulink Simulation

Figure 10. Astana wind farm design

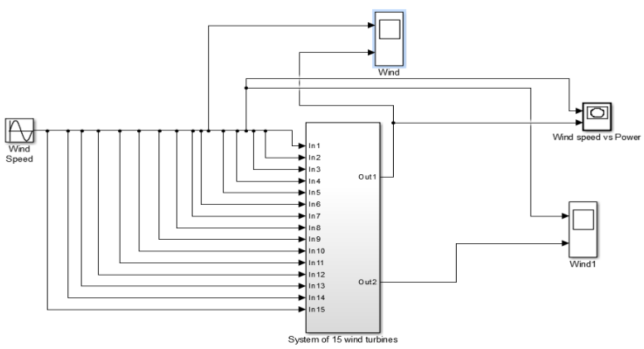

Figure 11. The Simulink model for wind turbine

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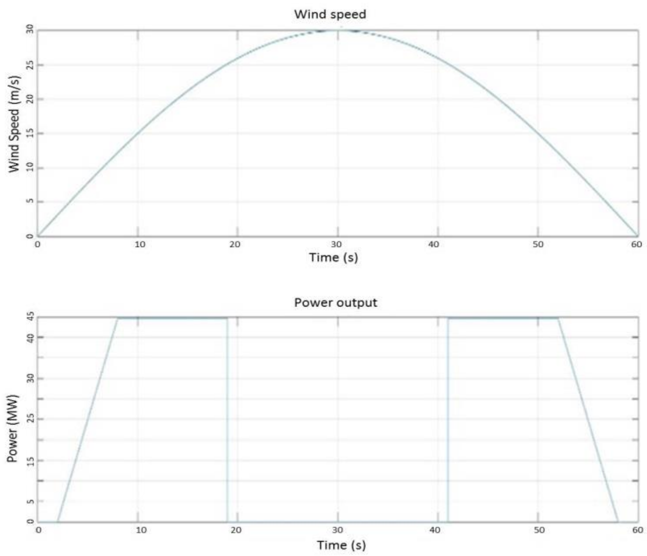

Figure 12. Wind farm simulation results

Here is the Simulink model for wind turbine simulation (see Fig. 11). The simulation provides the turbine output power, and wind speed.

For simulation, the wind speed was taken as sinusoidal wave, with peak values equal to 30, which is maximum possible wind speed in the region.

So, Fig. 12 provides two graphs: one for wind speed and another one for power output. It can be seen that, when wind speed reaches to 3 m/s, wind turbines start to produce energy, and when wind speed reaches to 25 m/s (cut-out speed) then wind turbines stop to generate energy. There is a point on figure, when turbines start to generate constant amount of energy. This wind speed is known as rated output speed. At that speed turbines reach to their maximum point, and operate in stable condition.

IV. **FINANCIAL ANALYSIS**

Every project requires detailed financial analysis, in order to estimate how much it will cost, and how long it will take to pay-off it.

TABLE VI. Capital cost

Turbines + Installation & Transportation	48 250 000$
Storage blocks	1 173 000$
Maintenance	4 630 000$
Inflation	12%
Total cost	54 053 000$

TABLE VII. Operational revenue

Electricity cost	0.0565$
Average electricity growth cost	8%
Required energy	180 000 MWh/year
Average growth of electricity cons	4.5%
Corporate income tax	12%
Cost for electricity	10 170 000

Tables above (Table VI and VII) provide the capital cost and operational revenue of the project, respectively. The financial expenses for the first year of the project include cost of land, storage blocks, installation & maintenance of all 15 turbines, and transportation. Also, it was estimated that due to inflation, each year capital cost of the project will increase by 12%. It can be seen from Table VII, that cost for electricity is not high, but with increase of electricity consumption and average electricity cost, pay-off period was calculated to be approximately 7 years (see Fig. 12).

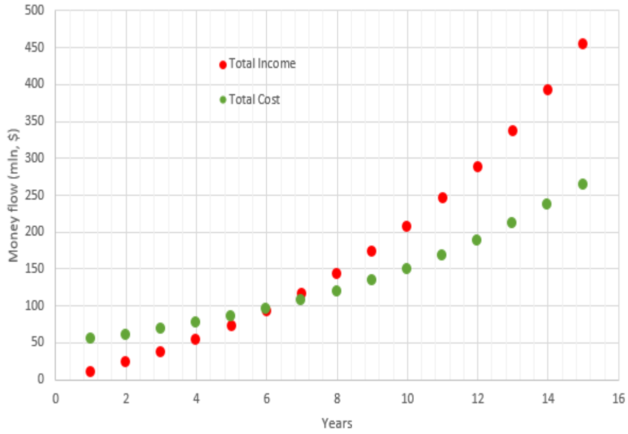

Figure 12. Total cost vs Total income

V. **ENVIRONMENTAL IMPACTS**

It is known that wind energy is one of the cleanest and safest of the renewable energies. However, it still has negative effect on the environment. Of course, the effects are considered to be minor, but they still have to be analyzed to provide reasonable evaluation for the project. The environmental impact can be divided into three main categories:

1) Land pollution: According to [19], during the construction and operation about 14164 m^2 of land per 1 MW is affected. Moreover, about 4047m^2 of land is always in use, and it can spoil the soil. However, the spoiled soil still can be used for pasture or agriculture [19].

2) Wildlife: It is known that the wildlife on Kazakhstan is very wide and diverse. To be precise, there are about 150 species of birds and 9 species of bats in the North part of KZ, which periodically fly close to Astana [20]. As it is stated in [21], it was scientifically proven that turbines cause deaths and injuries to those species. The damage can be explained by changes in landscape and pressure drop near wind farms [21]. However, those studies state that the casualties are low, if the wind farm doesn't stay on the route of migration of birds. According to [22], there no migration roads in Astana, so wild plant has to be safe for wildlife.

3) Water and air pollution: Water is mainly used only during construction process, so the water is not polluted much. In case of the air, it also has effect only during construction period. Moreover, during the operation of wind farm, there is heat emission, which is also has to be taken into account. However, this emission is much lower compared to other sources of emission, such as natural gas and coal [23].

VI. **CONCLUSION**

During this feasibility analysis, it was necessary to analyze potential of wind power in Astana, Kazakhstan. Site for construction was chosen close to the edge of the city (5 km), and at the same time close to high voltage transmission lines. The detailed analysis of construction site was conducted. All important factors, such as wind speed, wind turbine type, annual energy consumption of city, meteorological factors, were considered during this research. It was proposed to use 15 Vestas V112 horizontal axis wind turbine with rated power 3.3MW, in order to produce 50 MW of energy. This type of turbines provides efficient, reliable, and stable amount of energy even during the low speed of wind. In order to get maximum profitability from the research, layout of the farm was also analyzed by using Homer Pro software. Moreover, during this research economical side of the project was discussed, and it was found that it will take approximately 7 years to get payback from the project. Finally, environmental impact of the wind farm was analyzed, and it was found that on chosen location, farm will not cause side effects on environment.

So, for the future the wind power plant can be improved to make it more echo and society friendly. First of all, noise of the turbines could be reduced by using more advanced prototypes of blades. Also, to improve security of the farm, internet of things can be applied, which will allow to control the wind farm 24/7, even if being on another side of the planet. Finally, with increase of the annual energy consumption, it will be necessary to expand the farm to fulfill energy needs of the city.

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