Wind turbines application for energy savings in Gas transportation system

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Abstract

The Thesis shows the perspectives of involving renewable energy resources into the energy balance of Russia, namely the use of wind energy for the purpose of energy supply for the objects of the Russian Gas transportation system. The methodology of the wind energy technical potential calculation is designed and the wind energy technical potential assessment for onshore and offshore zones of Russia is presented.

The analysis of Russian Gas transportation system in terms of energy consumption is carried out when comparing the map of wind resources in Russia with the map of Russian Gas transportation system and the perspective of wind turbines installation is shown in order to offset energy consumption of the selected object of the Gas transportation system.

The decision-making algorithm for wind turbines selection is developed for installation on the wind farm.

Also indicators of investment attractiveness of the project of using wind turbines for compression stations energy supply were calculated.
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Introduction

THE NECESSITY OF RENEWABLE ENERGY INVOLVEMENT IN RUSSIAN ENERGY CONSUMPTION

Russia is the leading energy country in the world steadily holding the third place after China and the United States of America for the energy production. According to BP statistical data in 2012 the world oil reserves are amounted to 235,8 billion of tones [1]. The graph in Figure 1 shows the countries with the largest oil reserves in the world (Proved Reserves) that are amounted to more than 10 billion tones (total reserves of 191,7 billion of tones, or 81,3% of world reserves).

Figure 1 Countries with the largest oil reserves in the world in 2012, billions of tones

Russia has the eighth place in the world with oil reserves of 11,9 billion tones. World gas reserves according to BP statistical data at the end of 2011 are amounted to 208,4 trillion of m³ [2]. The graph in Figure 2 shows the countries with the largest gas reserves in the world (Proved Reserves) that are amounted to more than 2 trillion of m³ (total reserves 186,9 billion tons, or 89,7% of world reserves).
Russia is the world leader in terms of gas reserves (44.6 trillion of m³). As follows from the data shown in Figures 1 and 2, in 2012 Russia with production levels of 1059.2 Mtoe was the world leader in the production of hydrocarbons [1]. If it is a lot or a little - try to evaluate it in terms of current world trends. In Figures 3 and 4 the world's largest oil producers (production level of over 100 million of tones) and gas producers (production level of over 100 billion of m³) in 2012 depending on their reserves [1,2] are reflected.
As it can be seen from the diagrams Russia is far ahead in global trends in production, especially of oil production. If you follow the trend, the level of oil production with existing reserves would have to be 230-240 millions of tones, that can satisfy the annual consumption level, which ranges from 140-145 million of tones, and gas production would have to be 390-400 billions of m³ [4], which also would satisfy the domestic demand for gas. However, Russia can not abandon such a high rate of production as the proceeds from the sale of oil and gas account for more than 54% of the budget revenues of the country. Due to the fact that
Russia is a huge country that occupies an area of over 17 million km², and about 70% of which is located in the northern and arctic regions, Russia is one of the largest consumers of energy – 694,2 Mtoe in 2012 [1]. So it is necessary to know how much energy is spent on the reproduction of GDP, and how much goes to the extended infrastructure heating - these issues are discussed below.

The diagram in Figure 5 shows the dependence of the energy intensity of the G-20 countries on their territory.

**Figure 5 Energy intensity of the G-20 countries (toe/1000 USD of GDP) in 2012 [4]**

The diagram shows that:

- Countries with a large territory are not the leaders in energy efficiency because the larger area of the country is the more energy is spent on extended infrastructure service.
- Large "northern" countries such as Canada and Russia have comparable levels of energy intensity – 0.222 and 0.206 toe/1000 USD GDP including PPP, which is significantly above the world average, which can also be explained in terms of the climatic characteristics of the "northern" countries.

Thus, it is a must to burn a lot of fuel for power and heat generation to secure a comfortable living on the huge northern territory.

Figure 6 shows the dynamics of GDP growth excluding PPP [3] and energy consumption growth [1] in Russia in 2002-2012.
Analyzing Figure 6 very good results in terms of energy efficiency can be obtained - if it is possible to increase GDP without a significant increase in energy consumption or when it decreases, it is definitely a good thing, since this implies that either the country uses modern technology with energy savings in all industries, or the country goes to the latest release of products with high added value, such as software products, production of chips or products requiring implementation of nanotechnology and other things that lead to a significant increase in GDP but does not require additional energy or that all occurs simultaneously what is even better. However, nowadays large-scale restructuring of the Russian economy is not observed, the economy is primarily focused on the extraction and processing of mineral raw materials and fuel. It can be assumed that such a result is observed due to the fact that Russia inherited from the Soviet Union a huge, redundant infrastructure, but this huge infrastructure is not used at the moment. And we continue to maintain it as it is largely tied to the social needs of its citizens. For example, in Russia there are many cities and towns created around the core enterprises, especially in the defense sector. The entire infrastructure of these cities and towns do not work for many years, or work with a partial load, and energy service of this infrastructure has to be continued. The paradoxical picture - energy continues to be spent and industries do not generate GDP in general, or create a small fraction of what could be created. Over the past 10 years the specific energy consumption in Russia decreased with the highest rate, more than 5 times - from 1,82 to 0,345 toe/1000 USD of GDP!

Now we estimate what proportion of energy consumed in Russia goes to GDP reproduction. For this purpose we analyze Figure 7, which shows the curves of annual changes in GDP, excluding PPP (billions of USD) [3] and energy consumption (Mtoe) [1] in Russia for the period 2002-2012, as well as the values of the specific energy, calculated as the ratio of these changes.
According to published researches [4], taking into account all the assumptions and approximations, we can estimate the energy efficiency of the Russian economy in 22-25% - this is the proportion of energy that goes to the GDP reproduction, the rest goes to the extended infrastructure service, including heat and energy losses. As a significant warming in Russia in the near future is not expected, as well as the structural changes in the economy and in the social policy of the state, so in Russia people will continue to burn up to 75-78% of the fuel for heating themselves! Therefore, the perspective of development of renewable energy is obvious, especially in the decentralized energy supply systems. Traditional hydrocarbon resources will come to the end soon.
1 REVIEW OF WIND ENERGY IN THE WORLD

1.1 History of wind power

History of wind power begins from ancient times. Wind energy reliably serves people during more than 6000 years. Wind energy has been used in navigation until the steam engine invention which replaced the sails on ships. First simple wind turbines used in ancient times were in Egypt and China. In Egypt around Alexandria still stone windmills remain with drum-type vertical axis built during the II-I centuries BC. In the VII century BC in Persia (Iran) wind turbines were built with more sophisticated design – with a horizontal axis of rotation. Later on in the VIII-IX centuries windmills appeared in Western Europe and in Russia. Since XIII century wind turbines are widely used for water lifting, grinding grain and as a power drive for various machines and mechanisms in Netherlands, Denmark, England and Russia, Figure 1.1 [6].

Figure 1.1 Aspects of a medieval-type windmill for grinding grain (left) and an American-type windmill used for water pumping (right)

Wind power in XIX-XX centuries.

USA. By the middle of the XIX century in the United States more than 6 million small wind turbines was built with a unit capacity of up to 0,75 kW which were used to generate electricity, water lifting and other work, Figure 1.2.
For water lifting wind turbines are usually used with all-metal propeller with diameter of 3,7-4,9 m, rotating on horizontal shaft and fitted with tail in a wind wheel to guide the direction of the wind. Wind wheel with diameter of 3,7 m developed a capacity of about 120 W at a wind speed of 6-7 m/s and could raise 160 l/min of water to a height of about 7 m [7].

Low-power wind turbines usually performed with a two- or three-bladed wind wheel of vane type connected through a reduction gear with a DC generator. The largest existing wind turbine was "Smith-Putnam" wind turbine. With the participation of aerodynamics Karman and some employees from MIT Putnam developed high-power wind turbine to generate energy to power the existing mains of «Central Vermont Public Service Company». «S. Morgan Smith Company» designed and experienced this wind turbine in early 1940. Bladed vane type wind wheel with the diameter of 53 m and weighing of 16 tones developed capacity of 1,25 MW at rated speed 28 rpm, Figure 1.3 [6].
Figure 1.3 The first megawatt-sized wind turbine was built in 1941. The Smith-Putnam project on Grandpa's Knob, Vermont, was for a two-bladed, 53 m diameter, 1.25 MW machine [6]

Comprehensive economic studies have shown that the wind turbines of this type at that time could not compete with the electrical installations of conventional type. Therefore, further research on this new designed wind turbines was abandoned.

Since the 1970s the production of large mega-watt wind turbines was started with horizontal axis and with two blades, Figure 1.4 and 1.5.

Figure 1.4 The 38m diameter, 100 kW MOD-0 installed in 1975 [6]
Denmark. At the end of the XIX century in Denmark there were about 3 thousands of wind turbines which were used in the industry and about 30000 wind turbines of other types that were applied for domestic purposes. Their total capacity was about 200 MW. In 1890 the Danish government launched a broad program of development of high capacity wind turbines. In 1910 a few hundred of these wind turbines was built. They had four blades and rotor diameter of 23 m, mounted on a tower with height of 24 m and connected by a mechanical transmission with an electric generator located at the base of the tower. Rated power of the generator varied from 5 to 25 kW.

After the World War II the Danes developed and tested three experimental wind turbines with installed capacity of 12, 45 and 200 kW designed to work in energy system. They operated successfully until 1960. The development project was stopped when it was revealed that the cost of electricity generated by wind turbines was twice larger than cost of energy generated by heat engine [7].

UK. In the late 1940s and throughout the 1950s significant work on the design of wind turbines was carried out in the UK.

In 1950 the «Enfield Cable Company» developed original 100 kW wind turbines and installed them in the UK and Algeria. Installed system had a hollow tower with height of 26 m and 24 m rotor diameter with hollow blades provided with outlet openings at the ends [6]. Due to the occurring pressure drop the air entering through openings at the bottom of the tower moves along through the turbine and is ejected through holes in the ends of the blades, Figure 1.6.
France. Between the years 1958-1966 several large wind turbines were built and worked in France. There were three wind turbines with three-bladed horizontal-axis wind wheel of vane type that worked near Paris. The first one was calculated for the capacity of 800 kW at a wind speed of 16,5 m/s. Wind wheel with rotor diameter of 30 m and the generator and transmission system with a total mass of 160 tones were placed on the tower with height of 30 m.

Two other wind turbines were built in the south of France. Smaller one with wind wheel with rotor diameter of 21 m and rated speed of 56 rpm worked with asynchronous generator with a rated speed of 1539 rpm and had the capacity of 132 kW at a wind speed of 12,5 m/s. In France several research facilities with a vertical axis also were built and tested in this period [7].

Germany. In Germany a number of improvements for wind turbines were carried out including design of light wind wheels with constant speed and control system for turning blades. For wind turbines lightweight fiberglass and plastic blades were used; generator was mounted on a tower of a hollow tube of small diameter reinforced with wire braces, Figure 1.7 [6]. The largest of the wind turbines which had 100 kW of capacity at a wind speed of 8 m/s worked successfully in the period of 1957-1968. These developments have been used in some of the most advanced wind turbines to be built till nowadays.
Russia and Soviet Union. At the beginning of the XX century Russian scientist Nikolai Zhukovsky developed the theory of high-speed wind turbine and put the scientific foundations for creation of high speed wind turbines that work more effectively using wind energy. Such wind turbines were built by his students after the organization of the Central aero-hydrodynamic Institute in 1918. Soviet scientists and engineers theoretically proved fundamentally new schemes and created perfect wind turbines and wind power station in design of different types with capacity up to 100 kW for the mechanization and electrification processes in agricultural production and other purposes [7].

In 1937 advanced wind power station was built with capacity of 100 kW near Yalta. Annual energy output was about 280000 kWh with power (in the wind) efficiency of 0.32. Generator and control devices were installed on the top of a tower with 30 m height. Rated speed of the wind wheel was regulated by turning blades. The tower had inclined pole mounted on a trolley which moved along a circular track for the wind wheel orientation on the wind direction, Figure 1.8 [7].
Wind power station successfully worked for 3 years until it was destroyed during the World War II at the end of 1941.

At the end of the 1940s active development of wind turbines were begun in Central aero-hydrodynamic Institute and other organizations. From 1950 to 1955 the country produced up to 9000 wind turbines in a single year with capacity up to 30 kW.

However, the use of wind energy in large-scale energy sector was not proved - oil was relatively cheap, capital investment in the construction of thermal power plants decreased, hydropower was developed. In 1960-1980 Russian energy sector has been focused on the construction of large thermal power plants, hydro and nuclear power plants: wind turbines were unable to compete with the giants of the electric power, and at the end of the 1960s their production has been closed.

Later large-scale projects have been developed for the construction of wind farms in different regions of the country. But the political and economic crisis of the 1990s stopped the work on these projects. Another important thing was the misunderstanding of the developers of the fact that there is no possibility to manufacture tools and structures with the absence of maintenance services. The first failure led to long outages that, in turn, strengthened skeptical attitude about wind energy in general.

Currently, the total installed capacity of all wind farms constructed in Russia is about 16,8 MW [9]. Today it is considered that the most powerful is the wind farm located in the Kaliningrad region, operated since 2002 and consists of 21 wind turbines (Vestas - manufacture) with total capacity of 5,1 MW.

Other main wind farms are the following:

- Vorkuta WF – 1,25 MW (250 kW x 5);
- Kalmyk WF (1 MW x 2);
- Anadyr WF (250 kW x 10);
- Bashkir WF (550 kW x 4);
- Wind farm on Bering Island 0,5 MW (250 kW x2);
— Kamchatka WF— 1,5 MW;
— Rostov WF – 0,3 MW (30 kW x 10) [10].

According to The World Wind Energy Association in 2013 Russia had the 69th place in the world in total installed capacity of wind farms [11].

In January 2009 Prime Minister (at that time) V. Putin signed the order of the Government of the Russian Federation № 1-r "The main directions of the state policy in the sphere of energy efficiency increase of electric power generated from renewable energy sources in the period up to 2020", that requires the share of RES in the volume of production and consumption of electricity energy from renewable energy sources (excluding hydropower plants with installed capacity more than 25 MW) to increase to 4,5% to 2020. During the period of 2014-2020 it is planned to build 3600 MW of installed capacity of wind farms [12].

1.2 Overview of wind energy resources and expected trends in the world

The World Wind Energy Association in its annual report for 2013 [11] gives the following main indicators of the wind power industry:

- The worldwide wind capacity reached 318,5 GW, out of which 35,6 GW were added in 2013, not more than in 2012.
- Wind power showed a growth rate of 12,8 %, the lowest rate in more than a decade.
- All wind turbines installed by the end of 2013 worldwide can provide 640 Terawatthours per annum, more than 4 % of the global electricity demand.
- Altogether, 103 countries and regions used wind power for electricity generation; Iceland has become the 100th country that is using wind power.
- China installed around 16 GW of new wind turbines and became the world leader of new installed capacity.

Further there are the main indicators for the wind power industry in 2012 which are also actual [9]:

- Continents:
  — Asia accounted for the largest share of new installations (36,3 %), followed by North America (31,3 %) and Europe (27,5 %). Latin America stood for 3,9 % and Australia/Oceania for 0,8 %. Africa (0,2 %) is still a tiny wind market.
  — Latin America and Eastern Europe continue to be the most dynamic world regions while Africa showed stagnation, with only Tunisia and Ethiopia installing new wind farms.
- Asia:
  — China continued to be the largest Asian market and added 13 GW, however, significantly less than in the previous year.
  — India was again the third largest market for new wind turbines worldwide, adding 2,5 GW.
  — The third largest Asian wind market, Japan, still grew very slowly and installed less than newcomer Pakistan.
- North America:
  — The US market set a new record by adding 13 GW.
  — The Canadian market slowed down and grew below the global average.
- Europe:
  — Germany continued its role as the largest and most stable market in Europe with 31 GW, followed by Spain with 22,8 GW.
— UK took over the position as second largest European market for new turbines from Spain which installed even less than Italy.

— Italy, France and the UK continued to be the medium-sized markets, with total capacity between 7.5 and 8.5 GW. Poland, Romania and Sweden became major markets for new turbines.

- The share of offshore wind in the overall capacity increased to 1.9 %, after 1.5 % in 2011.

### 1.2.1 General situation in the world

With no doubt wind energy has become the basis of energy systems in many countries around the world as a reliable and affordable source of electricity production. In 2012 the capacity of the wind energy sector in the world reached 282.2 GW compared to 236.7 GW in 2011, to 196.9 GW in 2010 and to 159.7 GW in 2009, Figure 1.9.

**Figure 1.9 World total installed capacity (GW) in 1997-2012**

The market of new wind energy capacity set a new record: 44.6 GW of wind capacity was installed in 2012, that is 12% more compared to 2011, when it was introduced 39.8 GW of new wind capacity, Figure 1.10.

**Figure 1.10 New installed capacity (GW) in 1998-2012**

Significant, even at the global level, is the share of wind power in a global energy supply: potentially all wind turbines installed worldwide by the end of 2011 produce 580 TW-hours of electricity which corresponds to
more than 3% of global energy consumption. In 2012 100 countries were named as the countries that use wind energy to generate electricity. The 100th country has become Iceland, a country with almost 100% of energy supply from renewable energy sources. New wind turbines have been installed in 46 countries around the world, four countries less than in the previous year. In 2012 the commodity circulation of the global wind energy sector amounted to 60 billion of Euros (75 billion USD).

A very good indicator of the market activity is the average growth rate. "The growth rate" is the ratio of the total installed capacity for the present year and the previous year. After the growth rate of 30% which was demonstrated by the wind sector over the past decade, the last three years this value decreased significantly: in 2012 the growth rate has decreased to 19.1% that is the lowest growth rate over the past two decades what is presented in Figure 1.11.

For many years the five largest markets are the driving force of the world wind energy market: China, USA, Germany, Spain and India. During the last two decades the largest share of the global wind energy is account on these countries. In 2012 the total capacity of wind energy in these countries is amounted to 207 GW or 73% of the world's wind energy capacity, which is not much less than in the previous year. At the same time the top 10 wind energy markets increased their performance on the new facilities commissioned during the year from 35 GW to 37 GW (83% of the new capacity installed in the world), while their share in the total installed capacity has decreased from 87% (in 2011) to 86% in 2012. Among the major markets in 2012 China and the United States played a significant role: the share of each of the two countries amounted to 29%. China has shown a significant increase in its share in the global market which reached its maximum in 2012 when every second new wind turbine was installed in China, Figure 1.12.
Wind energy markets of India and Germany showed stable development and growth rate of 2,4 GW while the Spanish market grew by only 5%, or 1,1 GW. In 2012 the main markets include 12 countries (in 2011 there were 10 countries), where installed capacity increased from 0,5 GW to 2,5 GW, that is India, Germany, United Kingdom, Italy, Spain, Brazil, Canada, Romania, Poland, Sweden, France and Turkey. Fourteen wind power markets in the world (4 markets more than in 2011) showed an average growth rate increasing its capacity in the range of 100 to 500 MW, that is in Mexico, Australia, Belgium, Austria, Denmark, Bulgaria, Norway, Portugal, Ireland, Ukraine, Puerto Rico, the Netherlands, Greece, as well as in a new market of Pakistan. By the end of 2012 the total installed capacity of all wind farms was over 1 GW in 24 countries, what is by 2 countries more compared to the year 2011. Romania and Mexico are the new countries in the "Gigawatt Club".

1.2.2 Offshore wind energy

Over the past years the market of offshore wind energy was very unstable. In 2012 the growth rate of the offshore wind energy sector has received a strong impulse and increased by 54% after a weak enough 2011 year, when the growth rate of the capacity was only 14%. By the end of 2012 the total installed capacity of offshore wind farms was 5,4 GW, and 1,9 GW of which were installed during the 2012 year. In 2011 this value was 397 MW, and in 2010 – 1,1 GW. In 2012 the growth rate of offshore wind energy was well above the average growth rate of the onshore wind energy. The share of offshore wind energy in the total installed capacity of global wind industry has grown from 1,5% in 2011 to 1,9% in 2012. The share of new offshore wind capacity has reached 4,3% in 2012, after only 1,0% in 2011. Table 1.1 shows that 13 countries have offshore wind farms, 11 of which are located in Europe, and 2 wind farms - in Asia.

In 2012 only 5 countries installed large offshore wind farms, that is: UK, Belgium, China, Germany and Denmark, Figure 1.13. UK has 74% of the world market of offshore wind (compared to 2011 - 46%); during this year new sea-based wind turbines with total capacity of 1423 MW were installed in the country. The country plays an important role and has a dominant position in the offshore wind energy sector. More than each three wind turbines in the UK were installed in the sea. More than one of the two offshore wind turbines operating in the world today is installed in British waters. Denmark has the second place in the world for the total offshore wind turbines capacity installed in the country, but with very modest growth rate - 7%. In 2012 Belgium became the second largest market for new offshore wind turbines doubling its installed capacity from 195 MW to 380 MW. China has become one of the leading players in the market of offshore wind power, almost doubled its total capacity of offshore wind turbines installed in the country. Nevertheless, the offshore wind energy sector of China still has only a minor fraction of 0,5% of the market. In the coming
years China plans to install 5 GW of offshore wind capacity. Despite the rather ambitious goal the development of offshore wind power in Northern Germany and the Baltic Sea is far behind expectations: offshore wind turbines installed in the country, as well as in China, represent only a small fraction of the total wind energy capacity - less than 1%. In countries such as Japan and South Korea ambitious programs for the development of offshore wind power are also adopted.

Table 1.1 Offshore wind energy market [9]

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>United Kingdom</td>
<td>2947,9</td>
<td>1423,3</td>
<td>1524,6</td>
<td>1341</td>
<td>688</td>
</tr>
<tr>
<td>2</td>
<td>Denmark</td>
<td>921</td>
<td>63,4</td>
<td>857,6</td>
<td>854</td>
<td>663,6</td>
</tr>
<tr>
<td>3</td>
<td>China</td>
<td>389,6</td>
<td>167,3</td>
<td>222,3</td>
<td>123</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>Belgium</td>
<td>379,5</td>
<td>184,5</td>
<td>195</td>
<td>195</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>Germany</td>
<td>280,3</td>
<td>65</td>
<td>215,3</td>
<td>107</td>
<td>72</td>
</tr>
<tr>
<td>6</td>
<td>Netherlands</td>
<td>249</td>
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<td>249</td>
<td>249</td>
<td>247</td>
</tr>
<tr>
<td>7</td>
<td>Sweden</td>
<td>164</td>
<td>0</td>
<td>164</td>
<td>164</td>
<td>164</td>
</tr>
<tr>
<td>8</td>
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<td>0</td>
<td>30</td>
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<td>30</td>
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<tr>
<td>9</td>
<td>Japan</td>
<td>25,3</td>
<td>0,1</td>
<td>25,2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Ireland</td>
<td>25,2</td>
<td>0,2</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>Spain</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>Norway</td>
<td>2,3</td>
<td>0</td>
<td>2,3</td>
<td>2,3</td>
<td>2,3</td>
</tr>
<tr>
<td>13</td>
<td>Portugal</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>5426</td>
<td>1903,8</td>
<td>3522,3</td>
<td>3102,3</td>
<td>1955,9</td>
</tr>
</tbody>
</table>

Figure 1.13 Top 5 in Offshore Wind (MW)
1.2.3 Future challenges and prospects

Six major factors will have a decisive impact on the mid-term and long-term prospects of wind power [9]:

1. The ongoing debate on climate change and how to find emission free energy solutions.
2. The depletion of fossil as well as nuclear resources, especially reflected in the increasing oil prices which especially represent a huge burden for the developing countries.
3. An increasing number of local communities, regions and countries are proving practically that 100% renewable energy is possible.
4. The increasing awareness regarding the hazardous risks related with the utilization of nuclear energy, driven by reports on the nuclear disaster in Fukushima.
5. The increasing awareness regarding the potentials and actual contributions of wind and other renewable energies to an energy supply which is economically, socially as well as ecologically sustainable.
6. Further improvements in wind energy and related technologies, including backup and storage technologies.

In order to make use of the full potential of wind and other renewable energies, it will be of crucial importance to strengthen the related frameworks, institutions and policies. The world community as well as national governments will have to set up additional policies in favor of wind energy.

Incentives for decentralized and integrated 100% renewable energy supply need to be created, especially for developing countries. Social acceptance is also the key issue for the use of wind power.

It will be of crucial importance that renewable energy eventually moves into the center of the debate at the UN Climate Change conferences. Some experts have already proposed to create a completely new global forum for the worldwide expansion of renewable energies.

1.2.4 Forecast and trends 2020

It can be seen that appetite for investment in wind power is strong and many projects are in the planning stage. Further substantial growth can especially be expected in China, India, Europe and North America. High growth rates can be expected in several countries in Latin America, particular in Brazil, as well as in new Asian and Eastern European markets. In the mid-term, also some of the African countries will see major investment, in Northern Africa, and also in South Africa. Based on the current growth rates, the expectations for the future growth of the global wind capacity are the following: in 2016 the global capacity is expected to be 490 GW. By the end of year 2020 at least 700 GW can be expected to be installed globally [11]. Annual growth of new wind capacity is expected to be 57 GW to the year 2017 [13]. Development and prognosis of wind energy is shown on Figure1.14 and Figure 1.15.
Figure 1.14 Total Installed Capacity 1997-2020 (GW). Development and Prognosis (data from WWEA)

Figure 1.15 Annual growth rate of new installed capacity of wind energy in 1990-2017. Development and Prognosis (data from Navigant research)
1.3 Scientific and technical basis of wind power

1.3.1 Physical principles of converting wind energy into electricity

The work of the surface under the wind power influence on it.

Wind speed is defined as the distance in meters that is traveled by the mass of air in one second. The wind speed is constantly changing in value and direction. The reason for these changes is the uneven heating of the earth's surface and roughness of the terrain.

Wind speed is the most important characteristic of the technical properties of the wind. Wind flow in the cross-section F has a kinetic energy determined by the expression [7]:

\[ E = \frac{mV^2}{2}. \] (1.1)

Air mass that flows through the cross-section F with speed V is equal to:

\[ m = \rho F V. \] (1.2)

Wind energy varies with the cube of its speed:

\[ \frac{mV^2}{2} = \frac{\rho F V^3}{2}. \] (1.3)

Let's see how many percent of the wind energy can be turned into useful work by the surface positioned perpendicularly to the direction of the wind and moves in the same direction which is the example of wind turbines of carousel type.

The power T is equal to the force P multiply by the speed V:

\[ T = P \cdot V. \] (1.4)

The same work can be obtained either at the expense of great strength at a low speed movement of the working surface or vice versa, due to low strength and hence low surface area, but with a correspondingly increased speed of its movement.

It is supposed that we have a surface F located perpendicular to the wind direction. Air flow due to inhibition of it by the surface receives backwater and will flow around the surface and produce pressure force \( P_x \). Due to this force the surface will move in the direction of flow with a velocity \( U \) (Figure 1.16).

Figure 1.16 The force of the wind on the surface
Thus, the value of work is equal to the pressure force multiply by the speed $U$ which is the speed of surface $F$ movement, i.e.:

$$T = P_x \cdot U,$$

where $P_x$ – pressure force that is equal to:

$$P_x = C_x \cdot F \cdot \frac{\rho}{2} \cdot (V - U)^2,$$

where $C_x$ – aerodynamic drag coefficient;

$F$ – the projection of the surface area in a plane perpendicular to the direction of air flow.

$$T = C_x \cdot F \cdot \frac{\rho}{2} \cdot (V - U)^2 \cdot U.$$  \hspace{1cm} (1.7)

We define the ratio of the work developed by the moving of the surface to the energy of the wind flow, having a cross-section equal to the surface, i.e.:

$$\xi = \frac{C_x \cdot F \cdot \frac{\rho}{2} \cdot (V - U)^2 \cdot U}{F \cdot \frac{\rho \cdot V^3}{2}} = C_x \cdot (V - U)^2 \cdot \frac{U}{V^3}.$$  \hspace{1cm} (1.8)

After transformations we obtain:

$$\xi = C_x \cdot \left(1 - \frac{U}{V}\right)^2 \cdot \frac{U}{V}.$$  \hspace{1cm} (1.9)

The value of $\xi$ is called wind energy utilization coefficient.

The equation shows that $\xi$ depends on the speed of the surface movement in the direction of the wind flow. At a certain value of velocity $U$, $\xi$-coefficient has the maximum value. In fact if the speed of movement of the surface is zero, i.e. $U = 0$, the work of the wind energy is zero. If $U = V$, i.e. the surface moves with the speed of the wind, the work will also be equal to zero, since there is no force of resistance due to which the work is done. So the value of the velocity $U$ lies in the range between $U = 0$ and $U = V$.

It was set that in order to get the maximum $\xi$-coefficient the surface must move at the following speed:

$$U = \frac{1}{3} \cdot V.$$  \hspace{1cm} (1.10)

**Operation of the wind wheel of vane type.**

Vane wind wheel work due to oblique impact when blades move perpendicular to the direction of the wind speed opposite to the direct impact, as was discussed in the previous case. A scheme of this wheel is shown in Figure 1.17.

On a horizontal shaft blades are fixed and their number can be two or more in modern wind turbines. The wheel consists of a swing (a) and a blade (b) that is fixed on swing, so that it forms an angle $\Phi$ with the plane of rotation. This angle is called the angle of the blade wedged (Figure 1.17). Thus air stream comes to the blade with a relative velocity $W$ at an angle $\alpha$, which is called the angle of attack, and acts with the force of $R$. The angles $\Phi$ and $\alpha$ largely determine the efficiency of the vanes.
The force \( R \) is spread on the forces \( P_x \) and \( P_y \) (Figure 1.18, a). Forces-\( P_x \) produce pressure in the direction of the wind speed, which is called the frontal pressure. \( P_y \)-forces act in the plane \( y - y \) of wind wheel rotation and create torque.

**Figure 1.18** a - the air flow forces on the blade element; b - a graphic representation of the relative air flux that comes on the blade elements located at different radius of the wind wheel

The maximum forces resulting in rotation of the wheel are obtained at a certain angle of attack \( \alpha \). The relative velocity \( W \) of the air flow that comes on the blade increases. Along with this increase the angle of attack \( \alpha \) decreases, and at a certain circumferential speed \( \omega R \) (where \( \omega \) is the angular velocity), the angle will become negative (Figure 1.18, b). Consequently, not all elements of the wing will have a maximum lifting force [14].

If we decrease the angle \( \phi \) for each element of the blade so that we can have the most favorable angle of attack \( \alpha \) and it remains roughly constant, we get the condition under which nearly all elements of the blade will operate at its maximum lifting force.

Appropriate angles of the blade wedged with a good aerodynamic profile of the blade provide a high coefficient of utilization of wind energy. The well-manufactured models have this coefficient to be equal to near 46% [14].
1.3.2 Wind turbine construction. Classification of wind turbines

Wind turbine converts the kinetic energy of the wind into mechanical or electrical energy that is convenient for practical use. Wind turbines are classified in many ways: the design of the wind wheel; the position of its axis of rotation relative to the ground surface; principle of action; rotational speeds, etc.

There are two main types of systems: horizontal-axis and vertical-axis wind turbines (Figure 1.19). Horizontal-axis wind turbines represent about 98% of all wind turbines connected to the grid power systems.

Wind turbine consists of the following basic elements and nodes:

1. Rotor or wind wheel which converts the energy of wind into rotational energy of the shaft;
2. Cabin or gondola where gearbox (some turbines operate without gearbox), generator and other mechanical and electrical equipment are usually located;
3. Tower that supports the rotor and the gondola;
4. Electrical and electronic equipment: control panel, electric cables, the equipment for the network connection, a lightning protection system, etc.;
5. Foundation that determines the stability of wind turbine.

Figure 1.19 Horizontal-axis and vertical-axis wind turbines

According to the number of blades wind turbines can be one, two, three and multi-bladed. In the electric power industry two-and three-bladed wind turbines are mainly used. For high-power wind turbines 3-bladed wind wheels are the most appropriate to ensure smooth operation and minimize the power moments on the axis of the wind wheel.

Vertical-axis wind turbines have a number of advantages, the main one is the lack of the necessity to orient the wind wheel on the wind. The second advantage is the ability to have all the mechanisms at the bottom, which means no need for construction of a strong tower. However, the disadvantages of these wind turbines
are much more important: it is necessary to have the starting external force for the rotation of wind wheel, the lack of use of wind flow of the upper layers (up to 100 m), a complex set of power problems.

Savonius wind turbine has greatest coefficient of wind energy utilization that is 18%. Good aerodynamic characteristics of vane wind turbine, constructive opportunity to produce them with a large capacity, relatively light weight per unit of power are the main advantages of such wind turbines. Coefficient of wind energy utilization for the vane wind turbine is much higher than for the carousel wind turbine.

The most common types of vertical-axis wind turbines are the following:

1. **The cup rotor (anemometer)**. This type of wind wheel is spinning by power of resistance. The shape of the bowl of vane provides almost linear dependence of the wheel speed on the wind speed.

2. **Savonius rotor**. Wind wheel also rotates by resistance force. Its blades are made from thin sheets of curved rectangular form and are characterized by simplicity and cheapness. Torque is created by a different resistance to the air flow provided by the concave and convex rotor blade. Due to the large geometric filling this wind wheel has great torque and is used to pump water (Figure 1.20 a).

3. **Darrieus rotor**. Torque is generated by lift force arising on two or three thin curved bearing surfaces having an aerodynamic profile. Lifting force is maximum at the moment when the blade intersects with the high velocity stream of incoming air. The rotor can’t start to rotate independently therefore to run it normally generator is used operating like a power drive (Figure 1.20 b).

4. **Masgruv rotor**. The blades of the wind wheel in working condition are arranged vertically but have the ability to rotate or folded around a horizontal axis when disconnected. There are various options of Masgruv’s rotors, but they are turned off in strong winds.

5. **Evan’s rotor**. The blades of the rotor can turn around a vertical axis in an emergency situation and during the power control [7].
By the method of power control all wind turbines are divided into two types: Pitch- and Stall-regulation.

---

- Pitch-regulation is a change in the angle of attack of the blade in accordance with the speed of the wind (Figure 1.21 b);
- Stall-regulation is when the angle of attack of the blade is unchanged but the blade profile along the length is such that the efficiency of individual sections of the blade decreases with increasing wind speed. As a result after reaching the rated power with increasing wind speed wind turbine power growth does not occur or occurs but not significantly (Figure 1.21 a).

Figure 1.21 a- Stall-control; b- Pitch-control [15]

For further understanding of the working principles of wind turbines it is necessary to consider two important parameters related to the design of wind wheel: power (in the wind) efficiency $C_p$ and tip speed ratio for the blade $\lambda$.

### 1.3.3 Power in the wind efficiency

Power (in the wind) efficiency is sometimes called as the criterion of Zhukovsky-Betz, with the names of two scientists who theoretically proved its limited value for the perfect wind wheel - 0.593. Thus, by introducing the concept of $C_p$-coefficient one can calculate the power output from any wind turbine using the following equation [7]:

$$P_{WT} = \frac{1}{2} \rho V^3 S C_p$$  \hspace{1cm} (1.11)

where: $P_{WT}$ – real power output from the wind turbine, W;
S – swept area (for horizontal axis wind turbines \( S = \pi R^2 \));

\( V \) – wind speed, m/sec;

\( \rho \) – air density, kg/m³;

\( C_p \) – power (in the wind) efficiency.

For modern wind turbines according to the technical data sheets of manufacturers, the maximum \( C_p \)-coefficient is in the range of 0,45...0,52.

To calculate the electric power output from the wind turbine the expression (1.11) should be multiplied by the overall efficiency of mechanical and electrical components of wind turbine. Thus, the final formula is the following:

\[
\frac{1}{2} \cdot \frac{1}{4} \cdot 3,14 \cdot D^2 \cdot C_p \cdot \rho \cdot V^3 \cdot \eta_{mech} \cdot \eta_{el} \\
\text{or} \quad P_{WT} = 0,3925 \cdot D^2 \cdot \rho \cdot V^3 \cdot C_p \cdot \eta_{mech} \cdot \eta_{el}. \tag{1.12}
\]

where:

\( P_{WT} \) – real power output from the wind turbine, W;

\( D \) – rotor diameter, m;

\( V \) – wind speed, m/sec;

\( \rho \) – air density, kg/m³;

\( C_p \) – power (in the wind) efficiency;

\( \eta_{mech}, \eta_{el} \) – total efficiency of mechanical and electrical components of wind turbine.

Typically, modern wind turbines have the overall efficiency of mechanical and electrical components in the range of 0,90...0,95 [7].

### 1.3.4 **Tip speed ratio**

Tip speed ratio-\( \lambda \) is defined as [16]:

\[
\lambda = \frac{\omega \cdot R}{V}, \tag{1.14}
\]

where: \( \omega \) - angular velocity of the wind wheel, rad/sec;

\( R \) - radius of the wind wheel, m,

\( V \) - average velocity of the wind flow, m/sec.

Tip speed ratio determines the number of pole pairs of the generator, i.e. its dimensions and material. The higher tip speed ratio is, the less the number of pole pairs the generator has and, therefore, the smaller its size is. Furthermore, with increasing of the tip speed ratio the frequency of generated electric current is closer to a standard in the grid (~ 50 Hz).

Wind turbines are low-speed installations compared with other energy installations. Thus, even for the high-speed wind wheels the rated speed of the generator may be insufficient to obtain a high-quality current with appropriate frequency. In practice, when design the wind turbines the frequency of the current is increased by the use of gears (manual transmission that increases the frequency of rotation of the generator), as well as the use of multi-pole generators of large diameter. Also electrical schemes are used to increase the frequency of
the current. However, all these solutions are associated with increased material capacity of wind turbines, therefore tip speed ratio is the determining criterion to select the type of wind turbines.

Using the power in the wind coefficient and tip speed ratio we analyze the graph shown in Figure 1.22.

**Figure 1.22 Typical dependence of the Cp-coefficient and tip speed ratio-λ:** 1 - perfect wind wheel; 2, 3 and 4 - two, three and multi-bladed horizontal axis rotors; 5 - Darrieus rotor (vertically oriented wind wheel using the lift force); 6 - Savonious rotor (vertically oriented wind wheel, using the force of resistance); 7 - four-bladed wooden wind wheel of the wind mills [16]

The graph shows why for electricity generation in most cases three-bladed horizontal axis wind turbines are used with a lifting force for electricity generation (Cp-coefficient is 0.4-0.5). Wind turbines that use the lift force have a greater Cp-coefficient than the one uses the force of resistance. However, two-bladed wind turbines have the best ratio of λ and Cp, but are rare in the industry and are not applied.

There are two reasons for that:

- with too high λ-ratio the peripheral speed of the blade may exceed the speed of sound in the air (~ 331 m/s) and goes to the flutter mode;
- two-bladed wind turbines are subjected to complex dynamic loads that occur due to the presence of two (depending on the number of blades) orthogonal center of gravity.

### 1.3.5 Classification of wind farms

**Onshore wind farms.** Onshore wind farms are currently the most common types of wind farms. Wind turbines are installed on the hills or elevations. Industrial wind turbine is constructed on a prepared site during 7-10 days. For construction process the road to the construction site, heavy lifting equipment with the boom of more than 50 meters are needed, as the nacelle can be mounted at a height of about 50 meters. Wind power plant is connected to the transmitting power grid.

**Offshore wind farms.** Offshore wind power plants are constructed in the sea: 10-12 kilometers from the coast (Figure 1.23). Offshore wind power plants have several advantages:

- they are almost invisible from the shore;
they do not occupy the land;
— they have a higher efficiency due to regular sea winds.

The wind power plants are constructed in parts of the sea with little depth. Tower of wind turbines is mounted on foundations of piles hammered to a depth of 30 meters. Electricity is transmitted via underwater cables. These wind farms are more expensive in construction than onshore ones. Generators require higher towers and massive foundations.

**Figure 1.23 Offshore wind power plant, Copenhagen, Denmark [6]**

![Offshore wind power plant](image)

**Floating wind turbine concept.** The first prototype of a floating wind turbine was designed by «H Technologies BV» company in December 2007. 80 kW wind turbine is mounted on a floating platform in the distance of 10,6 nautical miles from the coast of southern Italy in the area of the sea with the depth of 108 meters.

The Norwegian company «StatoilHydro» developed floating wind turbines for offshore wind power stations for the large depth. «StatoilHydro» company constructed a demo version of such wind turbine with a capacity of 2,3 MW in September 2009. The turbine called «Hywind» weighs 5300 tones and has the height of 65 meters. It is located 10 kilometers from the island Karma, near the south-west coast of Norway. The steel tower of the wind turbine goes under the water on a depth of 100 meters. Tower rises over the water on 65 meters. The rotor diameter is 82,4 m. For stabilization of the wind turbine tower and setting it to the desired depth the ballast (gravel and stones) is located in the bottom of the tower. In this case to avoid the drift of the tower three cables with anchors are fixed on the bottom. Electricity is transmitted by underwater cable [15] (Figure 1.24).
Figure 1.24 Floating wind turbine concept [15]
2 PERSPECTIVES FOR WIND ENERGY DEVELOPMENT IN RUSSIA

2.1 Wind energy potential assessment in Russia

As has been shown earlier, Russia is one of the world leaders in domestic energy consumption, but energy efficiency is low. Implementation of energy saving measures will require huge expenditures of material and financial resources and a large amount of time [17]. But it is not obvious that these measures will give us positive results and economic benefits that we expect. Consequently, it is very promising to start involving renewable energy into the country's energy balance assuming that our huge territory will give us competitive advantages over other countries. To do this, first of all, we need to evaluate the technical potential of renewable energy resources.

In the present study the methodology of assessing the technical potential of one of the most widespread source of renewable energy - wind energy, in Russia is presented.

2.1.1 Methodology of wind energy potential assessment in Russia

In this part of the thesis the calculation of the wind energy technical potential in Russia is shown, and the area that is necessary for wind turbines installation in each zone of average annual wind speed distribution is determined at a given load factor [18]. Based on these results the conclusions in the form of graphs and tables were made. The data used in the calculations are given in Table 2.1.

Table 2.1 Given data for the calculations

<table>
<thead>
<tr>
<th>Rotor diameter - D, m</th>
<th>50-100 meters with 10 meters interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average annual wind speed, m/sec</td>
<td>according to the given data [19]</td>
</tr>
<tr>
<td>Area occupied by a single wind turbine, m²</td>
<td>depends on the rotor diameter</td>
</tr>
<tr>
<td>Load factor, K_load</td>
<td>according to the operation conditions</td>
</tr>
<tr>
<td>Air density - ( \rho ), kg/m³</td>
<td>1,225</td>
</tr>
<tr>
<td>Power (in the wind) efficiency - ( C_p ) [7]</td>
<td>0,45</td>
</tr>
<tr>
<td>Overall efficiency of mechanical and electrical components of wind turbine - ( \eta_{mech} \cdot \eta_{el} ) [7]</td>
<td>0,9</td>
</tr>
<tr>
<td>Total area of the territory of Russia, m²</td>
<td>17,098 \cdot 10^{12}</td>
</tr>
<tr>
<td>Overall energy consumption in Russia- Wen.cons., GW\cdot hour/year [1]</td>
<td>8,074 \cdot 10^{6}</td>
</tr>
</tbody>
</table>

Calculation steps.

1. Figure 2.1 shows a map of the average wind speed distribution on the territory of Russian Federation. This map defines zones where average wind speed dominates and defines area of the territory in Russia where the technical potential of wind energy is implemented.

With the help of the program «Universal Desktop Ruler» [20] we find an area where the necessary wind speed dominates, as a percentage of the total territory of Russia.
Thus, the area where the necessary wind speed dominates, as a percentage of the total territory of Russia, is presented in Table 2.2 and the graph, Figure 2.2.

Table 2.2 Area where the necessary wind speed dominates, as a percentage of the total territory of Russia

<table>
<thead>
<tr>
<th>Wind speed (V), m/sec</th>
<th>Percentage of the total territory of Russia, q, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 4 m/sec</td>
<td>0,12</td>
</tr>
<tr>
<td>4 m/sec</td>
<td>36,54</td>
</tr>
<tr>
<td>5 m/sec</td>
<td>31,53</td>
</tr>
<tr>
<td>6 m/sec</td>
<td>9,17</td>
</tr>
<tr>
<td>7 m/sec</td>
<td>20,23</td>
</tr>
<tr>
<td>8 m/sec</td>
<td>2,41</td>
</tr>
</tbody>
</table>
Figure 2.2 Area where the necessary wind speed dominates, as a percentage of the total territory of Russia

Territories where wind speed is less than 4 m/sec are not considered in the calculation, since the wind turbine starts to operate with a minimum wind speed of 3 m/sec or more.

Consequently, almost all the territory of Russia is perspective for wind power development, as the territory with wind speed less than 4 m/sec is amounted to 0.12% of the total area of Russia.

Then, the area where the technical potential can be realized is determined by the relation:

\[ S_T = q \cdot S_{Russia} \]  \hspace{2cm} (2.1)

where: \( S_T \) - area where the technical potential can be realized, m\(^2\);
\( q \) - area where the necessary wind speed dominates, as a percentage of the total territory of Russia, %, table 2.2;
\( S_{Russia} \) - total area of the territory of Russia, m\(^2\), table 2.1.

2. Real power output from the wind turbine at a given wind speed and rotor diameter [7]:

\[ P_{WT} = \frac{1}{2} \cdot \frac{1}{4} \cdot 3.14 \cdot D^2 \cdot C_p \cdot \varrho \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}) \]  \hspace{2cm} (2.2)

where: \( P_{WT} \) – real power output from the wind turbine, W;
\( D \) – rotor diameter, m, table 2.1;
\( V \) – wind speed, m/sec, table 2.1;
\( \varrho \) – air density, kg/m\(^3\), table 2.1;
\( C_p \) – power (in the wind) efficiency, table 2.1;
\( \eta_{mech} \cdot \eta_{el} \) – total efficiency of mechanical and electrical components of wind turbine, table 2.1.

3. Annual energy production, GW\text{hour}/year:

\[ W_{WT} = P_{WT} \cdot 8760 \]  \hspace{2cm} (2.3)

where: \( P_{WT} \) – real power output from the wind turbine, W;
4. Wind Farm layout.
It is very important to choose the wind farm layout. Small groups with two to four wind turbines are often put on a straight line, perpendicular to the predominant wind direction. The distance between turbines is measured in rotor diameters, since the size of the wind wake depends on the size of the rotor. A common rule of thumb is to site the turbines 5 rotor diameters apart if they are set in one row. Larger wind power plants can have several rows of turbines. In that case, the distance between rows usually is 7 rotor diameters (Figures 2.3 and 2.4) [6, 21]. This ideal model for the layout can be applied in an open and flat landscape and offshore.

Figure 2.3 Wind farm layout

Figure 2.4 Standard wind farm layout. In this wind farm, sited on Öland in Sweden, the rows are perpendicular to the predominant wind direction
The actual layout of a wind farm is, however, often formed by the limits set by local conditions, like land use, distance to dwellings, roads, and the power grid. If there are height differences on the site, this will also influence how the turbines should be sited in relation to each other to optimize power production. It is usually not reasonable to increase the distance between turbines to eliminate the impact from wind wakes completely; it is an inefficient use of land. In areas where one or two opposing wind directions are very dominant, the in-row distance between the turbines can be reduced to 3–4 rotor diameters [6]. As technical potential of wind energy is estimated for the whole territory of Russia no limits are set for the calculations. In the calculations the total territory of the country is used and the wind farm layout is the following: the in-row distance is (5∙D) and the distance between rows (7∙D) [6].

Based on the assumptions the necessary number of wind turbines that can be installed in each zone with the dominating wind speed can be calculated from:

\[ N_{WT} = \frac{S_T}{(7D \cdot 5D)} \],

where: \( S_T \) – area where the technical potential can be realized, m²; 
(7D∙5D) – area occupied by a single wind turbine, m².

5. Technical potential of wind energy is, GW·hour/year:

\[ W_T = P_{WT} \cdot 8760 \cdot N_{WT} \cdot K_{load} \],

where: \( W_T \) – technical potential of wind energy, GW·hour/year; 
\( K_{load}=0.5 \) – load factor for wind turbine.

The technical potential calculation results for the whole territory of Russia and the total number of wind turbines that can be installed on that territory depending on the rotor diameter and average wind speed are shown in table 2.3:

<table>
<thead>
<tr>
<th>Rotor diameter, m</th>
<th>Total number of wind turbines, ( N_{WT} )</th>
<th>Total technical potential of wind energy ( W_T ), GW·hour/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1,952∙10⁸</td>
<td>6,847∙10⁷</td>
</tr>
<tr>
<td>60</td>
<td>1,355∙10⁸</td>
<td>6,847∙10⁷</td>
</tr>
<tr>
<td>70</td>
<td>9,958∙10⁷</td>
<td>6,847∙10⁷</td>
</tr>
<tr>
<td>80</td>
<td>7,624∙10⁷</td>
<td>6,847∙10⁷</td>
</tr>
<tr>
<td>90</td>
<td>6,024∙10⁷</td>
<td>6,847∙10⁷</td>
</tr>
<tr>
<td>100</td>
<td>4,879∙10⁷</td>
<td>6,847∙10⁷</td>
</tr>
</tbody>
</table>

In Figure 2.5 the dependence of power output of wind turbine on rotor diameter and annual average wind speed is shown.

Figure 2.6 represents the number of wind turbines dependence in each zone of annual average wind speed distribution on rotor diameter.
Figure 2.5 The dependence of power output of wind turbine on rotor diameter and annual average wind speed.
Figure 2.6 The number of wind turbines dependence in each zone of annual average wind speed distribution on rotor diameter

Analyzing Table 2.3 and Figures 2.5 and 2.6, it can be concluded that from each wind turbine depending on the rotor diameter and wind speed it is possible to obtain from 0.03 MW to nearly 1 MW of installed capacity. Also it should be noted that the installed capacity of wind turbines increases along with the growth of the rotor diameter and the average wind speed as well as the number of wind turbines that can be installed in each zone where the average annual wind speed dominates decreases.

From the calculations made by special programs follows that the total technical potential of wind energy in Russia does not depend on the rotor diameter and the technical potential has the constant value and equal to $6,847 \times 10^7$ GW· hour/year, which corresponds to the use of approximately 6 billion of toe per year (~ 50% of the world's total energy consumption [1]).

This result requires some explanation. Theoretically it is possible to explain why the total wind power generated by the wind turbines in a wind farm doesn’t depend on the rotor diameter of wind turbines, as it is shown below.

1) Real power output from the wind turbine at a given wind speed and rotor diameter, equation (2.2):

$$P_{WT} = \frac{1}{2} \cdot \frac{1}{4} \cdot 3.14 \cdot D^2 \cdot C_p \cdot p \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el})$$

or

$$P_{WT} = k_1 \cdot D^2,$$

where: $k_1$ – coefficient including average wind speed, air density, $C_p$ - coefficient, overall efficiency of mechanical and electrical components of wind turbine, so

$$k_1 = \frac{1}{2} \cdot \frac{1}{4} \cdot 3.14 \cdot C_p \cdot p \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}).$$

$D$ – rotor diameter.
2) Number of wind turbines in a wind farm:

\[ N_{WT} = \frac{S}{(A\cdot B)D^2} = \frac{k_2}{D^2} \]  \hspace{1cm} (2.7)

where: \( k_2 \) – coefficient including area of the territory \( S \), coefficients \( A \) and \( B \); so \( k_2 = \frac{S}{(A\cdot B)} \).

\( D \) – rotor diameter;

\( S \) – area of the territory for wind farm installation;

\((A\cdot B)D^2 \) – area occupied by a single wind turbine with the chosen layout \((A\cdot D \times B\cdot D)\), where \( A \) and \( B \) - coefficients showing the distance between the wind turbines in a row and between rows, depending on the rotor diameter [6].

3) Power output from a wind farm:

1. \[ P_{WF} = P_{WT} = k_2 \cdot k_1 \cdot D^2 = k_1 \cdot k_2 = k_3, \]  \hspace{1cm} (2.8)

where: \( k_3 = k_1 \cdot k_2 = 1 \cdot \frac{1}{2} \cdot \frac{1}{4} \cdot 3,14 \cdot C_P \cdot \rho \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}) \cdot \frac{S}{(A\cdot B)}, \) so \( k_3 \) coefficient doesn’t depend on the rotor diameter.

Equation (2.8) shows that the total wind power generated by the wind turbines in a wind farm doesn’t depend on the rotor diameter of wind turbines, using the chosen wind farm layout \((A\cdot D \times B\cdot D)\).

Now we try to consider two cases when choosing wind turbines, it is necessary to consider the following factors:

— the amount of land for wind turbines installation, \( S \), because renting or buying land is very expensive;

— the power of the chosen object \( P_{object} \) which must be offset by energy generated from the wind farm.

Given data for the calculations are the following:

1. \( S \) – the amount of land for wind turbines installation.
2. \( P_{object} \) – the power of the chosen object which must be offset by energy generated from the wind farm.
3. \( N_{WT} \) – number of wind turbines in a wind farm.
4. \((A\cdot B)D^2 \) – area occupied by a single wind turbine with the chosen layout \((A\cdot D \times B\cdot D)\), where \( A \) and \( B \) - coefficients showing the distance between the wind turbines in a row and between rows, depending on the rotor diameter [6].

**Case 1.** The power of the chosen object must in 100% be offset by energy generated from the wind farm with the unlimited amount of land.

In this case:

1. Real power output from the wind turbine at a given wind speed and rotor diameter, equation (2.2) and (2.6):

\[ P_{WT} = \frac{1}{2} \cdot \frac{1}{4} \cdot 3,14 \cdot D^2 \cdot C_P \cdot \rho \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}) \],

or \( P_{WT} = k_1 \cdot D^2 \).

2. Number of wind turbines that is necessary to offset the power of the chosen object:

\[ N_{WT} = \frac{P_{object}}{P_{WT}} = \frac{P_{object}}{(k_1 \cdot D^2)}. \]  \hspace{1cm} (2.9)
3. Amount of land $S$, that is necessary for wind turbines installation:

$$S = N_{WT} (A \cdot B) D^2 = \frac{P_{object}}{(k_1 \cdot D^2)} (A \cdot B) D^2 = \frac{P_{object}}{k_1} (A \cdot B).$$

Equation (2.10) shows that the power generated in a wind farm used to offset the power of the chosen object is:

$$P_{WF} = P_{object} = \frac{S}{(A \cdot B) D^2} \cdot k_1.$$

In the case when the amount of land is unlimited, the total wind power generated by the wind turbines in a wind farm that is necessary to offset the power of the chosen object doesn’t depend on the rotor diameter of wind turbines, using the chosen wind farm layout $(A \cdot D \times B \cdot D)$.

**Case 2.** The amount of land for wind turbines installation is limited.

In this case:

1. Real power output from the wind turbine at a given wind speed and rotor diameter, equation (2.2) and (2.6):

$$P_{WT} = \frac{1}{2} \cdot 1.14 \cdot 3.14 \cdot D^2 \cdot C_p \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}) \ ,$$

or

$$P_{WT} = k_1 \cdot D^2.$$

2. Number of wind turbines in limited area $S$:

$$N_{WT} = \frac{S}{(A \cdot B) D^2}.$$

3. The power generated in a wind farm situated in area $S$:

$$P_{WF} = N_{WT} P_{WT} = \frac{S}{(A \cdot B) D^2} \cdot k_1 \cdot D^2 = \frac{S}{(A \cdot B)} \cdot k_1.$$

In this case it is necessary to check if the power generated in a wind farm can offset the power of the chosen object, so this condition must be satisfied $P_{WF} \geq P_{object}$.

Anyway, when the amount of land for wind farm construction is limited, the total wind power generated by the wind turbines in a wind farm that is necessary to offset the power of the chosen object doesn’t depend on the rotor diameter of wind turbines, using the chosen wind farm layout $(A \cdot D \times B \cdot D)$.

Also we evaluate on what part of Russia wind turbines installation is possible using the chosen wind farm layout $(5 \times 7$ of rotor diameter) in order to fully compensate the country's annual energy consumption. Domestic energy consumption in Russia in 2012 is amounted to 694,2 million of toe or $8.074 \times 10^6$ GW·hour/year [1]. Knowing the total energy consumption in Russia and technical potential of wind energy, it is possible to determine the area required for wind turbines installation at a given load factor of 50% for wind turbines:

$$S_{WT} = \frac{W_{en.\,cons.}}{W_T} \cdot S_{Russia},$$

where: $S_{WT}$ – area of Russia for wind turbines installation, km$^2$;

$W_{en.\,cons.}$ – overall energy consumption in Russia, GW·hour/year;

$W_T$ – wind energy technical potential, GW·hour/year;

$S_{Russia}$ – total area of the territory of Russia, km$^2$. 

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Using the values obtained previously in equation (2.14), we obtain that area of **11.8% of the territory of Russia** (near 2 million of km²) would be able to fully compensate the domestic energy consumption in the country in 2012 with each wind turbine load factor equal to 50% and $C_p$-coefficient equal to 0.45.

### 2.1.2 Wind energy potential assessment in coastline in Russia

Separately we calculate the potential of wind energy in the coastline zone of Russia (excluding the coastlines of the Caspian, Azov, Black and Baltic seas, where there is minimum space for wind turbines installation than near the coastline of North and East Seas) using the above mentioned methodology. Initial data for calculation are summarized in Table 2.4.

<table>
<thead>
<tr>
<th><strong>Table 2.4 Initial data for calculation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average annual wind speed in the coastline zone, m/sec [18]</strong></td>
</tr>
<tr>
<td><strong>Rotor diameter - $D$, m [6]</strong></td>
</tr>
<tr>
<td><strong>Load factor, $K_{\text{load}}$</strong></td>
</tr>
<tr>
<td><strong>Air density - $\rho$, kg/m$^3$</strong></td>
</tr>
<tr>
<td><strong>Power (in the wind) efficiency - $C_p$ [7]</strong></td>
</tr>
<tr>
<td><strong>Overall efficiency of mechanical and electrical components of wind turbine - $\eta_{\text{mech}} \cdot \eta_{\text{el}} [7]$</strong></td>
</tr>
<tr>
<td><strong>Total length of the North and East coastline of Russia, km</strong></td>
</tr>
</tbody>
</table>

Calculation is carried out with an average wind speed in the coastline zone of Russia equal to 12 m/s, which is the smallest since the wind speed in the coastline of the northern seas is equal to 10-15 m/s or more, Figure 2.7 [23].
For the wind turbines layout the following scheme was chosen: wind turbines are set in a row, the distance between the wind turbines in a row is 6 rotor diameters and the distance between rows - 9 rotor diameters (usually this distance is 8-10 rotor diameters) [6]. In the calculation it is considered that wind turbines are installed in line along the northern and eastern maritime border of Russia, the distance between wind turbines is 9 rotor diameters.

The necessary number of wind turbines that can be installed in each zone with the dominating wind speed can be calculated from:

$$N_{WT} = \frac{L}{(9D)}$$  \hspace{1cm} (2.15)

where: $L$ – total length of the of the North and East coastline of Russia, m, table 2.4;

$(9D)$ – distance between wind turbines, m.

The technical potential calculation results for the coastline of Russia and the total number of wind turbines that can be installed on that territory depending on the rotor diameter and average wind speed, $V=12$ m/sec, are shown in table 2.5:

<table>
<thead>
<tr>
<th>Rotor diameter, m</th>
<th>Total number of wind turbines, $N_{WT}$</th>
<th>Total technical potential of wind energy $W_T$, GW·hour/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>45 336</td>
<td>5,412·10$^5$</td>
</tr>
<tr>
<td>100</td>
<td>40 802</td>
<td>6,014·10$^5$</td>
</tr>
<tr>
<td>110</td>
<td>37 093</td>
<td>6,615·10$^5$</td>
</tr>
<tr>
<td>120</td>
<td>34 002</td>
<td>7,216·10$^5$</td>
</tr>
<tr>
<td>130</td>
<td>31 386</td>
<td>7,818·10$^5$</td>
</tr>
</tbody>
</table>
In Figure 2.8 the dependence of power output of wind turbine and the number of wind turbines on rotor diameter and annual average wind speed is shown.

Figure 2.9 represents dependence of the wind energy technical potential in the coastline of Russia on rotor diameter with the given annual average wind speed.

Figure 2.8 Dependence of power output of wind turbine and the number of wind turbines on rotor diameter and annual average wind speed (12 m/sec)

In the coastline of Russia it is possible to obtain maximum of installed capacity (from 2,5 to 5,7 MW) from each wind turbine depending on the rotor diameter and wind speed.
Figure 2.9 Dependence of the wind energy technical potential in the coastline of Russia on rotor diameter with the given annual average wind speed (V=12 m/sec)

Technical potential of wind energy in the coastline zone of Russia has almost linear dependence on the rotor diameter and increases when rotor diameter increases.

Separately technical potential of wind energy for non-freezing coastline of Russia was calculated that are coastlines of the Kola Peninsula, the Sakhalin island and Primorsky Krai, as this coastline zone is the most promising for the wind turbines installation.

Calculations of the technical potential of wind energy is made by using the same given data and with the same methodology that was mentioned above, except for the length of the coastline of the Kola Peninsula, the Sakhalin island and Primorsky Krai, Figure 2.10 [24, 25]:

L (the Kola Peninsula) ≈ 1601, 9 km;
L (the Sakhalin island) ≈ 3163, 7 km;
L (Primorsky Krai) ≈ 1401, 6 km.
Figure 2.10 The coastline of the Kola Peninsula, the Sakhalin island and Primorsky Krai (mentioned with green color)

The wind turbines layout is the same as was mentioned before: wind turbines are installed in line along the coastline, the distance between wind turbines is 9 rotor diameters.

The technical potential calculation results for the non-freezing coastline of Russia and the total number of wind turbines that can be installed on that territory depending on the rotor diameter and at a given average wind speed (V=12 m/sec) are shown in table 2.6:

Table 2.6 Calculation results

<table>
<thead>
<tr>
<th>D, m</th>
<th>Power output from a wind turbine, MW</th>
<th>Total number of wind turbines</th>
<th>Total technical potential of wind energy, GW-hour/year</th>
<th>Total number of wind turbines</th>
<th>Total technical potential of wind energy, GW-hour/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>2,726</td>
<td>1978</td>
<td>2,36·10^4</td>
<td>3906</td>
<td>4,66·10^4</td>
</tr>
<tr>
<td>100</td>
<td>3,365</td>
<td>1780</td>
<td>2,62·10^4</td>
<td>3515</td>
<td>5,18·10^4</td>
</tr>
<tr>
<td>110</td>
<td>4,072</td>
<td>1618</td>
<td>2,89·10^4</td>
<td>3196</td>
<td>5,70·10^4</td>
</tr>
<tr>
<td>120</td>
<td>4,845</td>
<td>1483</td>
<td>3,15·10^4</td>
<td>2929</td>
<td>6,22·10^4</td>
</tr>
<tr>
<td>130</td>
<td>5,687</td>
<td>1369</td>
<td>3,41·10^4</td>
<td>2704</td>
<td>6,74·10^4</td>
</tr>
</tbody>
</table>

In Figure 2.11 the dependence of total number of wind turbines and in Figure 2.12 the dependence of technical potential of wind energy for the non-freezing coastline of Russia on rotor diameter at a given annual average wind speed is shown.
It can be seen from these graphs that:

- The technical potential of wind energy for non-freezing coastline of Russia ranges from $2 \cdot 10^4$ to $3,4 \cdot 10^4$ GW-h/year for the Kola Peninsula and Primorsky Krai, and from $4,6 \cdot 10^4$ to $6,7 \cdot 10^4$ GW-h/year – for the Sakhalin island.

- The largest technical potential depending on the wind turbine rotor diameter can be obtained when installing wind turbines along the coastline of the Sakhalin island, as the length of its coastline is the largest compared to the coastline length for the Kola Peninsula and Primorsky Krai.
Thus, the world's richest land and marine reserves of wind energy resources along with large territory of our country and optimal wind turbines installation locations allow us to consider the wind energy as one of the most economical, effective and promising sectors of energy in Russian Federation.

2.2 Actuality of wind turbines application in gas transportation systems

Actuality of wind turbines application in gas transportation systems is supported by the following factors [26]:

- The total number of emergency and planned outages in external power supply systems for gas transportation systems increased by 1.7 times in 2009 compared to 2005, and their duration increased by 2.2 times. The total duration of the emergency and planned outages reaches 150,000 hours.
- Depreciation of the electric grid is 40.5%.
- Electrical network cannot provide the required reliability category.
- Reservation of power networks is difficult due to the need to build long transmission lines (80-120 km).
- Isolation of power districts, the inability to transfer excess capacity.
- Decentralized energy supply, remoteness of areas.
- Lack of regular energy sources, decentralized energy supply, use the power generated by the diesel power plants.
- In 2014 the price for gas will be on the basis of equal profitability for both internal and external customers.
- According to the forecasts, the average price for gas for all consumers will increase by 1.8 times in 2012–2015 compared to 2011, and in 2020 by 16% compared with 2015.

2.3 Comparison of the wind resources maps with the map of Russian Gas Transportation System. Prospects of wind turbines application in gas transportation systems

Figure 2.13 shows the map of Russian gas transportation system combined with the average wind speed distribution map on the territory of Russian Federation.
Figure 2.13 The map of Russian gas transportation system combined with the average wind speed
distribution map on the territory of Russian Federation

This map shows that there are many areas where the average wind speed exceeds 6,0 m/sec. The highest
average wind speeds are found along the coastline of the Barents, Kara, Bering and Okhotsk seas. Other areas
with relatively high wind speeds (5-6 m/sec) include the coastline of the East Siberian, Chukchi Sea and the
Laptev Sea in the north and the Sea of Japan in the east. Lower wind speed (3,5-5 m/sec) is found on the
coasts of the Black, Azov and Caspian seas in the south and the White Sea in the north-west. The perspective
wind energy development zones include North West of the country (Murmansk and Leningrad region), the
northern territory of the Urals, the Kurgan region, Kalmykia, Krasnodar Krai, Far East.

Considering the combined map of Russian gas transportation system with the average wind speed
distribution map on the territory of Russia as well as analyzing the information provided by "Cartographic
Information Center INCOTEC" [27], and using the program «Universal Desktop Ruler» [20], and due to the
lack of other information relating to the location of main gas pipelines in Russia, we can roughly determine
the percentage of the total length of the main gas pipelines located in a particular region with dominating
average annual wind speed, what is presented in Table 2.7 and in Figure 2.14.

Table 2.7 Distribution of the main gas pipelines in the zones with dominating average annual wind
speed as a % of the total length of gas pipelines

<table>
<thead>
<tr>
<th>Wind speed, V, m/sec</th>
<th>% of the total length of gas pipelines in the zone with dominating average annual wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 4 m/sec</td>
<td>13,4</td>
</tr>
<tr>
<td>4 -5 m/sec</td>
<td>78,2</td>
</tr>
<tr>
<td>6-8 m/sec</td>
<td>8,4</td>
</tr>
</tbody>
</table>
Based on available data we can conclude that 86.6% of the gas transportation system, that is available today in Russia, are promising for wind turbines application in order to offset energy consumption of the selected objects in gas transportation system, as almost all regions are suitable for wind power development (average annual wind speed in these regions exceeds 4 m/sec).
3 UNIFIED GAS SUPPLY SYSTEM AS THE OBJECT OF ENERGY DEMAND

3.1 Gas transportation system in Russia

Unified Gas Supply System (UGSS) established in the country is the world's largest centrally managed unique technological complex comprising production facilities, transportation, processing, storage and distribution of gas. Gas transportation system (GTS) is included in the Russian Unified Gas Supply System and is a necessary and important link of UGSS, providing a continuous cycle of gas transportation from the fields to the consumers. GTS is able to provide an uninterrupted supply of gas to consumers, having a significant reserve of safety.

GTS comprises a network of trunk pipelines and underground gas storage facilities. At the end of 2012 the length of gas pipelines inside Russia's borders is 168,3 thousand km. GTS has more than 280 compression stations including more than 4100 installed gas pumping units (GPU). In this case, the total power of GPU for linear compression stations is about 43,9 thousand MW, at booster compression stations in gas and gas-condensate fields - is about 5015,2 MW and at 25 underground gas storage facilities - approximately 838,31 MW [28].

All objects including in GTS can be decomposed on energy facilities. As the object of research, I chose the most important object of UGSS - linear compression stations which are the largest consumers of electricity in the UGSS.

In the Unified Gas Supply System compression stations of different types are used defined by their technological applications:

- booster compression stations;
- injection compression stations;
- linear compression stations;
- compression stations in underground gas storage facilities;
- compression stations for cooling stations of natural gas;
- «onshore» compression stations with increased power of GPA;
- compression stations for liquefied natural gas plant;
- compression stations on offshore platforms;
- compression stations for low-pressure gas and associated gas compression;
- mobile compression units.

Compression station is a complex of buildings and energy technology equipment designed to increase the pressure of the gas during its production, transportation and storage. At compression stations it can be performed the gas purification processes, compression and cooling of natural gas. The main technological process at compression station is the compression of natural gas and, consequently, the main system is the compression system equipped with gas pumping units (GPU).

Linear compression stations are an integral and inseparable part of the trunk gas pipeline that provides gas transportation. Linear compression stations are used to compensate the loss of gas pressure in the preceding sections and the performance of the compression stations determine operation conditions of gas pipelines.

The compression station includes the following main facilities and systems, providing its main functions - cleaning, compressing and cooling of the gas:

- compression system comprising one or more compression stations equipped with pumping units;
• cleaning of natural gas equipped with a cyclone dust collectors and filters - separators;
• cooling of natural gas including air coolers, as well as, if necessary, chillers and turbo expanders;
• system of fuel, starting and pulsed gas preparation;
• piping arrangement of the compression stations;
• automatic control system;
• the power supply system, water supply, heat supply, sewerage, communications, cathodic protection, etc.

The interaction of the linear part of gas pipeline and the compression station is performed via connection node of the compression station [29]. Using a connection node provides the following regimes of the gas pipeline operation:
• gas supply along with gas compression in compression station;
• gas supply by its bypassing (when compression station doesn’t work);
• gas supply during the passage of treatment devices in the cavity of tube.

Currently, the gas pumping units with turbine, electric or piston power drive are used in compression stations. At the beginning of 2009 gas pumping units at compression stations of "Gazprom" were as follows: gas pumping units with gas turbine power drive (GGPA) accounted for approximately 87,2% of the total installed capacity of power drive, electrically driven gas compressor units (EGPA) – 12,3% and reciprocating gas compressor units – 0,5% (Table 3.1 and Table 3.2).

### Table 3.1 Types of EGPA [29]

<table>
<thead>
<tr>
<th>Type of unit</th>
<th>Capacity, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ-4500</td>
<td>4,5</td>
</tr>
<tr>
<td>STM-4000; STD-4000</td>
<td>4</td>
</tr>
<tr>
<td>STD-12,5; SDG-12,5</td>
<td>12,5</td>
</tr>
<tr>
<td>EGPA -25</td>
<td>25</td>
</tr>
<tr>
<td>EGPA - 6,3; EGPA - 6,3K</td>
<td>6,3</td>
</tr>
</tbody>
</table>

### Table 3.2 Types of reciprocating gas compressor units [29]

<table>
<thead>
<tr>
<th>Type of unit</th>
<th>Capacity, kW</th>
<th>Efficiency of power drive, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper - Bessemer</td>
<td>736</td>
<td>29</td>
</tr>
<tr>
<td>10 GC, 10 GMC</td>
<td>736</td>
<td>32</td>
</tr>
<tr>
<td>10GCM/ 10GCNA</td>
<td>1100/1178</td>
<td>32</td>
</tr>
<tr>
<td>MC-8</td>
<td>2060</td>
<td>36</td>
</tr>
<tr>
<td>DR-12</td>
<td>5500</td>
<td>36,5</td>
</tr>
<tr>
<td>MC-8M</td>
<td>2200</td>
<td>36</td>
</tr>
</tbody>
</table>
Analysis of trends of gas pumping units at compression stations shows that at the present time and in the foreseeable future the main type of gas compressor units is pumping units with gas turbine power drive [28].

Gas turbine driven compressor units has the efficiency of 24% to 39.4%. Average passport efficiency of gas turbine driven compressor units was about 29.5% in the beginning of 2009.

Gas turbine driven compressor units used nowadays have the capacity of 2.5 - 4 - 6.3 (8) - 10 (12) - 16 (18) - 25 MW, and the basic capacity ranges from 10 to 18 MW (Table 3.3).

<table>
<thead>
<tr>
<th>Capacity, MW</th>
<th>≤ 8</th>
<th>10-12</th>
<th>16-18</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power output, %</td>
<td>12.2</td>
<td>30.7</td>
<td>44.8</td>
<td>12.3</td>
</tr>
<tr>
<td>Efficiency of gas turbine system, %</td>
<td>24.30</td>
<td>27.35</td>
<td>29.36</td>
<td>28.39</td>
</tr>
</tbody>
</table>

Table 3.3 Basic capacity of GGPA [29]

One of the most common types of gas turbine driven compressor units currently in use at the compression stations is the unit of stationary type GPA-10-4 with the utilization of heat from the exhaust products (nowadays about 680 GGPA of this type operates at the compression stations).

In the period from 1999 to 2008 in the new constructed and reconstructed compression stations 577 new gas pumping units were installed with turbine power drive with total capacity of more than 8.5 million kW [29]. Installed units are mostly a new generation units with an effective passport efficiency at the level of 30 - 39%. Besides the most popular units in this period were the units with a capacity of 16 MW, the number of such units is 326, these units have power more than 60% of the total capacity of all installed gas pumping units.

### 3.2 Electricity generation stations

Uninterrupted supply of the objects with electricity at the compression stations largely ensures the stability, reliability and efficiency of the entire gas industry.

For industrial sites and settlements (camps, social and cultural facilities, etc.), located in the areas of natural gas production and systems of main gas pipelines passing, where there are no power supply systems and the natural and climatic conditions are characterized as very heavy, it is necessary to develop special technical solutions in the field of power supply, to ensure their efficiency and durability, even in extreme situations. As a rule, these objects have relatively small facilities and the construction of traditional powerful TEPs in these conditions, there are a number of specific problems of economic and technical properties [30]. Alternative and enough reliable solution to the problem in these conditions is the creation of local energy supply systems with the minimum length of the outgoing transmission lines from mobile block and superblock power plants equipped with electrical units with piston or turbine power drive, located in the area of loads.

In the case of absence of external power supply or if there is only one source, the Electricity generation station should be designed in the areas where compression stations with the gas turbine driven compressor units are located.

Power output and the number of units of Electricity generation station should take into account the reliability of power supply to the compressor station and backup in cases of the emergency shutdown of their work and preventative maintenance.
As the fuel for units of Electricity generation station gas transported through the pipeline is used, and it should be prepared in accordance with the technical requirement, as well for this purpose diesel fuel can be used.

Increased interest in the problem of Electricity generation station construction also contributes to a number of factors specific to the natural gas industry [32, 33]:

- vast territory for the compressor stations of trunk pipelines that requires the construction of long-distance transmission lines, that is, for example, for projects in Western Siberia and the Far North generally not economically effective (that means construction, maintenance and transmission losses over long distances);
- increased demands on reliability and safety of electricity supply to gas production, transportation and processing of gas, which made the main technological equipment have the first category of energy supply;
- a significant amount of reconstructions of the compression stations and other objects of gas industry coming in the next few years.

As the analysis shows, most perspective is to be considered a mobile power station turbine-powered, with the following advantages [30,32]:

- small weight and dimensions, i.e. mass and dimensions parameters 3-4 times less than the power plants with reciprocating internal combustion engines;
- the ability to create mobile easy-transporting power plants of up to 6 MW or more;
- operative replacement of the failed motor (up to 8 hours) and its maintainability in factory;
- allowable level of vibration, the minimum volume of construction work to install power plants, etc..

With all the advantages, gas turbine engines losses for piston internal combustion engines in such parameters as:

- minimum start-up time (up to 30 seconds);
- reception of 100 % of the load time for 30 - 60 seconds after the signal to start.
- high-performance work on partial loads;
- efficiency (approximately 1,5 times higher than GTE).

These qualities determine the priority in the creation of mobile power plants with piston internal combustion engines having a power range from 100 to 2500 kW, for gas-turbine engines - from 2500 up to 50 000 kW and more [30].

### 3.3 Existing and proposed electricity generation schemes for compressor stations

Compression stations belong to the first category of energy supply where power outages are not allowed. Supply reliability and quality of electric power reduction as well as electricity price increase at the centralized energy supply systems caused the interest increase in the problem of construction the own sources of energy for the gas industry [30].

The main consumers of electricity in the compression stations with gas turbine driven compressor units are:

- support mechanisms of gas turbine driven compressor units,
- pumping and ventilation systems,
- control systems, signaling and communication,
— gas cooler,
— lighting systems.

In the case when the compressor stations have EGPA, they are the main consumers of electricity.

Additional power consumers at the compressor stations are the power equipment and lighting systems in repair and maintenance units, pumps of external water supply and sewage, auxiliary buildings at industrial sites of the compression stations, residential settlements, as well as consumers of the surrounding area of the compression stations, etc..

Power output of main consumers of electricity at standard compressor stations equipped with GGPA is 600 - 700 kW at 30 - 40 thousand kW of installed capacity of power generating units. The total capacity of the typical electricity consumers at the compression stations with gas turbine power drive ranges from 1500 to 4000 kW, but the total capacity of electricity consumers at the compression stations which include EGPA may significantly exceed this level [30].

Let’s consider 5 main options of electricity generation schemes for compression stations (Figure 3.1):

1. The first electricity generation scheme includes two independent centralized power sources. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used;

2. The second electricity generation scheme includes one independent centralized power sources. As a second independent source Electricity generation station is used. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used. The main (basic) source of power is the external power source, reserve source is Electricity generation station;

3. The third electricity generation scheme includes one independent centralized power sources. As a second independent source Electricity generation station is used. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used. The main (basic) source of power is the Electricity generation station, reserve source is the external power source;

4. The fourth electricity generation scheme includes one independent centralized power source. As a second independent source Electricity generation station is used. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used. External power source and electricity generation station work in parallel. The power for Electricity generation station is selected so that it covers the maximum load of power consumption at the compression station working in the nominal mode. In these conditions when the power of electricity consumption is more than 2500 kW from an economic point of view it is advisable to use a gas turbine driven compressor units at the Electricity generation station. According to experts investigation when the external power source and electricity generation station work in parallel this gives a very strong economic performance since in this case there is no need to have a back-up generator sets.

5. The fifth electricity generation scheme includes Electricity generation station with no connection to an external electricity source. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used.

At the moment there are three most typical electricity generation schemes implemented at the compression stations:

the first one - two independent centralized power sources;

the second one - one (main) independent centralized power source, the second is Electricity generation station;
As the new electricity generation schemes for compression stations using wind power plant the author of the Thesis proposed the following, Figure 3.2:

1. The electricity generation scheme includes one main (basic) source of power - the Electricity generation station, the reserve source is the Wind power plant. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used.

2. The electricity generation scheme includes one main (basic) source of power - Wind power plant, the reserve source is the Electricity generation station. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used.

3. The electricity generation scheme includes one main (basic) source of power - independent centralized power source, the reserve source is the Wind power plant. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used.

4. The electricity generation scheme includes one main (basic) source of power – Wind power plant, the reserve source is the independent centralized power source. As emergency sources gas diesel generator (GDG) and storage battery (SB) are used.
Reliability of the Electricity generation station is provided by the reasonable choice of a type of power drive generators of electricity, unit capacity and the number of generators. When designing the Electricity generation station at the compression station it is required irrespective to the total capacity of power consumption at the compression station that the number of generators is less than two.

The unit of capacity of power drive generators is selected from the list of sizes of generators recommended for use in gas industry facilities subject to the maximum operational life of the unit and the least cost for the construction of the Electricity generation station [31].

To select the optimal electricity generation scheme at the constructed and reconstructed compressor stations it is necessary to use the methodology of economic comparison of electricity generation scheme to define the type of the unit, capacity and the number of power generating units installed in the Electricity generation stations, as well as it is necessary to consider the system of criteria defining an economically viable transition from one generation scheme to another.
4 WIND FARM APPLICATION FOR ENERGY SUPPLY FOR COMPRESSION STATIONS

4.1 Decision making algorithm for wind turbines selection in a wind farm

If you choose a wind power plant (Wind Farm) in order to meet the energy needs of the compression station it is necessary to understand if we choose a lot of wind turbines with a small rotor diameter, which are cheaper or less wind turbines, but with a large rotor diameter that are, obviously, much more expensive? The answer to this question is very important because there are more than 100 major manufacturers of wind turbines in the world with different rotor diameters and costs, and the number and type of the chosen wind turbine will determine the initial investment to the project construction. So it is necessary to choose a number of wind turbines which will fully provide the selected objects by energy, as compression station with electricity, for example, at minimum initial investment.

Designed algorithm for solving this problem is shown below.

4.1.1 Wind power plant layout onshore

In the second chapter of the Thesis it has been theoretically proved that the total power generated by the wind farm does not depend on the wind turbine rotor diameter when we use the following layout – \( A \cdot D \times B \cdot D \) (where A and B - coefficients showing the distance between the wind turbines in a row and between rows, depending on the rotor diameter).

Further it is shown how the cost of a single wind turbine and the initial investment to the Wind power plant construction depends on the rotor diameter.

1. Total number of wind turbines at a given territory \( S \):

\[
N_{WT} = \frac{S}{(A \cdot B)D^2} = k_1 \cdot D^{-2},
\]

where: \( S \) – area for wind farm construction;

\((A \cdot B)D^2\) – area occupied by a single wind turbine with the chosen layout \( A \cdot D \times B \cdot D \) (where A and B - coefficients showing the distance between the wind turbines in a row and between rows, depending on the rotor diameter);

\( D \) – rotor diameter;

\( k_1 \) – coefficient that doesn’t depend on the rotor diameter, so \( k_1 = \frac{S}{(A \cdot B)} \).

2. Wind turbine price depends on the rotor diameter as following:

\[
C_{WT} = k_2 \cdot D^n,
\]

where: \( C_{WT} \) – wind turbine price;

\( k_2 \) – coefficient depending on the country and manufacture;

\( D \) – rotor diameter;

\( n \) – index that determines the wind turbine price dependence on the rotor diameter (depending on the country and manufacture).

3. Initial investment in Wind power plant construction (CAPEX):
CAPEX = \lambda \cdot C_{WF} = \lambda \cdot C_{WT} \cdot N_{WT} = \lambda \cdot k_2 \cdot D^n \cdot k_1 \cdot D^2. \quad (4.3)

That is:

\[ \text{CAPEX} = k_3 \cdot D^{n-2}, \quad (4.4) \]

where: 
- \( C_{WF} \) - wind farm cost;
- \( C_{WT} \) - wind turbine price;
- \( \lambda \) - cost of logistics, engineering support, construction work, etc., defined as a percentage of the cost of the purchased equipment (10-15%);
- \( k_3 \) - calculated coefficient that doesn't depend on the rotor diameter, so \( k_3 = \lambda \cdot k_2 \cdot k_1 \);
- \( D \) – rotor diameter.

Both expressions (4.2) and (4.4) depend on the rotor diameter and index \( n \).

This problem is a non-linear programming optimization problem that requires to find a value of the rotor diameter which would minimize the initial investment for the Wind power plant construction. The optimum value of the desired criterion (initial investment to the Wind power plant construction - CAPEX) is usually determined at the minimum or maximum values of the optimized parameter (wind turbine rotor diameter), which in turn is determined by admissible values in real conditions (cannot be very small or very large).

Solution of this optimization problem will depend on values of index \( n \). Now we consider various cases for solving the problem.

1) Wind turbine price doesn’t depend on the rotor diameter and has the constant value, \( n=0 \).

If \( n=0 \), then:

\[ C_{WT} = k_2 \cdot D^n = k_2. \quad (4.5) \]
\[ \text{CAPEX} = k_3 \cdot D^{n-2} = k_3 \cdot D^2. \quad (4.6) \]

Initial investment in Wind power plant construction (CAPEX) depends on the rotor diameter as follows, Figure 4.1:

![Figure 4.1 CAPEX dependence on D at n=0](image)
Figure 4.1 shows that the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter and maximum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities.

2) Wind turbine price depends on the rotor diameter linearly, \( n = 1 \).

If \( n = 1 \), then:

\[ C_{WT} = k_2 \cdot D^n = k_2 \cdot D. \] \hspace{1cm} (4.7)

\[ \text{CAPEX} = k_3 \cdot D^{n-2} = k_3 \cdot D^{-1}. \] \hspace{1cm} (4.8)

So initial investment in Wind power plant construction (CAPEX) depends on the rotor diameter as follows, Figure 4.2:

3) Wind turbine price has quadratic dependence on the rotor diameter, \( n = 2 \).

If \( n = 2 \), then:

\[ C_{WT} = k_2 \cdot D^n = k_2 \cdot D^2. \] \hspace{1cm} (4.9)

\[ \text{CAPEX} = k_3 \cdot D^{n-2} = k_3. \] \hspace{1cm} (4.10)

Initial investment in Wind power plant construction (CAPEX) doesn’t depend on the rotor diameter and has the constant value, Figure 4.3:

---

Figure 4.2 shows that the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter and maximum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities.
In the case when initial investment in Wind power plant construction (CAPEX) doesn’t depend on the rotor diameter and has the constant value the chosen rotor diameter will depend on the necessary installed capacity of the wind turbine.

4) Wind turbine price has dependence on the rotor diameter with the third index, n=3. If \( n=3 \), then:

\[
C_{WT} = k_2 \cdot D^n = k_2 \cdot D^3. \tag{4.11}
\]

\[
\text{CAPEX} = k_3 \cdot D^{n-2} = k_3 \cdot D. \tag{4.12}
\]

Dependence of the wind turbine price on the rotor diameter with the third index is unclear, this cannot be in reality, but it is worth to consider this case theoretically.

Initial investment in Wind power plant construction (CAPEX) depends on the rotor diameter linearly, Figure 4.4.
Figure 4.4 shows that the minimum investment will be provided in the case of wind turbine selection with a minimum rotor diameter and maximum investment will be provided in the case of wind turbine selection with a maximum rotor diameter according to the technical capabilities.

5) Wind turbine price has dependence on the rotor diameter with the fourth index, n=4. If n=4, then:

\[ C_{WT} = k_2 \cdot D^n = k_2 \cdot D^4. \]  

(4.13)

\[ CAPEX = k_3 \cdot D^{n-2} = k_3 \cdot D^2. \]  

(4.14)

Dependence of the wind turbine price on the rotor diameter with the fourth index is unclear, but it is worth to consider this case theoretically.

Initial investment in Wind power plant construction (CAPEX) depends on the rotor diameter as follows, Figure 4.5:
Figure 4.5 shows that the minimum investment will be provided in the case of wind turbine selection with a minimum rotor diameter and maximum investment will be provided in the case of wind turbine selection with a maximum rotor diameter according to the technical capabilities.

It can be conclude that:

- if $0 \leq n < 2$ then the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter according to the technical capabilities.
- if $n = 2$ then the initial investment in Wind power plant construction doesn’t depend on the rotor diameter and has the constant value and the chosen rotor diameter will depend on the necessary installed capacity of the wind turbine.
- if $n > 2$ then the minimum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities.

Thus, for example, the decision making algorithm for wind turbines selection in the most possible case when the wind turbine price depends on the rotor diameter linearly ($n=1$) will be as following, Figure 4.6.

As it was shown before, if $n=1$, then:

\begin{align}
N_{WT} &= k_1 \cdot D^2, \\
C_{WT} &= k_2 \cdot D, \\
CAPEX &= k_3 \cdot D^{-1}.
\end{align}
Figure 4.6 Dependence of the number of wind turbines, wind turbine price and CAPEX on D at n=1

Figure 4.6 shows that at n=1 it is necessary to choose minimum wind turbines with a maximum rotor diameter according to the technical capabilities for CAPEX minimization. When we choose wind turbines with a minimum rotor diameter according to the technical capabilities the single wind turbine price will have minimum value but the initial investment to the Wind power plant construction will have maximum value.

4.1.2 Wind power plant layout offshore

Now we will investigate how the cost of a single wind turbine and the initial investment to the Wind power plant construction depends on the rotor diameter with offshore layout.

1. Real power output from the wind turbine at a given wind speed and rotor diameter from equations (2.2) and (2.6):

   \[ P_{WT} = \frac{1}{2} \cdot \frac{1}{4} \cdot 3,14 \cdot D^2 \cdot C_p \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}), \quad (2.2) \]

   or \[ P_{WT} = k_1 \cdot D^2, \quad (2.6) \]

2. The necessary number of wind turbines that can be installed along the coastline with length L can be calculated from (2.15):
where: \( L \) – coastline length;
\((9 \cdot D)\) – distance between wind turbines.

3. The power generated in a wind farm:

\[
P_{WF} = N_{WT} \cdot P_{WT} = \frac{L}{9 \cdot D} \cdot k_4 \cdot D^2 = k_4 \cdot D.
\]  
(4.15)

where: \( k_4 \) – calculated coefficient that doesn’t depend on rotor diameter, so \( k_4 = \frac{L}{9} \cdot k_1 \).

The total wind power generated by the wind turbines in a wind farm that is necessary to offset the power of the chosen object depends on the rotor diameter of wind turbines linearly, using the chosen wind farm layout.

4. Wind turbine price depends on the rotor diameter as following, equation (4.2):

\[
C_{WT} = k_2 \cdot D^n,
\]  
(4.2)

where: \( C_{WT} \) – wind turbine price;
\( k_2 \) – coefficient depending on the country and manufacture;
\( n \) – index that determines the wind turbine price dependence on the rotor diameter (depending on the country and manufacture).

5. Initial investment to the Wind power plant construction (CAPEX):

\[
\text{CAPEX} = \lambda \cdot C_{WF} = \lambda \cdot C_{WT} \cdot N_{WT} = \lambda \cdot k_2 \cdot D^n \cdot \frac{L}{9 \cdot D}.
\]  
(4.16)

That is:

\[
\text{CAPEX} = k_5 \cdot D^{n+1},
\]  
(4.17)

where: \( C_{WF} \) - wind farm cost;
\( C_{WT} \) - wind turbine price;
\( \lambda \) - cost of logistics, engineering support, construction work, etc., defined as a percentage of the cost of the purchased equipment (10-15%);

\( k_5 \) - calculated coefficient that doesn’t depend on the rotor diameter, so \( k_5 = \lambda \cdot k_2 \cdot \frac{L}{9} \).

Both expressions (4.2) and (4.17) depend on the rotor diameter and index \( n \).

Solution of this optimization problem will depend on values of index \( n \). Now we consider various cases for solving the problem.

1) Wind turbine price doesn’t depend on the rotor diameter and has the constant value, \( n=0 \).
If \( n=0 \), then:

\[
C_{WT} = k_2 \cdot D^0 = k_2.
\]  
(4.18)

\[
\text{CAPEX} = k_5 \cdot D^{0+1} = \frac{k_5}{D}.
\]  
(4.19)

Initial investment to the Wind power plant construction (CAPEX) and power output of the wind turbines depend on the rotor diameter as follows, Figure 4.7:
Figure 4.7 CAPEX and $P_{WT}$ dependence on $D$ at $n=0$

Figure 4.7 shows that the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter along with the largest power output from wind turbines, and maximum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities.

2) Wind turbine price depends on the rotor diameter linearly, $n=1$.

If $n=1$, then:

\[ C_{WT} = k_2 \cdot D^n = k_2 \cdot D. \]  
\[ \text{CAPEX} = k_5 \cdot D^{n-1} = k_5. \]  

Initial investment to the Wind power plant construction (CAPEX) and power output of the wind turbines depend on the rotor diameter as follows, Figure 4.8:
In the case when initial investment in Wind power plant construction (CAPEX) doesn’t depend on the rotor diameter and has the constant value the chosen rotor diameter will depend on the necessary installed capacity of the wind turbine and that will determine the economical potential of the project. So the largest installed capacity of the wind turbine will be when we choose wind turbine with the maximum rotor diameter according to the technical capabilities.

3) Wind turbine price has quadratic dependence on the rotor diameter, \( n=2 \).

If \( n=2 \), then:

\[
C_{WT} = k_2 \cdot D^n = k_2 \cdot D^2. \quad (4.22)
\]

\[
\text{CAPEX} = k_5 \cdot D^{n-1} = k_5 \cdot D. \quad (4.23)
\]

Initial investment to the Wind power plant construction (CAPEX) and power output of the wind turbines depend on the rotor diameter as follows, Figure 4.9:

**Figure 4.9 CAPEX and \( P_{WT} \) dependence on \( D \) at \( n=2 \)**

In this case it is not obvious which rotor diameter it is necessary to choose in order to have minimum initial investment to the Wind power plant construction and have the largest installed capacity of the wind turbines. In order to find the optimal solution of this problem we use a special program in MS Excel and calculate indicators of investment attractiveness of the project: \( NPV \), \( PI \), \( IRR \), \textit{payback period}; and compare the values of these indicators for wind turbines with different rotor diameter.

Given data for calculation can be found in table 4.1.
Table 4.1 Given data for calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average annual wind speed in the coastline zone, m/sec [18]</td>
<td>12</td>
</tr>
<tr>
<td>Rotor diameter - D, m [6]</td>
<td>90-130</td>
</tr>
<tr>
<td>Load factor, $K_{load}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Air density - $\rho$, kg/m$^3$</td>
<td>1.225</td>
</tr>
<tr>
<td>Power (in the wind) efficiency - $C_p$ [7]</td>
<td>0.45</td>
</tr>
<tr>
<td>Overall efficiency of mechanical and electrical components of wind turbine - $\eta_{mech}\eta_{el}$ [7]</td>
<td>0.9</td>
</tr>
<tr>
<td>Length of the coastline, m (value is given arbitrary)</td>
<td>3500</td>
</tr>
<tr>
<td>Electricity price, $C_{el}$ rub/kW-hour</td>
<td>4.5</td>
</tr>
<tr>
<td>Annual OPEX, %</td>
<td>10</td>
</tr>
<tr>
<td>The annual growth of operating expenses, %</td>
<td>3</td>
</tr>
<tr>
<td>The discount rate, %</td>
<td>12</td>
</tr>
<tr>
<td>Electricity tariff growth rate, %</td>
<td>5</td>
</tr>
<tr>
<td>Income tax, %</td>
<td>20</td>
</tr>
<tr>
<td>Amortization period, year</td>
<td>25</td>
</tr>
<tr>
<td>Wind turbine price, millions of rub.</td>
<td>depends on country and manufacture</td>
</tr>
</tbody>
</table>

Calculation steps.

- Real power output from the wind turbine at a given wind speed and rotor diameter from equation (2.2):

$$P_{WT} = \frac{1}{2} \cdot \frac{1}{4} \cdot 3,14 \cdot D^2 \cdot C_p \cdot \rho \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}).$$  \hspace{1cm} (2.2)

- The necessary number of wind turbines that can be installed along the coastline with length $L$ can be calculated from (2.15):

$$N_{WT} = \frac{L}{9\cdot D}.$$ \hspace{1cm} (2.15)

- Initial investment to the Wind power plant construction (CAPEX) from equation (4.3):

$$CAPEX = \lambda \cdot C_{WT} \cdot N_{WT}.$$ \hspace{1cm} (4.3)

The Danish company Vestas was selected as the manufacturing company which has the first place among the manufacturers and sales in the world (its market share in 2013 was 13,2%) [34]. Since the cost of the wind turbine is linked to its power output and rotor diameter it is necessary to find the cost of the unit of power generated by a single wind turbine. The average market value of price for a power unit is 60 147,5 rub./kW
On the basis of this price we calculate the cost for the whole wind turbine system considering the chosen model and that the cost of a wind turbine depends on the rotor diameter as \( n=2 \).

Wind turbines' models and prices are shown in Table 4.2.

### Table 4.2 Wind turbines' models and prices

<table>
<thead>
<tr>
<th>Wind turbines' models</th>
<th>Wind turbines' prices, millions of rub.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V90-3.0MW;</td>
<td>157,467</td>
</tr>
<tr>
<td>V105-3.3MW;</td>
<td>214,33</td>
</tr>
<tr>
<td>V112-3.3MW;</td>
<td>243,86</td>
</tr>
<tr>
<td>V117-3.3MW;</td>
<td>266,119</td>
</tr>
<tr>
<td>V126-3.3MW.</td>
<td>308,635</td>
</tr>
</tbody>
</table>

Revenue received from wind turbines operation, for the year:

\[
B = N_{WT} \cdot P_{WT} \cdot T \cdot k_{load} \cdot C_{el},
\]

where: \( B \) – revenue received from wind turbines operation, millions of rub./year;

\( T = 8760 \) hours – hours in the year;

\( K_{load} \) – load factor, table 4.2;

\( C_{el} \) – electricity price, rub/kW-hour, table 4.2.

Further we use a special program in MS Excel and calculate indicators of investment attractiveness of the project: \( NPV, PI, IRR, payback period \). Calculation results are presented in table 4.3.

### Table 4.3 Calculation results

<table>
<thead>
<tr>
<th>Rotor diameter, m</th>
<th>Number of wind turbines</th>
<th>Power output from Wind power plant, MW</th>
<th>NPV, millions of rub.</th>
<th>Payback period, year</th>
<th>PI</th>
<th>IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>5</td>
<td>12,5</td>
<td>964,18</td>
<td>7,7</td>
<td>2,11</td>
<td>24,83%</td>
</tr>
<tr>
<td>105</td>
<td>4</td>
<td>13,2</td>
<td>966,83</td>
<td>8,19</td>
<td>2,03</td>
<td>23,79%</td>
</tr>
<tr>
<td>112</td>
<td>4</td>
<td>13,2</td>
<td>732,61</td>
<td>10,55</td>
<td>1,68</td>
<td>19,85%</td>
</tr>
<tr>
<td>117</td>
<td>4</td>
<td>13,2</td>
<td>556,05</td>
<td>12,78</td>
<td>1,47</td>
<td>17,48%</td>
</tr>
<tr>
<td>126</td>
<td>4</td>
<td>13,2</td>
<td>218,83</td>
<td>18,81</td>
<td>1,16</td>
<td>13,89%</td>
</tr>
</tbody>
</table>

Table 4.3 shows that at \( n=2 \) it is necessary to choose wind turbines with a **minimum rotor diameter according to the technical capabilities for CAPEX minimization**. In this case indicators of investment project are more attractive: \( NPV \) is maximum, \( PI>1 \), \( IRR \) has also the maximum value, payback period is minimum.
It can be conclude that:

- if \(0 \leq n < 2\) then the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter according to the technical capabilities and with the largest installed capacity.

- if \(n = 2\) then the minimum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities (with given data in table 4.1). In this case indicators of investment project are more attractive.

### 4.2 Economic feasibility assessment of using wind turbines for compression stations energy supply

In this part of the Master Thesis we calculate indicators of investment attractiveness of the project of using wind turbines for compression stations energy supply: \(NPV, PI, IRR,\) payback period; and make a sensitivity analysis on the changes of such parameters as: annual OPEX; annual growth of operating expenses; discount rate; electricity tariff growth rate.

As the energy consumption object compression station «Sakhalin» (the Sakhalin Island) was chosen. According to the project documentation of the compression station "Sakhalin" its total installed capacity is 32 MW and the Electricity generation station generates 6 MW [37]. Distribution of energy generated by Electricity generation station for each electricity consuming facility in a compression station is shown in Table 4.4.

<table>
<thead>
<tr>
<th>Electricity consuming facility</th>
<th>Energy consumption, kW</th>
<th>Energy consumption, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>2400</td>
<td>40</td>
</tr>
<tr>
<td>Gas cooler</td>
<td>2100</td>
<td>35</td>
</tr>
<tr>
<td>Industrial base</td>
<td>1050</td>
<td>17,5</td>
</tr>
<tr>
<td>Sewage and wastewater treatment</td>
<td>230</td>
<td>3,83</td>
</tr>
<tr>
<td>Oil cooler</td>
<td>100</td>
<td>1,67</td>
</tr>
<tr>
<td>Intakes</td>
<td>70</td>
<td>1,17</td>
</tr>
<tr>
<td>Electric lighting</td>
<td>50</td>
<td>0,83</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6000</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

In this part of work two variants of Wind power plant layout are considered: onshore and offshore.

Given data for calculation can be found in table 4.5.
Table 4.5 Given data for calculation

<table>
<thead>
<tr>
<th>Data</th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average annual wind speed, m/sec [18]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor diameter - ( D ), m [6]</td>
<td>80</td>
<td>126</td>
</tr>
<tr>
<td>Energy consumption of the selected object, ( P_{EGS} ), MW</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Load factor, ( K_{load} )</td>
<td>0,5</td>
<td></td>
</tr>
<tr>
<td>Air density - ( \rho ), kg/m(^3)</td>
<td>1,225</td>
<td></td>
</tr>
<tr>
<td>Power (in the wind) efficiency - ( C_p ) [7]</td>
<td>0,45</td>
<td></td>
</tr>
<tr>
<td>Overall efficiency of mechanical and electrical components of wind turbine - ( \eta_{mech} \cdot \eta_{el} ) [7]</td>
<td>0,9</td>
<td></td>
</tr>
<tr>
<td>Electricity price, ( C_{el} ), rub/kW-hour</td>
<td>4,5</td>
<td></td>
</tr>
<tr>
<td>Annual OPEX, %</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>The annual growth of operating expenses, %</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>The discount rate, %</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Electricity tariff growth rate, %</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Income tax, %</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Amortization period, year</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Wind turbine price, millions of rub.</td>
<td>depends on country and manufacture</td>
<td></td>
</tr>
</tbody>
</table>

Calculation steps.

- Real power output from the wind turbine at a given wind speed and rotor diameter from equation (2.2):

\[
P_{WT} = \frac{1}{2} \cdot \frac{1}{4} \cdot 3,14 \cdot D^2 \cdot C_p \cdot \rho \cdot V^3 \cdot (\eta_{mech} \cdot \eta_{el}). \tag{2.2}
\]

- The necessary number of wind turbines to offset the energy consumption of the selected object:

\[
N_{WT} = \frac{P_{EGS}}{P_{WT}} \tag{4.29}
\]

- Initial investment to the Wind power plant construction (CAPEX) from equation (4.3):
CAPEX=λ·C_{WT}·N_{WT}. \hspace{1cm} (4.3)

where: wind turbine price depends on the rotor diameter as follows, equation (4.2):

\[ C_{WT}=k_2\cdot D^n, \] \hspace{1cm} (4.2)

The Danish company Vestas was selected as the manufacturing company [34]. Wind turbines’ models and prices are shown in Table 4.6.

Table 4.6 Wind turbines’ models and prices

<table>
<thead>
<tr>
<th>Wind turbines' models</th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbines' prices,</td>
<td>V80-2.0MW</td>
<td>V126-3.3MW</td>
</tr>
<tr>
<td>millions of rub. [35,36]</td>
<td>93, 42</td>
<td>247,134</td>
</tr>
</tbody>
</table>

• Revenue received from wind turbines operation, for the year, from (4.24):

\[ B=N_{WT}\cdot P_{WT}\cdot 8760\cdot k_{load}\cdot C_{el}. \] \hspace{1cm} (4.24)

• Further we use a special program in MS Excel and calculate indicators of investment attractiveness of the project: NPV, PI, IRR, payback period, when changing the following parameters: annual OPEX; annual growth of operating expenses; discount rate; electricity tariff growth rate.

Calculation results are presented in Table 4.7 for onshore layout and Table 4.8 for offshore layout.

Table 4.7 Calculation results for onshore layout

<table>
<thead>
<tr>
<th>Indicators of investment attractiveness</th>
<th>Annual OPEX (10%)</th>
<th>Annual growth of operating expenses (3%)</th>
<th>Discount rate (12%)</th>
<th>Electricity tariff growth rate (5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV, millions of rub.</td>
<td>-50% 731,46</td>
<td>+50% 372,65</td>
<td>-50% 590,05</td>
<td>+50% 506,63</td>
</tr>
<tr>
<td></td>
<td>1295,37</td>
<td>226,64</td>
<td>319,03</td>
<td>869,71</td>
</tr>
<tr>
<td>Payback period, years</td>
<td>5</td>
<td>9</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>PI</td>
<td>2,78</td>
<td>1,91</td>
<td>2,44</td>
<td>2,23</td>
</tr>
<tr>
<td></td>
<td>4,15</td>
<td>1,55</td>
<td>1,78</td>
<td>3,12</td>
</tr>
<tr>
<td>IRR</td>
<td>33,66%</td>
<td>22,11%</td>
<td>28,22%</td>
<td>26,85%</td>
</tr>
<tr>
<td></td>
<td>27,59%</td>
<td>27,59%</td>
<td>23,37%</td>
<td>31,54%</td>
</tr>
</tbody>
</table>
Table 4.8 Calculation results for offshore layout

<table>
<thead>
<tr>
<th>Indicators of investment attractiveness</th>
<th>Annual OPEX (10%)</th>
<th>Annual growth of operating expenses (3%)</th>
<th>Discount rate (12%)</th>
<th>Electricity tariff growth rate (5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50%</td>
<td>+50%</td>
<td>-50%</td>
<td>+50%</td>
</tr>
<tr>
<td>NPV, millions of rub.</td>
<td>590,63</td>
<td>116,01</td>
<td>403,58</td>
<td>293,23</td>
</tr>
<tr>
<td>Payback period, years</td>
<td>8</td>
<td>18</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>PI</td>
<td>2,09</td>
<td>1,21</td>
<td>1,74</td>
<td>1,54</td>
</tr>
<tr>
<td>IRR</td>
<td>24,88%</td>
<td>14,41%</td>
<td>20,25%</td>
<td>18,52%</td>
</tr>
</tbody>
</table>

Sensitivity analysis shows that the greatest effect on the indicators of investment attractiveness of the project have the following parameters: annual OPEX; discount rate; electricity tariff growth rate.

Thus:

- Discount rate changes show the biggest sensitivity than all other factors. Discount rate decrease leads to an improvement of the indicators of investment attractiveness of the project; discount rate increase - to deterioration of these indicators.
- The second factor is annual electricity tariff growth rate. Annual electricity tariff growth rate increase leads to an improvement of the indicators of investment attractiveness of the project; annual electricity tariff growth rate decrease - to deterioration of these indicators.
- The third factor is OPEX changes. OPEX changes decrease leads to an improvement of the indicators of investment attractiveness of the project; OPEX changes increase - to deterioration of these indicators.
- Annual growth of operating expenses has not a significant effect on the indicators of investment attractiveness of the project except on NPV values of the project.
5 CONCLUSIONS

1. Russia is one of the world leaders in domestic energy consumption, but energy efficiency is low. Therefore, the feasibility of renewable energy sources development is obvious assuming that the huge territory of Russia will provide a competitive advantage over other countries.

2. As the renewable energy source wind energy was considered as one of the most widespread resources in the world. Wind power has become the basis for energy systems in many countries around the world, being a reliable and affordable source of electricity production. Nowadays global wind power industry reached 318,5 GW of installed capacity, and 35,6 GW were added in 2013, the growth rate in the industry is 12,8%.

   According to the forecasts of The World Wind Energy Association to the end of 2020 at least 700 GW of wind power capacity can be installed in the world. And the annual growth of new wind capacity will reach about 57 GW per year until 2017.

3. Today the average installed capacity of wind turbines in the world ranges from 2.5 kW to 7 MW, which allows to use wind turbines for both small and large industrial objects to meet their energy consumption.

4. The Thesis presents the scientific and technical basis of wind energy: the main characteristics of the wind flow, review of the physical principles of converting wind energy into electricity, the construction and classification of wind turbines.

5. The technical potential assessment of wind energy in Russia is given for onshore and offshore zones. Total technical potential of wind energy in Russia is unique and equal to \(0.07 \times 10^9\) GW·hour/year, which corresponds to the use of approximately 6 billion of toe per year (~ 50% of the world's total energy consumption in 2012).

   The technical potential of wind energy for non-freezing coastline of Russia (the zone that is the most attractive for wind turbines installation offshore) ranges from \(2 \times 10^4\) to \(3.4 \times 10^4\) GW-h/year for the Kola Peninsula and Primorsky Krai, and from \(4.6 \times 10^4\) to \(6.7 \times 10^4\) GW-h/year - for the Sakhalin island.

6. From each onshore wind turbine it is possible to obtain from 0.03 MW to nearly 1 MW of installed capacity, and from each offshore wind turbine it is possible to obtain maximum capacity – from 2.5 to 5.7 GW, depending on the rotor diameter and wind speed.

7. It is theoretically explained that the total wind power generated by the wind turbines in a wind farm doesn’t depend on the rotor diameter of wind turbines, and depends on annual average wind speed, air density, Cp-coefficient, overall efficiency of mechanical and electrical components of wind turbine and other constant values.

8. It was obtained that area of 11.8% of the territory of Russia (near 2 million of km²) would be enough for wind turbines installation with rotor diameter ranges from 50-100 m to fully compensate the domestic energy consumption in the country in 2012.

9. The world’s richest land and marine reserves of wind energy resources along with large territory of the country and optimal wind turbines installation locations allow us to consider the wind energy as one of the most economical, effective and promising sectors of energy in Russian Federation.
10. The comparison of the map of Russian gas transportation system with the average wind speed distribution map on the territory of Russian Federation was carried out. The analysis of this comparison shows that 86.6% of the gas transportation system, that is available today in Russia, are promising for wind turbines application in order to offset energy consumption of the selected objects in gas transportation system, as almost all regions are suitable for wind power development (average annual wind speed in these regions exceeds 4 m/sec).

11. All objects including in Gas transportation system can be decomposed on energy facilities. As the object of research, the most important object of UGSS - linear compression stations were chosen which are the largest consumers of electricity in the Unified Gas Supply System.

A description of the compression station as an object of energy supply is presented including the energy consumption of the sub-objects. The characteristic of the electricity generation station is given with the description of the principle of its work.

12. As the new electricity generation schemes for compression stations using Wind power plant four new schemes were proposed (in addition to five basic schemes) where the Wind power plant is considered as the basic or reserve energy source working together with Electricity generation station or independent centralized power source of electricity.

13. Decision making algorithm for wind turbines selection in a wind farm is designed in the Thesis. This algorithm is presented as the solution of the optimization problem that requires to find a value of the rotor diameter which would minimize the initial investment for the Wind power plant construction, and the number of wind turbines would offset the electricity consumption of the chosen object, i.e. compression station.

Also the wind turbine price and the initial investment for the Wind power plant construction dependence on the rotor diameter is found out. This dependence is determined by index n (n - index that determines the wind turbine price dependence on the rotor diameter (depending on the country and manufacture)).

Thus, solution of this optimization problem will depend on values of index n. So various cases for solving the problem are considered when wind turbines are located onshore or offshore.

Wind Power Plant layout onshore:
1) If wind turbine price doesn’t depend on the rotor diameter and has the constant value (n=0), depends on the rotor diameter linearly (n=1) or has quadratic dependence on the rotor diameter (n=2), then the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter according to the technical capabilities.
2) If wind turbine price has dependence on the rotor diameter with the third index (n = 3) or has dependence on the rotor diameter with the fourth index(n =4), then the minimum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities.

Wind Power Plant layout offshore:
1) If wind turbine price doesn’t depend on the rotor diameter and has the constant value (n = 0) or depends on the rotor diameter linearly (n = 1), then the minimum investment will be provided in the case of wind turbine selection with a maximum rotor diameter according to the technical capabilities, and the total installed capacity will have the maximum value.
2) If wind turbine price has quadratic dependence on the rotor diameter (n = 2), then in order to find the optimal solution of this problem we use a special program in MS Excel and calculate indicators of investment attractiveness of the project: NPV, PI, IRR, payback period, and compare the values of these
indicators for wind turbines with different rotor diameter. The calculation shows that the minimum investment will be provided in the case of wind turbine selection with a minimum rotor diameter according to the technical capabilities.

14. In the Master Thesis we calculate indicators of investment attractiveness of the project of using wind turbines for compression stations energy supply: NPV, PI, IRR, payback period; and make a sensitivity analysis on the changes of such parameters as: annual OPEX; annual growth of operating expenses; discount rate; electricity tariff growth rate. Two variants of Wind power plant layout are considered: onshore and offshore.

Sensitivity analysis shows that the discount rate changes show the biggest sensitivity than all other factors; the second factor is annual electricity tariff growth rate; the third factor is OPEX changes. Annual growth of operating expenses has not a significant effect on the indicators of investment attractiveness of the project except on NPV values of the project.
6 List of references


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http://avpsoft.ru/products/udruler


[34] VESTAS company official website, available at http://www.vestas.com


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