Czech Technical University Prague
Faculty of Electrical Engineering
Department of Economics, Management and Humanities

Economic Appraisal of Small Hybrid Power Supply System

MASTER THESIS

Study program: Electrical Engineering, Power Engineering and Management
Branch of study: Management of Power Engineering and Electrotechnics
Scientific supervisor: Ing. Martin Beneš, Ph.D.

Aleksandr Kroshev

Prague 2019

MASTER‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Kroshev Aleksandr** Personal ID number: **492258**

Faculty / Institute: **Faculty of Electrical Engineering**

Department / Institute: **Department of Economics, Management and Humanities**

Study program: **Electrical Engineering, Power Engineering and Management**

Specialisation: **Management of Power Engineering and Electrotechnics**

II. Master’s thesis details

Master’s thesis title in English:

Economic Appraisal of Small Hybrid Power Supply System

Master’s thesis title in Czech:

Economic Appraisal of Small Hybrid Power Supply System

Guidelines:

1. Study technical potencial of wind energy in particular site.
2. Find technologically viable variants of supply with wind and diesel sources.
3. Calculate economic evaluation of variants.
4. Make a comparison of variants, provide sensitivity analysis.

Bibliography / sources:

1. Lukutin B. V., Shandarova E. B., Matukhin D. L., Igisenov A. A., Shandarov S. M.: Simulation and optimization of wind and diesel power supply systems, In : IOP Conference Series: Materials Science and Engineering, 2017.
2. Brealey R. A., Myers S. C., Allen F.:Principles of Corporate Finance, 10th edition, McGraw-Hill, 2011.
3. Lukutin B. V., Muravlev I. O., Plotnikov I. A.: Systemy elektosnabženija s vetrovymi i solnečnymy elektrostanciami, TPU, 2015

Name and workplace of master’s thesis supervisor:

Ing. Martin Beneš, Ph.D., Department of Economics, Management and Humanities, FEE

Name and workplace of second master’s thesis supervisor or consultant:

Date of master’s thesis assignment: **13.01.2020** Deadline for master's thesis submission: **22.05.2020**

Assignment valid until: **30.09.2021**

Ing. Martin Beneš, Ph.D. Supervisor’s signature	Head of department’s signature	prof. Mgr. Petr Páta, Ph.D. Dean’s signature

III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

.	
Date of assignment receipt	Student’s signature

Declaration:

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

Date Signature

ABSTRACT

The aim of this work is to design a hybrid wind-diesel power plant for decentralized power supply system of village Khorey-Ver, Nenets autonomous okrug, Russia. Due to low population density in the north of Russia it is not economically efficient to build overhead lines and connect small settlements to the grid. That is why power supply by diesel generators is commonly used. Primary cost of produced energy is 15- 30 times higher than in central power supply systems. In order to decrease cost of energy I consider introducing RES based power supply. High wind energy potential makes it possible to use wind as a source of energy. In this master thesis, I research potential of wind energy, analyze features of implementation wind turbines in the arctic conditions. In addition, I design scheme of hybrid power plant, choose all necessary equipment and compare different wind turbines. I define exact number of wind turbines for project to be economically efficient. After introduction of wind turbines cost of energy and fuel consumption decreases. Decrease in fuel consumption leads to reduction of CO_2 emissions, what makes project beneficial from economic and ecological point of view.

KEY WORDS

Renewable energy source, wind turbine, accumulator battery, hybrid power plant, economic analysis.

CONTENT

LIST OF ABBREVIATIONS

BL	Ballast load
CF	Cash flow
COE	Cost of energy
CPI	Consumer price index
DPP	Diesel power plant
HAWT	Horizontal axis wind turbine
IRR	Internal rate of return
L	Load
NAO	Nenets Autonomous Okrug
NPV	Net present value
OpEx	Operational expenditure
PI	Profitability index
PT	Primary transducer of wind energy
PV	Present value
RES	Renewable energy source
SCR	Silicon-controlled rectifier
UPS	Uninterruptible power supply
VAWT	Vertical axis wind turbine
VC	Voltage controller

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The current development of energy in Russia is characterized by an increasing of the cost of energy production. The greatest increase in the cost of energy is observed in the remote regions of Siberia and the Far East of Russia, Kamchatka, and the Kuril Islands, where decentralized power supply systems based on diesel power plants running on imported fuel are mainly used. The total cost of electricity in these areas often exceeds the world price level and reaches 0.25 or more US dollars per 1 kW • hour. [1]

World experience shows that a number of countries and regions are successfully solving energy supply problems today through the development of renewable energy. In order to intensify the practical use of renewable energy in these countries, various privileges for green energy producers are legally established. However, the decisive success of renewable energy is ultimately determined by its effectiveness in comparison with other more traditional fuel power plants today. The development of technical and legislative framework for renewable energy and the steady growth trends in the cost of fuel and energy resources already today determine the technical and economic advantages of power plants using renewable energy resources. Obviously, in the future, these advantages will increase, expanding the scope of renewable energy and increasing its contribution to the global energy balance. [1]

The aim of this work is to design a hybrid wind-diesel power plant for decentralized power supply system, village Khorey-Ver.

To achieve this goal we need to solve a number of problems:

- Calculate the current cost of electricity using only diesel fuel
- Determine potential of wind energy where the construction of wind turbines is planned
- Consider several options for a wind farm
- Carry out a feasibility study of various options of power supply and make a conclusion. [1]

1. Calculation of diesel power plant

1.1. Common information about objet of research

Khorey-Ver is a village in the north of Russia. Khorey-Ver is located on Colva River. The distance to the administrative center of the NAO Naryan-Mar is 215 km. The distance to the city from Usinsk is 160 km. The population of the village is 740 people. Location and population of this region is the main parameters which we will use in next calculations.

1.2. Calculation of required electricity, determination of the design load

Decentralized power supply systems vary a great deal in terms of installed capacity. They are difficult to classify. The most widely distributed decentralized power supply systems were used to provide electric power to the following consumer groups:

1. Individual consumers of small power from units to tens of kilowatt- cottages and country houses, weather stations, cell towers, field facilities;

2. Group non-industrial consumers with installed capacities from tens to hundreds of kW- individual large residential buildings and housing estates. Various objects of the social sphere trading enterprises and healthcare institutions, villages, villages, towns;

3. Industrial enterprises with installed capacity from hundreds to thousands of kW. [3]

In this village there are no large consumers and enterprises and the main consumers of the object, individual and group consumers. That is why we can classify our object as a 2 group.

Average resident of Russia spends 2 kWh per day, we will calculate based on the consumption by one person of about 800 kWh of electricity per year.

Then the annual consumption of electricity by the village will be:

$$W_{year} = n \cdot P = 740 \cdot 800 = 5{,}92 \cdot 10^5 \left[kW \cdot h \right] \tag{1}$$

where: n- amount of people,

P- annual consumption by 1 inhabitant, [$kW \cdot h$]

The seasonality factor is an of electricity consumption changes depending on the time of year. Coefficients for every month are given in table 1. Based on the table, we will consider December as the month with the highest consumption. The sum of the coefficients is equal to $K_s = 10{,}2$. [3]

Electricity consumption for 1 day of December will be equal:

$$W_{dec} = \frac{W_{year}}{K_s \cdot N_d} = \frac{5{,}92 \cdot 10^5}{10{,}2 \cdot 30} = 1{,}935 \cdot 10^3 \ \left[kW \cdot h \right] \tag{2}$$

where N_d - number of days in a month;

Table 1 – Seasonality factors for daily load schedules of decentralized consumers [3]

No.	Month	Season factor
1	January	1
2	February	1
3	March	0.8
4	April	0.8
5	May	0.8
6	June	0.7
7	July	0.7
8	August	0.7
9	September	0.9
10	October	0.9
11	November	0.9
12	December	1

Table 2 – Electricity consumption for every month

Month	Consumption, $kW \cdot 10^4$
January	5,80
February	5,80
March	4,63
April	4,63
May	4,63
June	4,06
July	4,06
August	4,06
September	5,22
October	5,22
November	5,22
December	5,80

Based on the typical electricity consumption schedule of decentralized consumers (Figure1), ratio between middle value and maximum (variation factor) is 2,35. [3]

The calculated power value will be equal to:

$$P_{design} = \frac{W_{dec} \cdot K_v}{N_h} = \frac{1.935 \cdot 10^3 \cdot 2.35}{24} = 201{,}5 \; [kW \cdot h] \qquad (3)$$

where N_h - number of hours in a day,

K_v - variation factor;

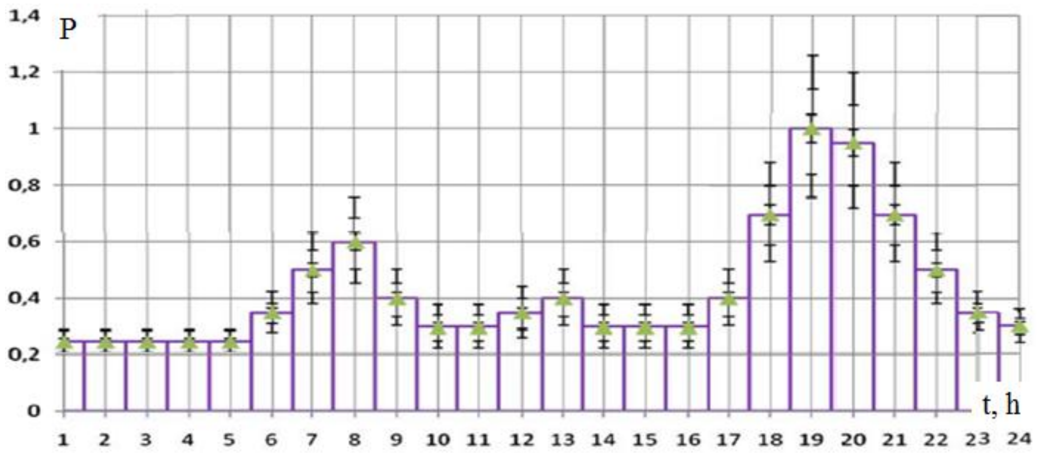

Figure 1 – Daily-load curve of loads of decentralized consumers [3]

Thus, estimated capacity of the facility is 201,5 kW. According to Table 3 and Figure 1 we may predict power consumption for every season and for every hour of a day.

Table 3 – Power consumption in every season

	Power consumption, kW			
Time, h	Winter	Spring	Summer	Autumn
0,00	50	40	35	45
1,00	50	40	35	45
2,00	50	40	35	45
3,00	50	40	35	45
4,00	50	40	35	45
5,00	60	48	42	54
6,00	100	80	70	90
7,00	120	96	84	108
8,00	80	64	56	72
9,00	60	48	42	54
10,00	60	48	42	54
11,00	70	56	49	63
12,00	80	64	56	72
13,00	60	48	42	54
14,00	60	48	42	54
15,00	60	48	42	54
16,00	80	64	56	72
17,00	140	112	98	126
18,00	200	160	140	180
19,00	190	152	133	171
20,00	140	112	98	126
21,00	100	80	70	90

Time,h	Winter	Spring	Summer	Autumn
22,00	70	56	49	63
23,00	60	48	42	54

1.3. Requirements for diesel generators of DPP

Diesel power stations in hybrid power supply system fulfill the most important functions of a guaranteed power source. The most important technical indicator of an autonomous diesel power plant providing power to decentralized consumers is the number and power of installed power units. This indicator determines the reliability of power supply system and efficiency of DPP depends on it.

Regulatory documents do not contain specific recommendations and methods for choosing the number and power of diesel generators. Meanwhile, this indicator is extremely important, since the technical and economic characteristics of the power plant largely depend on it.

Based on the need to provide consumers with electricity in any situation, the choice of the number and power of diesel generators should be carried out taking into account the following requirements:

1. Aggregate power of the units should be 25% more than the daily maximum load:

$$P_{cap} \geq 1,25 \cdot P_{design} \tag{4}$$

2. For ease of maintenance, it is advisable to choose a diesel generators of one size.
3. The load of diesel generators should be in the range of 25-80%.
4. The number of diesel units should be excessive in order to ensure the possibility of decommissioning of generators and for overhauls.[1]
5. The operating conditions of diesel power plants should comply with the climatic characteristics of the area.

Based on this, the required power of the units will be equal to:

$$P_{cap} = 1.25 \cdot P_{de\text{sign}} = 1.25 \cdot 201.5 \approx 250\ kW \cdot h \tag{5}$$

1.4. Calculations of equivalent annual cost for different options of diesel generators

At previous chapter we considered common requirements for diesel power plant. Next we should analyze several options of combination of diesel generators with different capacity of units, also we will consider system with accumulator battery.

Method of annual equivalent expenses

It is often necessary to compare several options of project. The multivariance of the task determines the implementation of feasibility studies in order to justify and select the most effective option. Decision making takes into account the cost of its implementation. The assessment is based on two main indicators:

---

[1] Lukutin B.V., Muravlev I.O., Plotnikov I.A. Sistemy elektrosnabzheniya s vetrovymi i solnechnymi elektrostantsiyami [Power supply systems with wind and solar power plants]. Education guidance. Tomsk: Tomsk Polytechnic University 2015. – 44 p.

capital investment [I] to create production and annual costs [E_F] of generating.

In this case capital investments are considered one-time costs, and production costs are considered as annual expenses. The compared options can have significant differences in the indicated component costs.

As an assessment of several options for technical solutions, it is advisable to use the formula:

$$C_a = C_n \cdot I + E_F \tag{6}$$

where: C_a - annual equivalent expenses,

C_n - normative coefficient, which equal to $C_n = \frac{T_{Fact}}{T}$,

T- lifetime of equipment,

T_{Fact} - equivalent duration of operation of diesel generator for one year.

I - capital investments,

E_F - expenses for fuel.

The criterion for choosing the option is the minimum of annual equivalent expenses. [4]

Method of calculation of consumption of fuel

According to specific fuel consumption curve we may find fuel consumption for specific load and find total fuel consumption for every option.

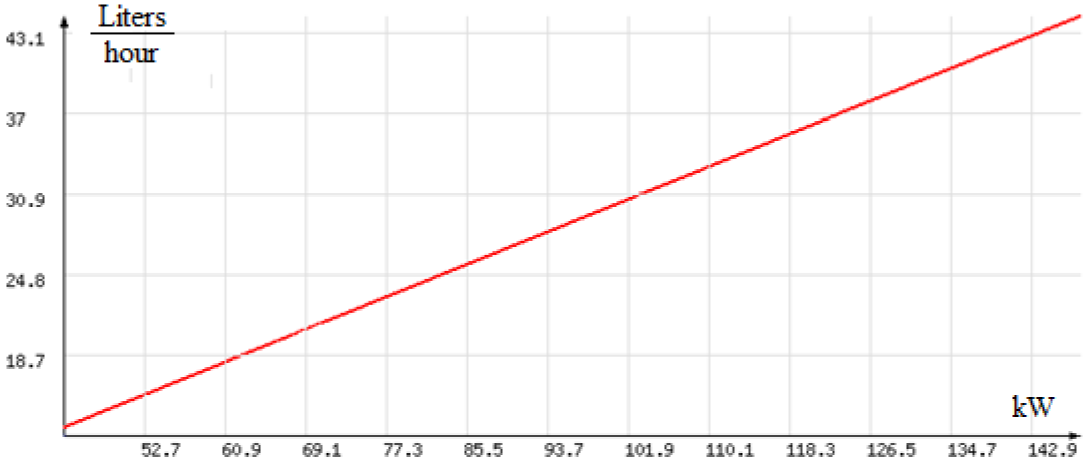

Figure 2 – Specific fuel consumption depends from load [5]

Different options of generators with equal power of units

For our purpose we can chose several options of diesel generators with different capacity power:

2 generators with 200 kW

3 generators with 165 kW

4 generators with 110 kW

6 generators with 70 kW

To compare these options we should analyze annual equivalent expenses cost of every option. We will consider only costs of generators and amount of consumed fuel. Accept that expenses for stuff, building and other do not depend from amount of generators. For every generator we have graph like at Figure 2. Using dependence of fuel consumption we may create linear function for every generator and calculate fuel consumption for every value of power generation using Table 3.

Table 4 – Schedule of operation of diesel generators (part of table)

Time ,h	Power, kW	CTG AD-70RE	Con. l	CTG AD-110RE	Con. l	CTG AD-165RE	Con. l	CTG AD-200RE	Con. l
0	50	1	15	1	14,1	1	12,5	1	15,4
1	50	1	15	1	14,1	1	12,5	1	15,4
2	50	1	15	1	14,1	1	12,5	1	15,4
3	50	1	15	1	14,1	1	12,5	1	15,4
4	50	1	15	1	14,1	1	12,5	1	15,4
5	60	2	18	1	16,9	1	15,0	1	18,4
6	100	2	30	2	28,1	1	24,9	1	30,3
7	120	3	36	2	33,7	1	29,9	1	36,2
8	80	2	24	1	22,5	1	19,9	1	24,3
9	60	2	18	1	16,9	1	15,0	1	18,4

Lifetime of one diesel generator is 20000 hours. According to Table 4(Schedule of operation of diesel generators depend on load and fuel consumption) we may calculate fuel consumption and calculate duration of operation for every option.

Table 5 – Equivalent annual cost

Type of generator	CTG AD-70RE	CTG AD-110RE	CTG AD-165RE	CTG AD-200R
Amount	6	4	3	3
Possible duration, h	120 000	80 000	60 000	60 000
Duration, h/year	15 288	11 102	9 646	9 100
Cost for unit, Rub	428 000	595 500	678 600	876 500
Consumption, l/year	198 820	186 483	165 276	202 101
Expenses for fuel, Rub/year	8 350 458	7 832 287	6 941 571	8 488 235
EAE, Rub	8 677 622	8 162 849	7 268 860	8 887 043

The most efficient variant is using generators with CTG AD-165RE.

Factors which influence for fuel consumption:

1. Temperature of the fuel is influence to efficiency: the lower temperature, the higher viscosity, the lower efficiency diesel generator;
2. Fuel quality: the presence of impurities and sulfur reduces efficiency and increases fuel consumption of DPP;
3. Good ventilation ensures high efficiency of the device;
4. Wear factor: wear of DPP leads to increasing of fuel consumption;
5. Mode of operation: in real case we have uneven load demand. Continuous changing of power consumption leads to additional fuel consumption. In practice we have additional consumption in at the level of 5% [9].

2. Integration of renewable source of energy

2.1. Horizontal axis wind turbines

Horizontal axis wind turbines (HAWT) have their axis of rotation horizontal to the ground and almost parallel to the wind stream. Most of the commercial wind turbines fall under this category. Horizontal axis machines have some distinct advantages such as low cut-in wind speed and easy furling. In general, they show relatively high power coefficient. However, the generator and gearbox of these turbines are to be placed over the tower which makes its design more complex and expensive. Another disadvantage is the need for the tail or yaw drive to orient the turbine towards wind. [14]

Depending on the number of blades, horizontal axis wind turbines are further classified as single bladed, two bladed, three bladed and multi bladed. Single bladed turbines are cheaper due to savings on blade materials. The drag losses are also minimum for these turbines. However, to balance the blade, a counter weight has to be placed opposite to the hub. Single bladed designs are not very popular due to problems in balancing and visual acceptability. Two bladed rotors also have these drawbacks, but to a lesser extent. Most of the present commercial turbines used for electricity generation have three blades. They are more stable as the aerodynamic loading will be relatively uniform. Machines with more number of blades (6, 8, 12, 18 or even more) are also available. The ratio between the actual blade area to the swept area of a rotor is termed as the solidity. Hence, multi-bladed rotors are also called high solidity rotors. These rotors can start easily as more rotor area interacts with the wind initially. Some low solidity designs may require external starting. [14]

Now consider two rotors, both of the same diameter, but different in number of blades; say one with 3 blades and the other with 12 blades. Which will produce more power at the same wind velocity? As the rotor swept area and velocity are the same, theoretically both the rotors should produce the same power. However aerodynamic losses are more for the rotor with more number of blades. Hence, for the same rotor size and wind velocity, we can expect more power from the three bladed rotor.

Then why do we need turbines with more blades? Some applications like water pumping require high starting torque. For such systems, the torque required for starting goes up to 3-4 times the running torque. Starting torque increases with the solidity. Hence to develop high starting torque, water pumping wind mills are made with multi bladed rotors. [14]

2.2. Vertical axis wind turbines

The axis of rotation of vertical axis wind turbine (VAWT) is vertical to the ground and almost perpendicular to the wind direction can receive wind from any direction. Hence complicated yaw devices can be eliminated. The generator and the gearbox of such systems can be housed at the ground level, which makes the tower design simple and more economical. Moreover the maintenance of these turbines can be done at the ground level. For these systems, pitch control is not required when used for synchronous applications. The major disadvantage of some is that they are usually not self starting. Additional mechanisms may be required to 'push' and start the turbine, once it is stopped. As the rotor completes its rotation, the blades have to pass through aerodynamically dead zones which will result in lowering the system efficiency. There are chances that the blades may run at dangerously high speeds causing the system to fail, if not controlled properly. Further, guy wires are required to support the tower structure which may pose practical difficulties. Features of some major vertical axis designs are discussed below.

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. [14]

Two distinctly different configurations are available for turbine design, the horizontal axis configuration and the vertical-axis configuration. The horizontal-axis machine has been the standard in Denmark from the beginning of the wind power industry. Therefore, it is often called the Danish wind turbine. The vertical-axis machine has the shape of an egg beater and is often called the Darrieus rotor after its inventor. It has been used in the past because of its specific structural advantage. However, most modern wind turbines use a horizontal axis design. Except for the rotor, most other components are the same in both designs, with some differences in their placements. [14]

Components of HAWT:

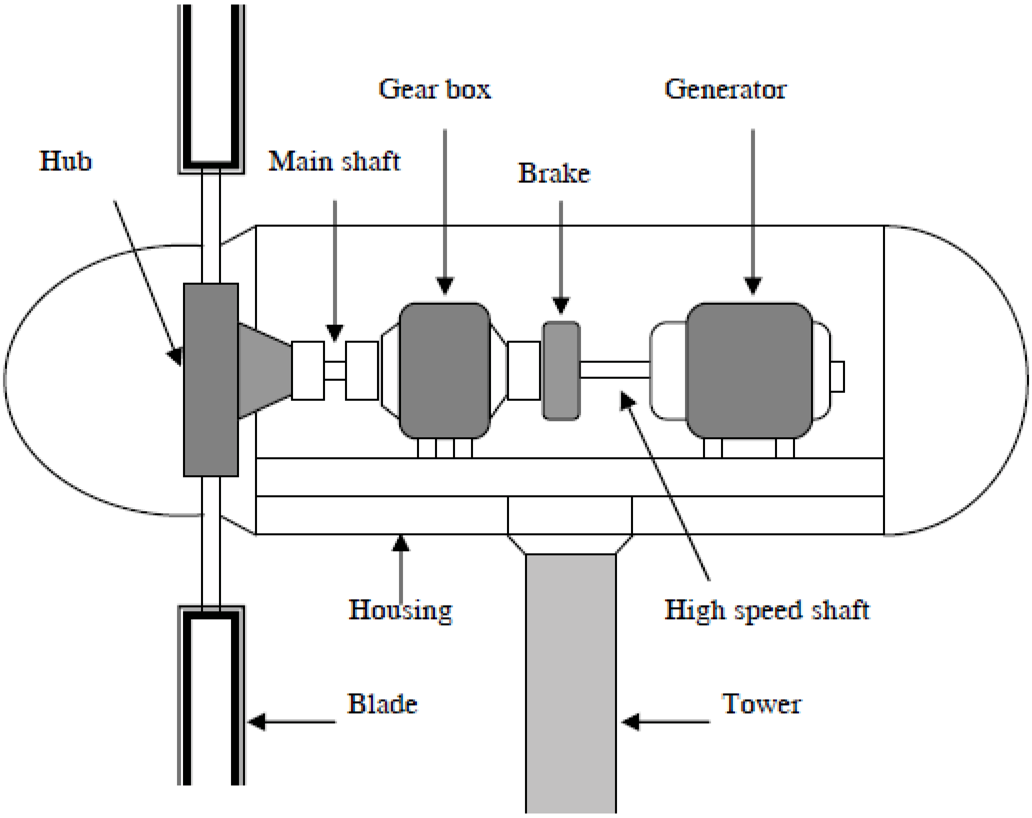

Figure 3 – Components of a wind electric generator [14]

The major components of a commercial wind turbine are:

1. Tower
2. Rotor

3. High speed and low speed shafts
4. Gear box
5. Generator
6. Sensors and yaw drive
7. Power regulation and controlling units
8. Safety systems.

Generator is one of the most important components of a wind energy conversion system. In contrast with the generators used in other conventional energy options, generator of a wind turbine has to work under fluctuating power levels, in tune with the variations in wind velocity. Different types of generators are being used with wind machines. Small wind turbines are equipped with DC generators of a few watt to kilowatt in capacity. Bigger systems use single or three phase AC generators. As large-scale wind generation plants are generally integrated with the grid, three phase AC generators are the right option for turbines installed at such plants. These generators can either be induction (asynchronous) generators or synchronous generators.

Most of the wind turbines are equipped with induction generators. They are simple and rugged in construction and offer impressive efficiency under varying operating conditions. Induction machines are relatively inexpensive and require minimum maintenance and care. Characteristics of these generators like the over speed capability make them suitable for wind turbine application. As the rotor speed of these generators is not synchronized, they are also called asynchronous generators.

2.2. Features of power supply and application of wind turbines at north regions

NAO is located in the north of the European part of the Russian Federation, almost completely beyond the Arctic Circle. It is washed by the White, Barents, Pechora and Kara seas. The area of the district is 177 thousand km2. It is part of the Arkhangelsk region, being both an independent subject of the Russian Federation.

Figure 4 – Location of Khorey-Ver village [7]

In a number of settlements fuel is delivered only by winter roads from the centers of municipalities. The main problem of delivery is related to the limited time of sea and river navigation. A very short period (1-2 weeks) is available for fuel delivery along rivers in the spring, when the water level is higher. Even large points Khorey-Ver and Harut, where about 800 people live, depend on such delivery.

From renewable energy sources in the Nenets Autonomous Okrug there is only wind-diesel complex in Amderm, which began to operate in September 2016. It includes four wind power plants with a total capacity of 200 kW (4 * 50 kW) and three diesel generators with a capacity of 100, 160 and 200 kW. The diameter of the wind wheel is 15 m, the height of the axis of the wind wheel is 25 m. Installations were made in China according to the project of Russian specialists, taking into account the Arctic operating conditions.

The design of wind turbines should take into account the underdeveloped infrastructure, limited transport accessibility and harsh climatic conditions of equipment operation. It should be adapted to low temperatures up to -50 ° C, hurricane winds up to 60 m/s, icing, have a base capable of reliably holding the structure on permafrost.

The management system for the joint operation of diesel and wind parts should provide a high proportion of the replacement of expensive diesel fuel, in principle a replacement of more than 50% is achievable. The design itself must take into account difficult delivery conditions and a short navigation period, lack of roads, assume maintenance without involving highly qualified specialists, allow installation and construction without the use of heavy equipment, have a high degree of automation and a remote monitoring and diagnostics system to minimize technological and operating costs, and in conditions of significant restrictions on communications.

Based on the experience of developing and commissioning a station in Amderm, scientists from St. Petersburg Polytechnic University formulated the following list of technical requirements:

- hydrophobic coating of the blades of a wind wheel, including painting in black (passive protection against icing);
- replacement of the pneumatic braking system with an electromechanical (increasing reliability and autonomy of work);
- anticorrosion coating of the stator and rotor of the generator;
- backup of wind parameters sensors in order to avoid breakdowns during strong winds and failure of the main sensors;
- reinforced tower structure made of frost-resistant steel;
- tower sectioning by weight not more than 3 tons / section (possibility of installation without expensive delivery and installation of cranes);
- installation of the inverter and control systems in a thermostated container;
- designing a special foundation for permafrost conditions (taking into account its possible degradation due to climate change).

2.3. Economical potential of wind energy at chosen region

The wind energy potential is defined as the total energy of a wind flow of a locality at a certain height above the earth's surface. Wind energy is characterized by speed, which is a random variable in space and time. Therefore, the energy characteristics of the wind are represented by a probabilistic description of the random process of changing the wind energy potential. The basis of the probabilistic approach is the discretization of the time process, which makes it possible to consider as independent and constant all the determined parameters on the sampling interval. As time intervals, hour, day, season, year are usually used.

To obtain reliable data on the average wind speeds of the territory, it is necessary to use significant volumes of measurements for a long period of time.

The average annual wind speed is defined as the arithmetic mean value obtained as a result of speed measurements at equal intervals of time for a given period: day, month, year, several years[2]:

$$V_{cp} = \frac{1}{n}\sum_{i=1}^{n} V_i \qquad (7)$$

where: V_i - wind speed in the measurement interval [m/sec],

n - amount of intervals;

Data for wind speed given at Table 6 for every three hour for 10 years (part of huge table)

Table 6 – Part of data of wind speed and direction [2]

Date, time	Wind direction	Speed, km/h
01.11.2019 21:00	Wind blowing from the west	1
01.11.2019 18:00	Wind blowing from the west-north-west	1
01.11.2019 15:00	Wind blowing from the west-north-west	1
01.11.2019 12:00	Wind blowing from the west-north-west	2
01.11.2019 09:00	Wind blowing from the west-north-west	2
01.11.2019 06:00	Wind blowing from the west	2
01.11.2019 03:00	Wind blowing from the west	2
01.11.2019 00:00	Wind blowing from the west	2
31.10.2019 21:00	Wind blowing from the west	3
31.10.2019 18:00	Wind blowing from the west	4

Wind rose characterizes the length of time in percentage terms during which the wind blows in a given direction. Table 7 shows the frequency of wind directions for Khorey-Ver corresponding for every direction.

---

[2] Lukutin B.V. Vozobnovlyayemye istochniki elektroenergii. [Renewable energy sources] Education guidance. Tomsk: Tomsk Polytechnic University, 2008. - 16 p.

Table 7 – Data with duration and direction of wind flow [2]

Direction	Amount of measurements	%
N	706	5,1
N-N-E	645	4,7
N-E	728	5,3
E-N-E	779	5,6
E	952	6,9
E-S-E	617	4,5
S-E	520	3,8
S-S-E	555	4,0
S	1105	8,0
S-S-W	1185	8,6
S-W	1496	10,8
E-S-W	1186	8,6
W	1245	9,0
W-N-W	825	6,0
N-W	672	4,9
N-N-W	621	4,5

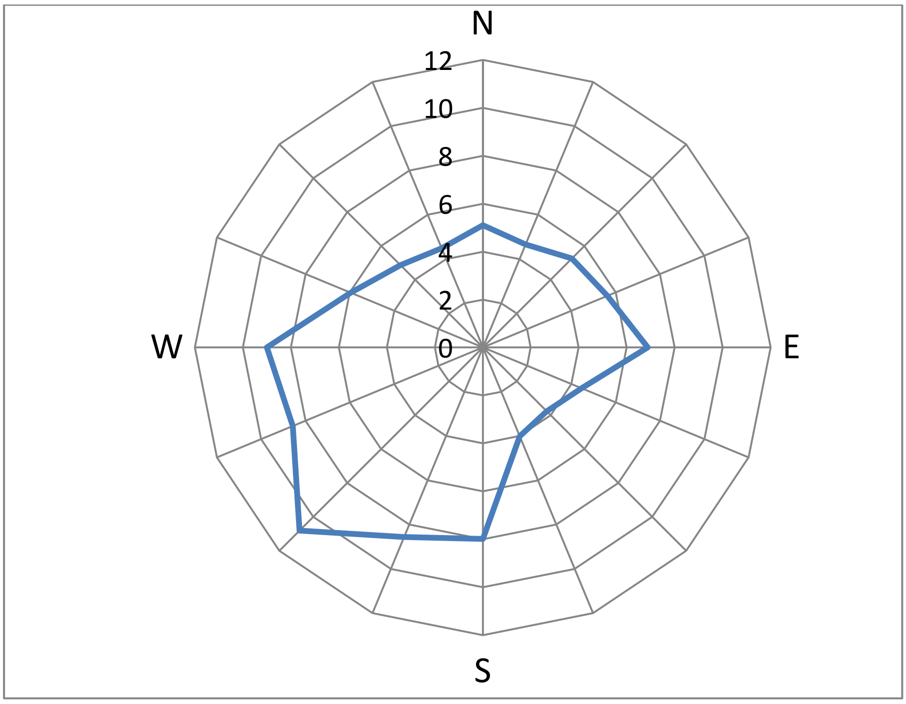

Figure 5 – Wind rose of village Khorey-Ver [2]

According to Figure 5 we may see, that most time wind blowing to south- west direction.

The average wind speed is an indicator allowing the use of wind farms in a given area. The criterion of using wind turbines is minimum value of the wind speed at which modern wind turbines begin to rotate and develop their rated power.

It is known that the wind speed increases with distance from the underlying surface, and the air flow becomes more stable. We recalculate the wind speed to the optimum height:

$$V_h = V_f \, (\mathrm{h}/\mathrm{h}_f)^{\alpha}, \tag{8}$$

where:

h_f - wind speed at a height of 10 meters [m],

h- necessary height [m],

α - coefficient of area, accepted 0,14 for chosen area. [1]

An important energy indicator repeatability of different gradations of wind speed can be considered as a percentage of the time during which one or another gradation of wind speed was observed. Gradation of wind speed is characteristic of wind speed duration. This characteristic is important for wind energy calculations related to the assessment of the operating time intervals of a wind power plant at various wind speeds. Distribution of wind speed by gradation allows us to calculate the generating of wind power for each month. Total energy that a particular type of wind farm can produce in the considered time interval is defined as the sum of the energies corresponding to each wind gradation.

Table 8 – Repeatability of different gradations of wind speed for every month [2]

Speed, m/sec	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
0	68	38	31	22	13	13	15	14	31	29	60	60
1	102	54	61	52	37	44	75	69	87	60	96	77
2	101	96	85	97	91	95	117	130	136	108	96	69
3	96	88	103	102	120	126	155	121	145	135	113	84
4	89	92	84	96	134	133	137	136	115	134	90	84
5	84	88	103	102	112	118	102	108	103	118	63	71
6	73	68	94	89	90	93	68	74	69	64	72	71
7	54	54	77	61	69	45	38	38	37	40	58	84
8	35	48	47	50	35	31	18	21	13	21	51	54
9	17	21	26	19	18	12	12	7	7	5	20	34
10	7	9	17	15	13	6	2	2	1	4	16	19
11	5	5	7	3	6	2	1	1	0	1	7	6
12	5	6	5	6	3	1	1	1	0	1	4	4
13	4	2	2	2	2	0	0	0	0	0	0	2
14	2	1	1	1	0	1	1	0	0	0	0	0
15	0	1	1	0	0	0	1	0	0	0	0	0
16	0	0	0	1	0	0	0	0	0	0	0	0
17	0	1	0	1	0	0	0	0	0	0	0	1
18	1	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	1	1	0	0	0	0	0

Table 9 – Average wind flow for every month for 10 years [2]

Month	Amount of measurements	Sum of speed, km/h	Av. Speed, km/h
Jan.	1243	4871	3,92
Feb.	1209	5323	4,40
Mar.	1240	5781	4,66
Apr.	1235	5679	4,60
May	1290	5902	4,58
Jun.	1237	5294	4,28
Jul.	1207	4588	3,80

Month	Amount of measurements	Sum of speed, km/h	Av. Speed, km/h
Aug.	1244	4740	3,81
Sept.	1235	4341	3,51
Oct.	1184	4520	3,82
Nov.	1030	4146	4,03
Dec.	1128	5097	4,52
Year	14482	60282	4,16

Generating power of wind turbine is defined as a function of wind speed:

$$P(V) = \frac{\pi}{8} \cdot D^2 \rho V^3 \cdot \eta \qquad (9)$$

where:

D - diameter of wind turbine [m],

$\rho = 1,23$ - density of air $\left[\frac{kg}{m^3}\right]$,

V - wind speed [m/sec],

η - efficiency of electromechanical converter;

Coefficient of efficiency include efficiency of wind turbine, transmission lossses and generator efficiency.

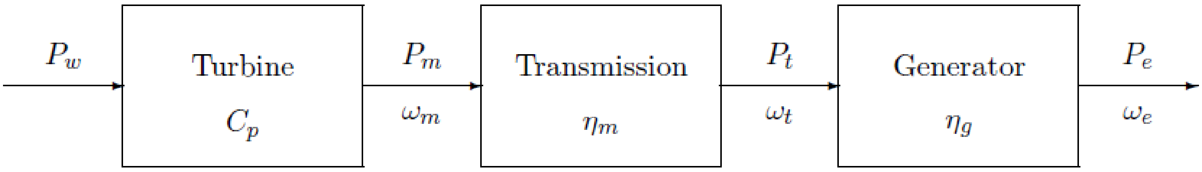

Figure 6 – Wind electric system [13]

where:

C_p - coefficient of performance of wind turbine,

η_m - transmission efficiency,

η_g - generator efficiency.

The coefficient of performance is not a constant, but varies with the wind speed, the rotational speed of the turbine, and turbine blade parameters like angle of attack and pitch angle. Pitch angle is the angle between the chord line of the blade and the plane of rotation. Angle of attack is the angle between the chord line of the blade and the relative wind or the effective direction of air flow.

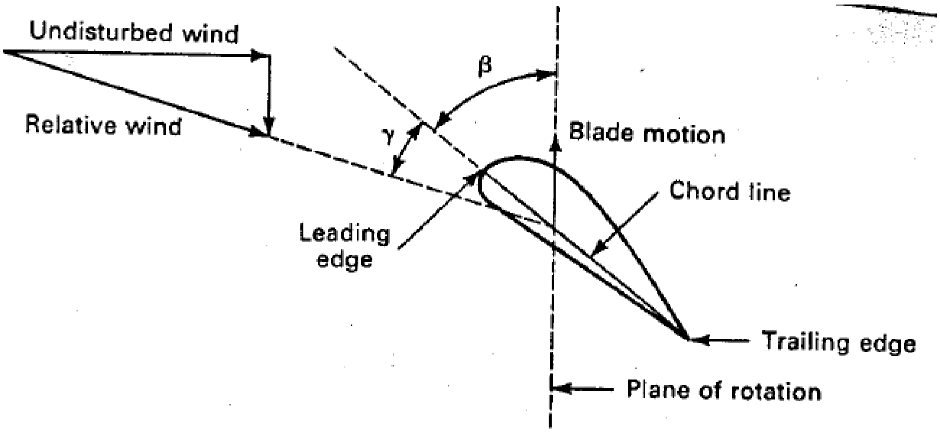

Figure 7 – Definition of pitch angle and angle of attack [13]

The large horizontal axis turbines normally have variable pitch. The pitch is varied to hold C_p at its largest possible value up to the rated speed of the turbine, and then is varied to reduce C_p while output power continues to increase with wind speed, in order to maintain the output power at its rated value. It is not practical to hold C_p constant with pitch control because of manufacturing and control limitations, so it will vary with wind speed even for a fixed rotational speed, variable pitch blade.

The factor 16/27 = 0,593 is sometimes called the Betz coefficient. It shows that an actual turbine cannot extract more than 59,3% of the power in an undisturbed tube of air of the same area. In practice, the fraction of power extracted will always be less because of mechanical imperfections. A good fraction is 35-40 percent of the power in the wind under optimum conditions, although fractions as high as 50 percent have been claimed. A turbine which extracts 40 percent of the power in the wind is extracting about two-thirds of the amount that would be extracted by an ideal turbine. This is rather good, considering the aerodynamic problems of constantly changing wind speed and direction as well as the frictional loss due to blade surface roughness. [13]

It is known that the wind speed increases with distance, and the air flow becomes more established. Wind speed at altitude can be estimated by the formula:

$$\mathrm{V}_h = V_w \left(\frac{\mathrm{h}}{h_w} \right)^{\alpha} \text{ [m/sec]} \tag{10}$$

where

V_h - wind speed at height of axis wind turbine [m/sec],

V_w - wind speed at the height of vane height [m/sec],

h - height of axis wind turbine [m],

h_w - height of vane height [m],

α - coefficient depending on the average wind speed at the height of the wind vane, equal to 1/7.

For our location we should choose one of wind turbines (Table 10):

Table 10 – Characteristics of wind turbines [12]

Turbine	Nominal power, kW	V start, m/sec	V nominal, m/sec	V furling, m/sec	D, m	Cost, RUB
Vestas V25	200	3,5	13	25	25	12 999 000
Micon M530	250	5	14,5	25	26	16 120 000
Nordtank 360	360	4,5	13	25	28	22 810 000
Condor Air 60	60	2,5	9	20	17,5	3 150 000

One of the major factors affecting the performance of a wind turbine is its power corresponds to different wind velocities. This is usually given by the power curve of the turbine. The power curve of the machine reflects the aerodynamic, transmission and generation efficiencies of the system in an integrated form. Typical curve represented on the Figure 8.

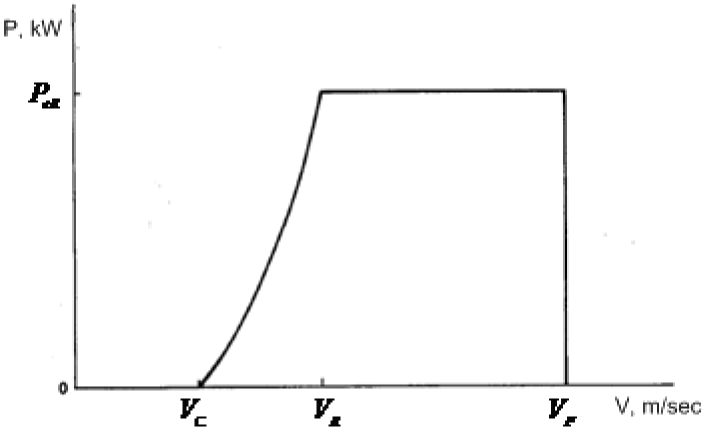

Figure 8 – Model wind turbine output versus wind speed [13]

where:

V_F - furling wind speed [m/sec],

V_R - rated wind speed [m/sec],

V_C - cut-in speed [m/sec],

P_{eR} - rated electrical power [kW].

The simplest model would use a straight line to describe the variation in output power between cut-in and rated wind speeds. We must remember, of course, that other monotonic functions will fit the observed data nearly as good as a straight line, or perhaps even better for some machines, and may yield more accurate energy estimates or more convenient analytic results. More accurate formula of estimation of performance of wind turbine is provided below [13]:

$$\begin{aligned} &P=0,\ (V<V_C)\ [kW] \\ &P=a+b\cdot V^K,\ (V_C<V<V_R)\ [kW] \\ &P=P_{eR},\ (V_R<V<V_F)\ [kW] \\ &P=0,\ (V_F>V)\ [kW] \end{aligned} . \tag{11}$$

where:

$$\begin{aligned} &a=\frac{P_{eR}\cdot V_C{}^K}{V_C{}^K-V_R{}^K}\ [\mathrm{kW}] \\ &b=\frac{P_{eR}}{V_R{}^K-V_C{}^K}\left[\frac{\mathrm{kW}}{\mathrm{m\cdot sec}}\right], K=2\,. \end{aligned} \tag{12}$$

Example of calculation of curve of producing power by Condor Air 60:

$$a=\frac{60\cdot 2{,}5^2}{2{,}5^2-9^2}=-5{,}017\ [\mathrm{kW}], \tag{13}$$

$$b=\frac{60}{2{,}5^2-9^2}=0{,}803\left[\frac{\mathrm{kW}}{\mathrm{m\cdot sec}}\right] \tag{14}$$

$$\begin{aligned} &P=0,\ (V<V_C)[kW], \\ &P(V)=-5{,}017+0{,}803\cdot V^2,\ (2{,}5<V<9)[kW], \\ &P=60,\ (9<V<20)[kW], \\ &P=0,\ (V>20)[kW]. \end{aligned} \tag{15}$$

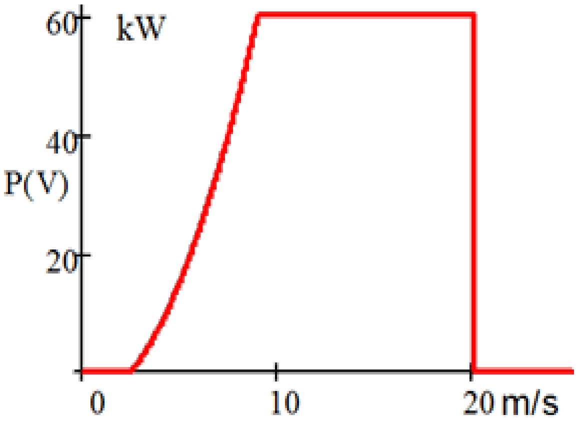

Figure 9 – Power curve of the wind turbine Condor Air 60

Function $P(V)$ allow us to calculate power which wind power installation can produce. We have 4 wind turbine (Table 11) and their performance correspond to specific wind speed. We have data of duration of specific wind speed for every month, thus the total energy generated from wind turbine is product of power for specific wind speed to duration of this speed:

$$W_{Total} = \sum_{i=1}^{N} P_i \cdot t_i \ \ [kW \cdot h] \tag{16}$$

where:

P_i - generated power of turbine [kW],

t_i - duration of this mode [h].

Table 11 – Performance of wind turbines

Speed, m/sec	Vestas V25	Nordtack 360	Condor air 60	Micon M530
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0,1	0	2,2	0
4	12,3	0	7,8	0
5	28	11,5	15,1	0
6	47,2	38,1	23,9	14,9
7	70	69,6	34,3	32,4
8	96,2	105,9	46,4	52,6
9	125,8	147	60	75,6
10	159	193	60	101,2
11	195,7	243,8	60	129,6
12	200	299,5	60	160,6
13	200	360	60	194,3
14	200	360	60	230,8
15	200	360	60	250
16	200	360	60	250

Using Table 11 and Table 8 we can calculate energy output for every month:

Table 12 – Performance of wind turbines for every month and consumption of energy

Month	Consumption, kW h	Vestas V25	Nordtack 360	Condor air 60	Micon M530
January	58000	20751	20339	9880	8345
February	58000	22523	22170	10715	9036
March	46300	27462	26933	13053	10924
April	46300	24931	24111	11944	9981
May	46300	23837	21557	11677	8940
June	40600	18832	15537	9642	6859

July	40600	14823	11723	7814	5327
Month	Consumption, kW h	Vestas V25	Nordtack 360	Condor air 60	Micon M530
August	40600	14283	10646	7589	4830
September	52200	12404	8928	6743	4140
October	52200	14465	10811	7657	4903
November	52200	22297	21621	10714	8654
December	58000	27305	27439	12935	10922
W total	591300	243912	221815	120364	92861

As we may see every turbine have different installed power, different cost, different power curve. We can find ratio between generated power and cost of wind turbine.

$$k_{ef} = \frac{W_{Total}}{Inv} \cdot 100 \left[\frac{kW \cdot h}{Rub} \right] \qquad (17)$$

where Inv - investment for wind turbine [RUB].

Table 13 – Coefficient of economical efficiency

	Vestas V25	Nordtack 360	Condor air 60	Micon M530
W_{Total} $[kW \cdot h]$	243 912	221 815	120 364	92 861
Inv, RUB	12 999 000	22 810 000	3 222 000	16 120 000
k_{ef}	1,88	0,97	3,73	0,58

The best option is wind turbine Condor air 60.

Choice of optimum scheme and capacity of wind turbine

A variant of the energy complex with two energy sources, each of which is able to cover the needs of the electric load at certain time intervals, is characterized by a maximum of possibilities for replacing diesel generation with energy from a renewable source. Reducing the operating time of the diesel part of the energy complex provides maximum diesel fuel savings and increases the life of the DPP.

The ability to turn off the DES during periods of high values of the potential of renewable energy is achieved by complicating the composition of the hybrid energy complex and algorithms for controlling its elements.

The most efficient structure of a wind generator with batteries and a backup diesel generator. The presence of rechargeable batteries allows to reduce the number of starts of the diesel generator and to exclude interruptions in power supply during switching of generating equipment. Typically, the available energy supply in batteries may be limited by the consumer’s supply time within an hour.

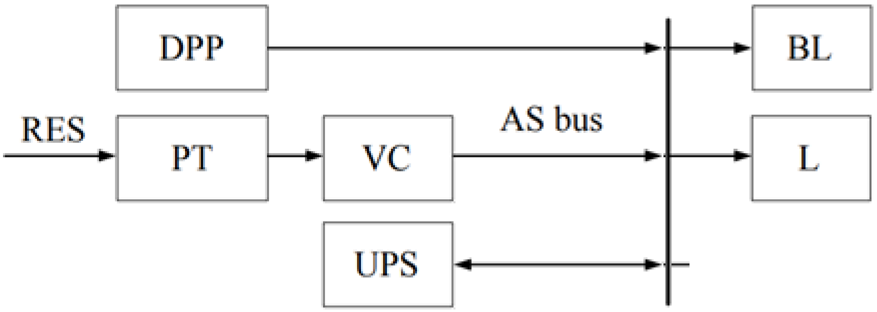

Figure 10 – Structure of Hybrid wind diesel power station [11]

DPP- diesel power plant,
L- load,
BL- ballast load,
UPS- uninterruptible power supply,
VC – voltage converter,
PT – primary transducer of wind energy.

2.4. Energy Storage

Energy storage can serve a very useful role in wind energy systems, particularly those in which the wind is to provide a large fraction of the total energy requirement. Energy storage can help to overcome mismatches between the availability of wind energy and the requirement for energy. There are many storage options to consider. These include batteries, compressed air, flywheels, and pumped hydroelectric, among others. There are two characteristics of particular interest: the quantity of energy that can be stored per unit cost and the rate at which energy can be absorbed or delivered. The time scale of the storage is also important – is it useful for dealing with fluctuations on the order of seconds, minutes, hours, or days? For example, pumped hydroelectric is typically used to cover daily variations in electrical load. Batteries are most effective for dealing with variations on the order of minutes to hours, and flywheels are used for smoothing power fluctuations on the order of seconds to minutes. At the present time, the most common storage medium for wind energy applications is batteries, and there has been renewed interest in compressed air energy storage and flywheels. Pumped hydroelectric also remains an attractive option for some situations. [15]

Battery energy storage is very common with smaller hybrid power systems and is occasionally used in larger electrical networks as well. Batteries have proven to be popular energy storage medium, based primarily on their convenience and cost. Battery storage systems are modular, and multiple batteries can store large amounts of energy. Lead acid batteries are most prevalent, although nickel–cadmium batteries are occasionally used. Batteries are inherently DC devices. Thus, battery energy storage in AC systems requires a power converter. An important aspect of batteries is their terminal voltage, which varies according to current and state of charge. The terminal voltage drops as the battery is discharged. When charging is initiated, the terminal voltage jumps to a value above the nominal cell voltage. As the cell becomes fully charged, the terminal voltage increases even more before gassing occurs (the production of hydrogen gas in the cells) and the terminal voltage levels off.

Total battery capacity is expressed in Amp-hours (Ah), a unit of charge, or kWh. Rated battery capacity is considered to be the Ah discharged at the rated current until the voltage has dropped to 1.75V per cell (10.5Vin a 12V battery). Usable battery capacity depends on the charge or discharge rate. High rates of discharge result in early depletion of the battery. The voltage soon drops and no more energy is available. At low discharge rates, the battery can provide much more total energy before the voltage drops. High charge rates result in rapidly increasing terminal voltage after only a short while.

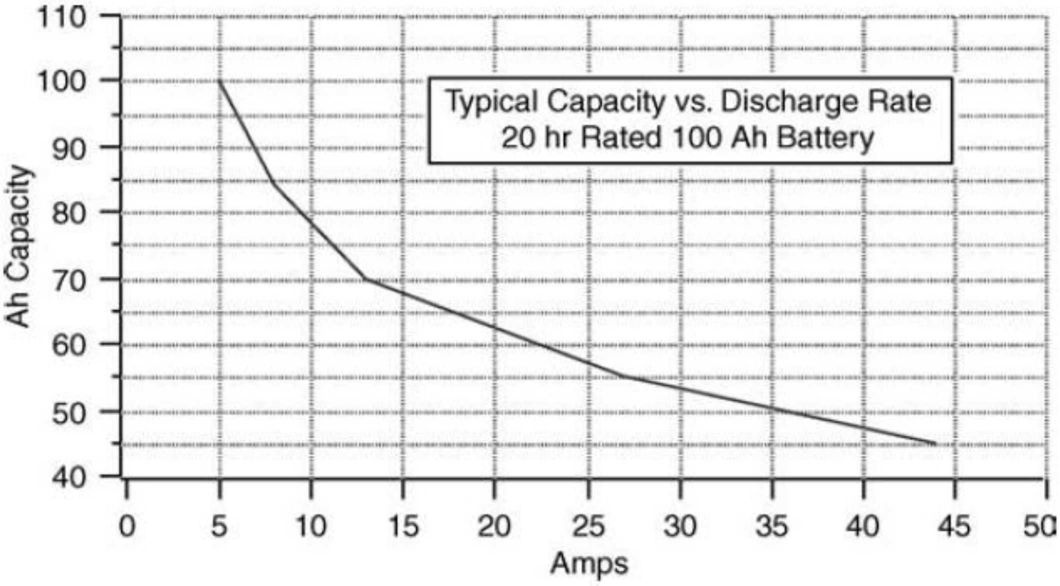

Figure 11 – Battery capacity vs. discharge rate curve [15]

Batteries are not 100% efficient. There are two measures of battery efficiency. Coulombic efficiency is the ratio of the charge delivered by the battery during discharging to the charge put into the battery during charging in one complete charge–discharge cycle. Typical coulombic efficiencies range from 90% to 100%. Coulombic efficiency is higher with lower charging currents (and reduced gassing).

The second measure of efficiency is energetic efficiency. Energetic efficiency is the ratio of the energy transferred from the battery to the energy provided to the battery in one complete charge–discharge cycle. Energetic efficiency reflects the lower voltages on discharge and the higher voltages required for charging. Energetic efficiencies are usually between 60% and 90%, depending on operating conditions. Temperature effects: battery capacity and life are functions of temperature. Usable battery capacity decreases as the temperature decreases. Typically, battery capacity at 0 degrees is only half that at room temperature. Above room temperature, battery capacity increases slightly, but battery life decreases dramatically.

Unlike other storage media, battery capacity decreases with use. Batteries are typically deemed to be exhausted when their capacity has dropped to 60% of the rated capacity. Battery life is often expressed as the number of charge–discharge cycles to a certain depth of discharge that one can get from the battery.

Generally, for a given battery, the deeper the cycle depth of discharge, the shorter is the life of the battery. Cycle life also depends on battery construction.

Long cycle life batteries last 1500–2000 deep discharge cycles whereas automotive batteries, for example, can only be deep discharged about 20 times. Battery life is sometimes modeled with techniques patterned after those developed for material fatigue. [15]

3. Power converters

3.1. Overview of power converters

Power converters are devices used to change electrical power from one form to another, as in AC to DC, DC to AC, one voltage to another, or one frequency to another. Power converters have many applications in wind energy systems. They are being used more often as the technology develops and as costs drop. For example, power converters are used in generator starters, variable-speed wind turbines, and in isolated networks. Modern converters are power electronic devices. Basically, these consist of an electronic control system turning on and off electronic switches, often called valves. Some of the key circuit elements used in the inverters include diodes, silicon-controlled rectifiers (SCRs, also known as thyristors), gate turn off thyristors (GTOs), and power transistors. The present trend is towards increasing use of IGBT.

3.2. Rectifiers

Rectifiers are devices which convert AC into DC. They may be used in: (1) battery-charging wind systems or (2) as part of a variable-speed wind power system.

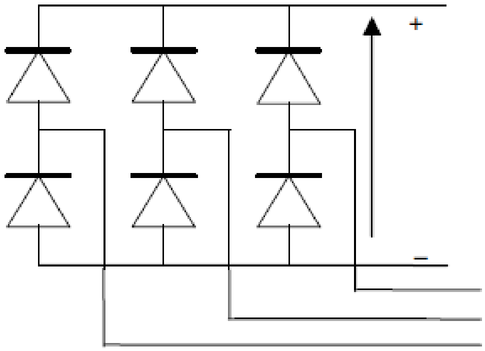

Figure 12 – Diode bridge rectifier using three-phase supply

The simplest type of rectifier utilizes a diode bridge circuit to convert the AC to fluctuating DC. An example of such rectifier is shown in Figure 12. In this rectifier, the input is three phase AC power; the output is DC. In some cases it is useful to be able to vary the output voltage of a rectifier. This may be done by using a controlled rectifier. In this case the primary elements in the bridge circuit are silicon controlled rectifier rather than diodes. The SCRs remain off until a certain fraction through the cycle, corresponding to the firing delay angle, and then they are turned on. [15]

3.3. Inverters

In order to convert DC to AC, as from a battery or from rectified AC in a variable-speed wind turbine, an inverter is used. Historically, motor generator sets have been used to convert DC into AC. These are AC generators driven by DC motors. This method is very reliable, but is also expensive and inefficient. Because of their reliability, however, they are still used in some demanding situations.

At the present time most inverters are of the electronic type. An electronic inverter typically consists of circuit elements that switch high currents and control circuitry that coordinates the switching of those elements. The control circuitry determines many aspects of the successful operation of the inverter. There are two basic types of electronic inverter: line-commutated and self-commutated inverters. The term commutation refers to the switching of current flow from one part of a circuit to another. [15]

Inverters that are connected to an AC grid and that take their switching signal from the grid are known by the rather generic name of line-commutated inverters. Figure 13 illustrates an SCR bridge circuit, such as is used in a simple three-phase line-commutated inverter. [15]

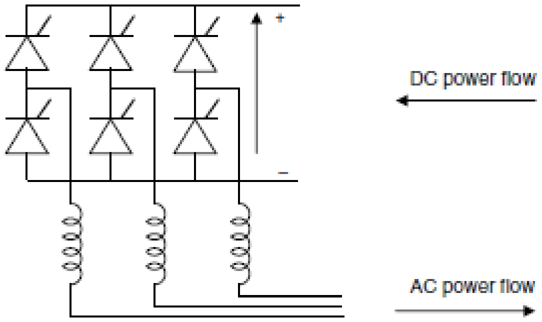

Figure 13 – Line-commutated SCR inverter

The circuit is similar to the three-phase bridge rectifier shown above, but in this case the timing of the switching of the circuit elements is externally controlled and the current flows from the DC supply to the three-phase AC lines. Self-commutated inverters do not need to be connected to an AC grid. Thus, they can be used for autonomous applications. They tend to be more expensive than line-commutated inverters.

The actual scheme of inverters may be of a variety of designs, but inverters fall into one of two main categories: voltage source inverters and current source inverters. In current source inverters, the current from the DC source is held constant regardless of the load. They are typically used to supply high power factor loads where the impedance is constant or decreasing at harmonic frequencies. Overall efficiencies are good (around 96%), but the control circuitry is relatively complex. Voltage source inverters operate from a constant voltage DC power source. They are the type most commonly used to date in wind energy applications. [15]

4. Economic appraisal of small hybrid power supply system

At this chapter I will analyze power supply system from economical stand point. For this purpose I need to consider main parameters of estimation of economical efficiency. After that, I will consider current power supply system and version after integration of RES.

4.1 Main economical parameters

Main parameters of estimation of economical efficiency are:

1. Net present value
2. Payback period
3. Internal rate of return
4. Profitability index
5. Prime cost

Net present value

Every investor wants the firm to invest in a project that is worth more than it costs. The difference between a project's value and its cost is its net present value (NPV). To calculate NPV we need to forecast generated CF (cash flow) by project over its economic life, determine the appropriate opportunity cost of capital. This should reflect both the time value of money and the risk involved in project. Using opportunity cost of capital to discount the project's future cash flows. The sum of the discounted cash flows is called present value (PV). NPV is calculating by subtracting investment from PV:

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \tag{18}$$

where:

r - opportunity cost,

T - lifetime of the project.

Payback period

A project's payback period is found by counting the number of years it takes before CF equals the initial investment. The payback rule states that a project should be accepted if its payback period is less than some specified cutoff period.

$$\sum_{t=0}^{T_p} \frac{CF_t}{(1+r)^t} = 0 \tag{19}$$

where:

CF – cash flow in the period t,

inv – initial investment in the project,

r – discount rate,

T_p – payback period,

Internal rate of return

Internal Rate of Return (IRR) is next criterion with which the project can be estimated in the economic point of view. Actually, IRR is a discount rate, when NPV of the project is equal to zero. IRR may be calculated with next formula:

$$\sum_{t=0}^{T} \frac{CF_t}{(1+IRR)^t} = 0 \tag{20}$$

where:

CF_t – cash flow in the period t,

inv – initial investment in the project,

IRR – internal rate of return (discount rate),

T - lifetime of the project.

Profitability index

The Profitability Index (PI) measures the ratio between the present value of future cash flows and the initial investment. The index is a useful tool for ranking investment projects and showing the value created per unit of investment:

$$Profitability\ index = \frac{NPV}{inv} + 1 \tag{21}$$

where:

NPV – net present value,

inv – initial investment in the project.

The greater profitability index the better.

Cost of energy

The cost of energy (COE) is defined as the unit cost to produce energy (in RUB/kW h):

$$COE = \frac{Exp}{W} \tag{22}$$

Where:

Exp - total expenses for 1 year [RUB],

W - produced energy for 1 year [kW h].

4.2 Price action of production of electricity

For total price of production of electrical energy influence:

cost of investment

salaries for staff
overhaul of equipment
inflation
price for fuel
cost of output energy

Inflation

Physically, inflation in an economy can be considered as the increase in prices of goods and services over a period of time. Thus inflation decreases the purchasing power of money. The Consumer Price Index (CPI) commonly shows the rate of inflation in an economy. In our calculations we will use average value of inflation for previous 10 years.

Table 14 – Inflation in Russia for 10 years [17]

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Inflation, %	8,78	6,10	6,58	6,45	11,36	12,91	5,38	2,25	4,27	3,05
Average compound, %	**5,92%**									

The formula for converting nominal cash flows in a future period t to real cash flows today is:

$$Real\ cash\ flow\ at\ the\ year = \frac{Nominal\ \ cash\ flow\ at\ the\ year}{(1+iflation\ rate)^{t}} \tag{23}$$

Depreciation

Depreciation is an accounting method of allocating the cost of a tangible or physical asset over its useful life or life expectancy. Depreciation represents how much of an asset's value has been used up. Depreciating assets helps companies earn revenue from an asset while expensing a portion of its cost each year the asset is in use. If not taken into account, it can greatly affect profits. [26]

Businesses can depreciate long-term assets for both tax and accounting purposes. For example, companies can take a tax deduction for the cost of the asset, meaning it reduces taxable income. For the purposes, in Russia taxpayers have the right to choose one of the following depreciation methods [18]:

1) linear method;

2) non-linear method.

Linear method of calculation:

$$Dep = \frac{INV}{T} \tag{24}$$

where:

INV - Initial investment [RUB],

T - lifetime of equipment, [years].

We will use linear method.

Price for fuel

At Figure 14 it is clear, that price for fuel constantly increasing. Russian internal market have their own features, price for fuel independent from price for oil in world market. We can take into account trend of prices for diesel fuel and calculate future value. Curve «a» represent historical data, curve «b»- compound dependence which close to this data. Formula of this growth is shown on the Figure 14. Annual growth is equal to 6,6%.

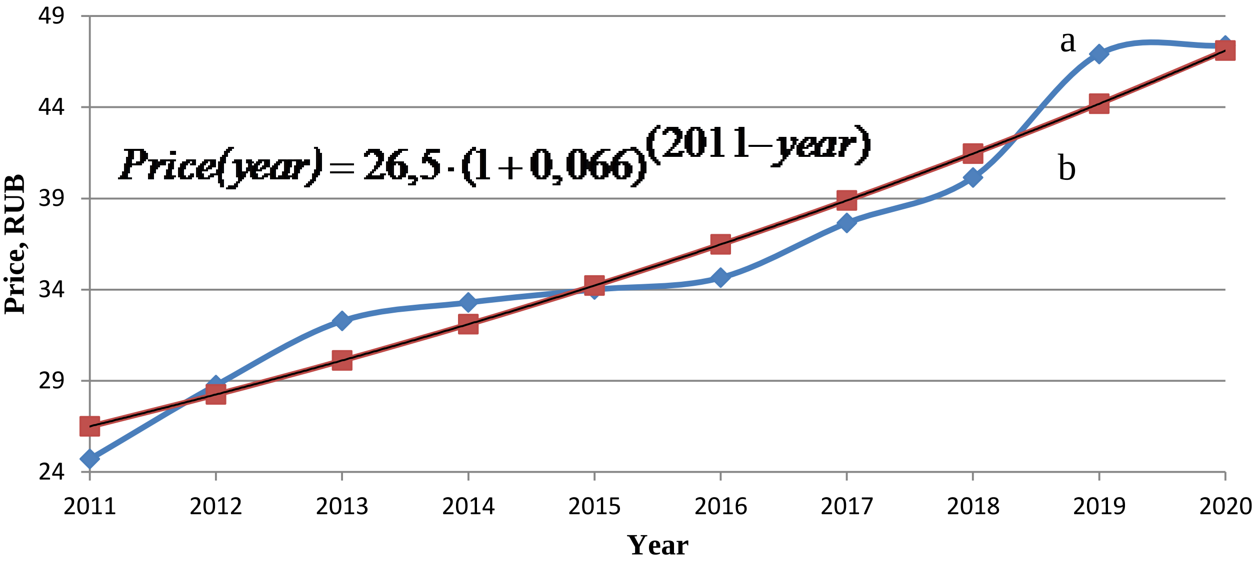

Figure 14 – Dynamic of price for diesel fuel [20]

According to Table 5 annual consumption of fuel 165 276 l.

Annual expenses for fuel:

$$E_{fuel} = L_{year} \cdot C_{liter} = 165200 \cdot 47,38 = 7\ 129\ 227\ Rub \qquad (25)$$

where:

L_{year} - annual consumption of diesel [l],

$C_{kW \cdot h}$ - price for 1 liter [RUB/l].

Revenue from selling of energy

According to [27] tariff for electrical energy for chosen region is 2,02 RUB/$kW \cdot h$[27]. Price for electrical energy increasing every year. This growth higher than inflation in Russia by 4,88% (average data for 10 years [21] . As a practice, prime cost in decentralized power supply system can be 10- 20 times higher than tariff. In this case government subsidize main part of energy supply.

Annual earnings from selling of electricity:

$$E_e = W_{year} \cdot C_{kW \cdot h} = 5{,}92 \cdot 10^5 \cdot 3{,}71 = 2\ 196\ 300\ Rub \qquad (26)$$

where:

W_{year} - annual consumption of electrical energy (formula) [$kW \cdot h$],

$C_{kW \cdot h}$ - price for $kW \cdot h$ [RUB/ $kW \cdot h$].

Initial investment and maintenance

Initial investments include investment in all equipment for operation of power supply system, start-up of equipment and its transportation. Information about expenditures for transportation for 1 wind turbine took from [22]. Next we will compare several options of power supply:

1. Without RES
2. With integration different amount of wind turbines

Table 15 – Initial investment in scheme without RES

Generator	Amount	Lifetime, hours	Price, RUB	Start-up costs, RUB	Total price, RUB
CTG AD- 165SD	3	20 000	700 000	70 000	2 310 000

For power supply we need 3 generators, but we should take into account that 1 of them is reserve generator and most of time only 1 generator will be in work, second generator will work at maximum mode. From Table 5 we may see that 9646 hours is equivalent time for system of generators. Further you may see schedule of technical maintenance of diesel generator CTG AD- 65SD depending from duration of operation. We need to service our generators every 250 hour or 38 times for 1 year.

Table 16– Schedule of technical maintenance of diesel generator and its cost [23]

Period, h	Cost, RUB	Number of maintenances for year
every 250 h	11 538	9
every 500 h	12 838	19
every 1000 h	19 663	9
every 5000 h	21 613	1
Total, RUB	546 344	

Annual equivalent cost for maintenance of diesel generators: **546 344 RUB.**

Expenditure for salaries

Four people should be involved in process of generation of electrical energy, but at specific moment of time at DPP at least 1 person should be present. We may calculate total salary for all workers:

$$\mathrm{S_{month}} = \mathrm{k_h} \cdot \mathrm{N} \cdot 12 \tag{27}$$

where:

$\mathrm{k_h}$ - salary for 1 hour for 1 worker, 350 RUB,

N - amount of hours per month, 720 hours,

As a result, we need to pay 3 000 000 RUB. Also we need to pay 30% from salary to funds: pension capital fund, compulsory medical insurance fund:

$$S_{ext} = 0{,}3 \cdot S_{month} = 907\ 200\ Rub \tag{28}$$

Total expenditures for salary equal to:

$$S_{total} = S_{ext} + S_{month} = 3\ 931\ 200\ Rub \tag{29}$$

We will annually increase salary for our workers according to inflation.

Table 17 – Input values of economical model no. 1

Elements of economical model	Cost, RUB	Annual growth, %
Generators, investment	2 310 000	6,71%
Technical maintenance	559 670	6,71%
Salaries	3 931 200	6,71%
Fuel	7 827 176	6,6%
Earnings from selling of electricity	1 195 840	10.8%

4.3. Integration of wind turbine in current power supply system

The principle of designing a wind-diesel power based on possibility of obtaining additional energy from wind turbines to reduce expenditures for fuel. We choose wind turbine Condor Air 60. All technical information is available in appendix 1. The diesel generators compensate lack of energy received from wind turbines. For this, the diesel generators should have an automatic start system. When transient process occurs, power demand is also covered by the power block Delta NH PLUS-series 20- 120 kVA (3ph-3ph) and rechargeable batteries.

Delta NH PLUS-series 20- 120 kVA adjust input value of voltage from wind generator from input voltage 208- 477 V to output 380 V. Also this device switches on accumulator batteries when we have low output from wind turbine. In a case when we have excess of generated power from wind turbine Delta NH PLUS charge accumulator batteries. When accumulator batteries have low stock of charge and we have low output from wind turbine we need to use diesel generators. Automatic throw-over circuit-breaker performs such function. All necessary equipment can be found in Table 18.

Table 18 – Equipment for scheme with integrated wind turbine

Equipment	Amount	Lifetime, years	Price, RUB	Total price, RUB
Wind turbine Condor Air 60	1	20	3 622 000	3 622 000
Power block Delta 20 kW	4	20	227 500	910 000
Power control box Delta	1	20	565 500	565 500
Storage battery Delta 200 Ah	40	10	43 000	1 720 000
Automatic transfer switch	1	20	478 800	478 800
Total				7 296 300

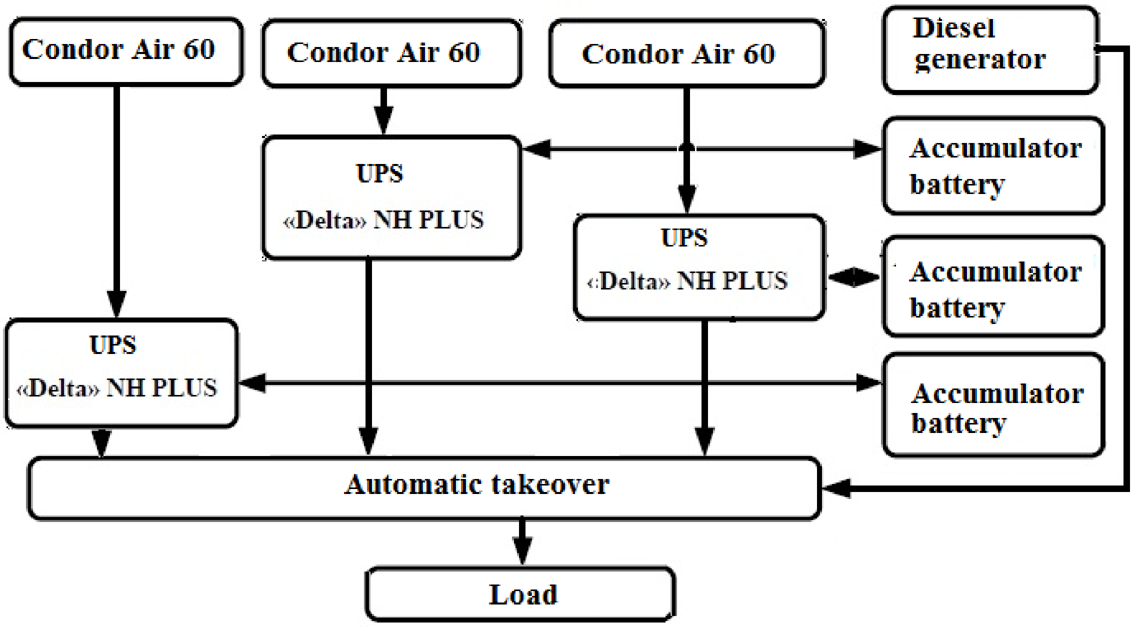

Figure 15 – Example of scheme of power supply with 3 wind turbines

We need to choose amount of wind turbines, all equipment in Table 18 given for one set of wind turbine. From Figure 16 it is clear, that increasing of rated power leads to increasing generated power and amount of wind turbines more than 3 in several month lead to excess of generated power in particular month. We can calculate how much fuel we will need after installing different amount of turbines. For scheme without wind turbines annual consumption is 165 275 l of fuel.

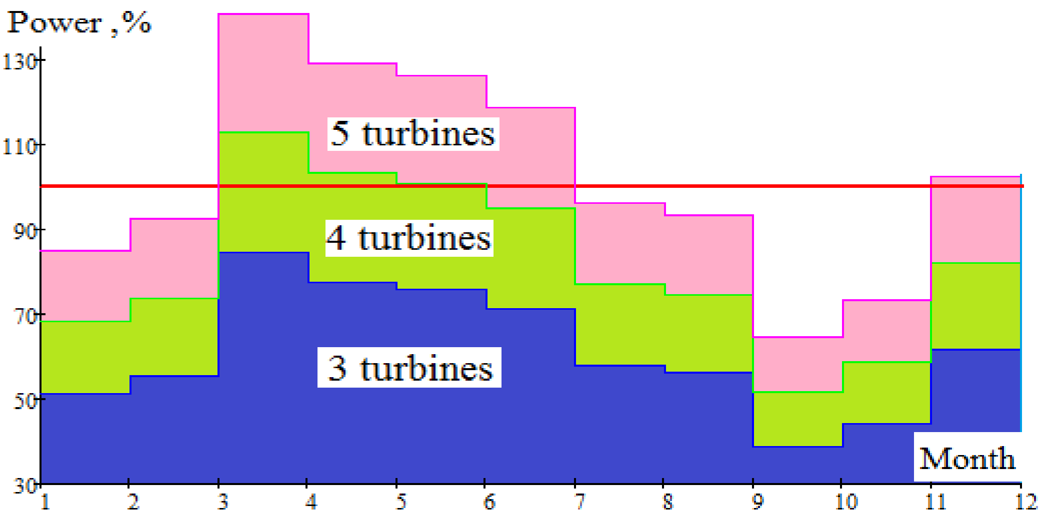

Figure 16 – Power consumption and production of power by different kind of turbines

Every turbine will produce energy and substitute production by diesel generators. It leads to decreasing of duration of operation, cost for maintenance and influence on value of depreciation. Table 19 represents numerical decreasing of these parameters.

Table 19 – Influence of wind turbine on diesel generators operation

Amount of wind turbines	0	3	4	5
Fuel consumption, l	165 275	64 346	37 860	24 862
Duration of operation, h	9 646	3 755	2 210	1 451
Cost of maintenance, RUB	546 344	212 705	125 152	82 185
Depreciation, RUB	371 371	144 584	115 500	115 500

In accordance with the current legislation in the field of tariff formation in electric power in the coverage area of the guaranteeing supplier establishes uniform tariffs for electricity regardless of the source of generation. Thus, the average tariff is formed by mixing tariffs centralized and decentralized energy supply zones. Average tariff will not cover expenses in decentralized area and we need to calculate value of subsidy.

Calculation of scheme with diesel generators

We can accept that company which will supply the settlement need to have discount rate equal to 10%. Lifetime of this project is 6 years. According to calculations of scheme with diesel generators (appendix 3) value of subsidy is equal to 10 599 712 RUB, COE is equal to 21,44 RUB/kW h.

Calculation of scheme with wind turbines

Lifetime of this project is 20 years. We can calculate NPV with different amount of wind turbines.

Table 20 – Dependence NPV on amount of turbines when discount rate 10%

Amount of wind turbines	3	4	5
NPV, RUB	16 288 149	17 856 064	14 884 341

As we may see, the best option is usage 4 turbines.

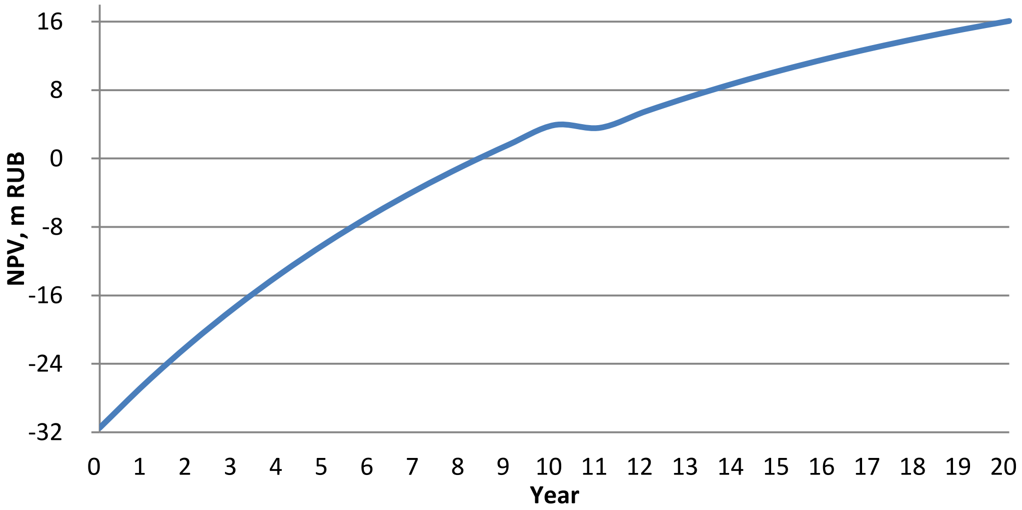

Figure 17 – Dependence NPV on year

Table 21 – Main economical parameters of scheme with 4 turbines

NPV, RUB	17 856 064
COE, RUB	13,12
IRR, %	17,46%
Payback period, years	8,3
PI	2,57

4.4. Sensitivity analysis

A sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions. In other words, sensitivity analyses study how various sources of uncertainty in a mathematical model contribute to the model's overall uncertainty. [28]

The most important parameters of our model:

1. Investment.
2. Fuel price.
3. Percentage of load coverage by wind turbines.
4. Discount rate.

Tornado diagram represents factors which have the biggest contribution to changes of NPV. As we may see the highest impact to changing NPV have discount rate and investments.

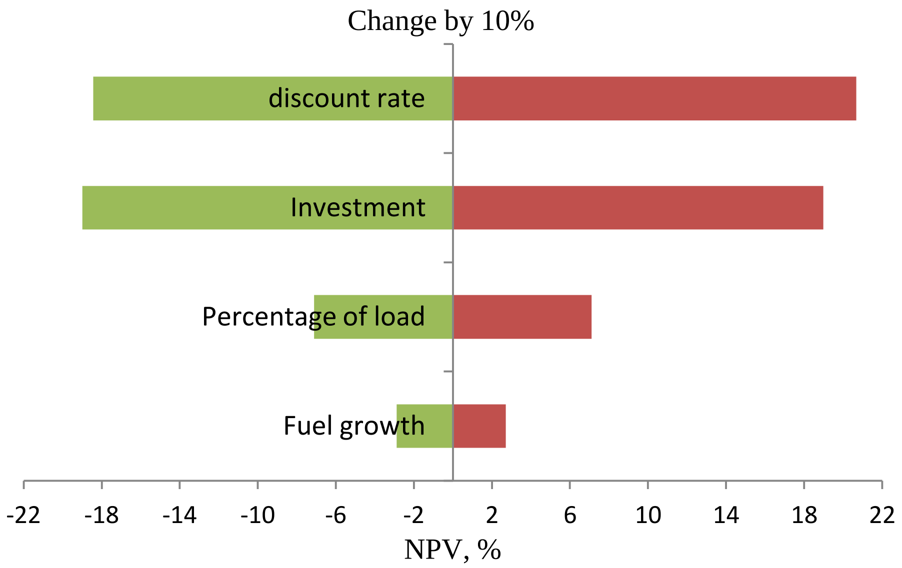

Figure 18 – Tornado diagram

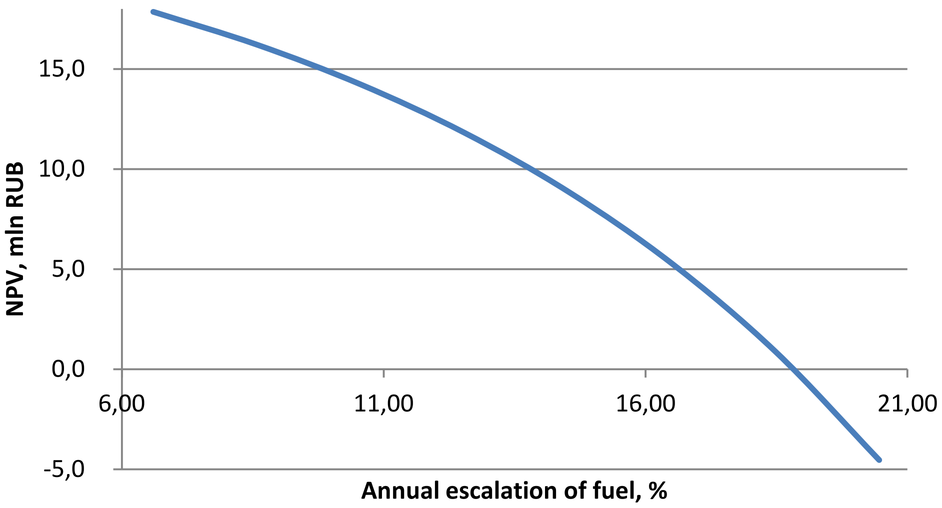

Figure 19 – Dependence NPV from annual escalation of fuel

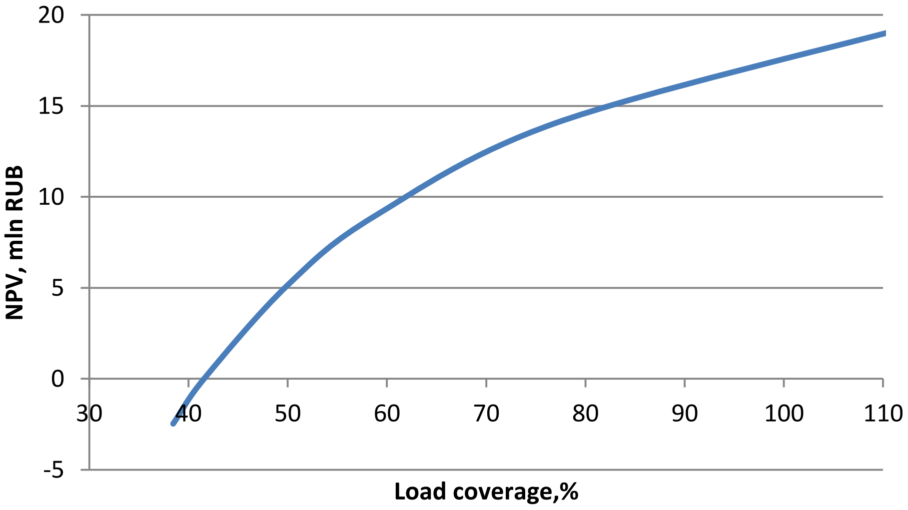

Figure 20 – Dependence NPV from load coverage

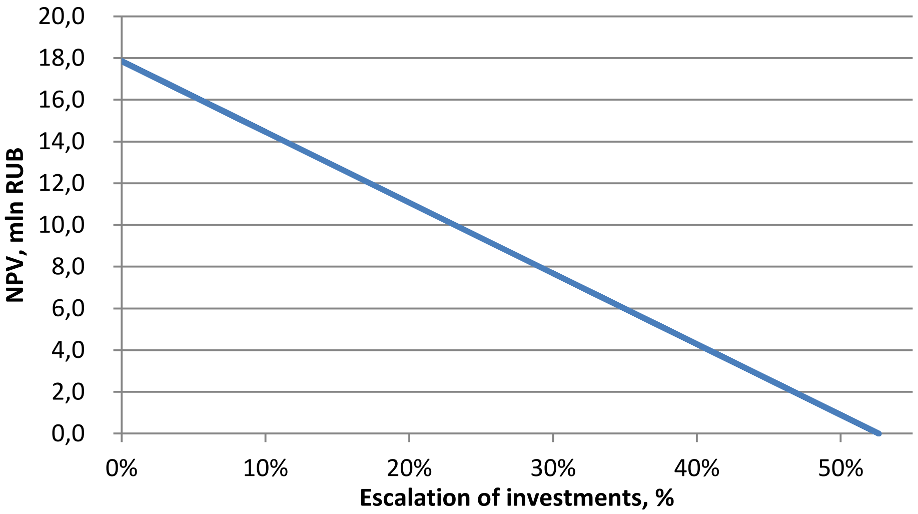

Figure 21 – Dependence NPV from escalation of investments

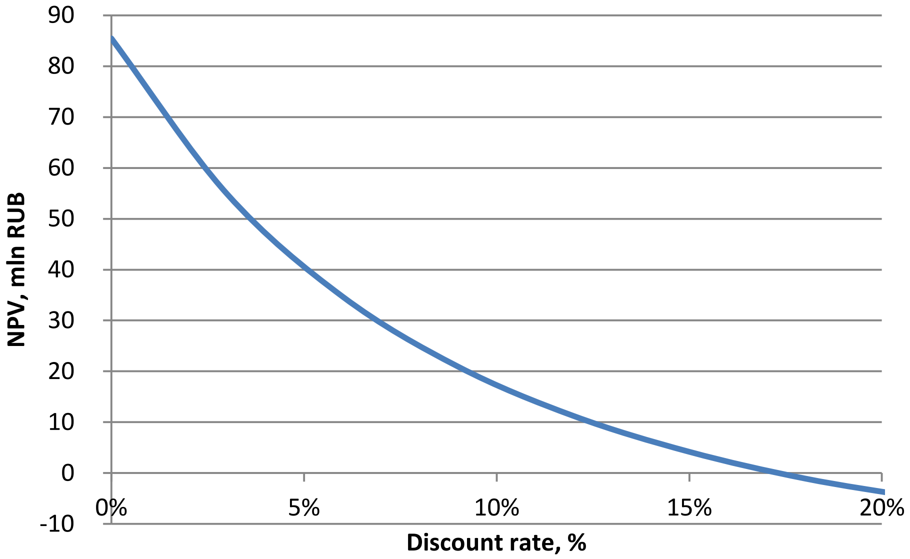

Figure 22 – Dependence NPV from discount rate

Table 22 – Critical parameters of economical model

Parameter	Value
Fuel escalation, %	16,4
Investment,%	52,3
discount rate, %	17,4
Percentage of load, %	41,8

CONCLUSION

In this paper I designed wind-diesel power supply system based on DPP in the Khorey- Ver village. Average wind velocity in the region is equal to 4,2 m/s. I chose 4 types of wind turbines and compared annual output taking into account initial investments- the most efficient option is CONDOR AIR WES 380/50-60 with nominal power 60 kW. Efficient scheme should include also storage of energy, which can be charged when I will have excess of energy output. For sustainable operation I need UPS DPH series 20-80/120 V which can charge storage of energy when in the case of excess of energy or take energy from batteries in the case of lack of energy production by wind turbines. When output from wind turbines is low and storage of energy discharged automatic takeover switch on diesel generators.

According to calculations, the most efficient variant is 4 wind turbines. Application of wind turbines with such numbers reduced fuel consumption from 142 to 33 ton annually.

Tariff in Nenets Autonomous Okrug is 3,71 RUB/kWh. Cost of energy in Khorey-Ver is 21,44 RUB/kWh, people pay less than cost of energy, government subsidy is 17,43 RUB for every kWh. After integration of wind turbines cost of energy is reduced from 21,44 to 13,12 RUB/kWh. Payback period of the project is 8,3 years.

I analyzed sensitivity of NPV from discount rate, escalation of investments, coverage of energy by wind turbines and fuel escalation. The highest contribution to NPV have discount rate and escalation of investments.

List of references

1. Lukutin B.V. Vozobnovlyayemye istochniki elektroenergii. [Renewable energy sources] Education guidance. Tomsk: Tomsk Polytechnic University, 2008. - 187 p.
2. Data of wind flow for 10 years for chosen object https://rp5.ru.accessed 15.10.2019.
3. Lukutin B.V., Muravlev I.O., Plotnikov I.A. Sistemy elektrosnabzheniya s vetrovymi i solnechnymi elektrostantsiyami [Power supply systems with wind and solar power plants]. Education guidance. Tomsk: Tomsk Polytechnic University 2015. – 128 p.
4. Klimova G.N. Elementy energosberezheniya v elektrosnabzhenii promyshlennykh predpriyatiy [Elements of energy saving in the power supply of industrial enterprises]. Education guidance. Tomsk: Tomsk Polytechnic University, 2008.
5. Catalog of diesel generators https://www.allgen.ru/ctg/ accessed 18.11.2019.
6. Location of Khorey-Ver village in a map https://www.google.com/maps/ accessed 18.11.2019.
7. Berdin V.KH., Kokorin A.O., Yulkin G.M., Yulkin M.A. Vozobnovlyayemyye istochniki energii v izolirovannykh naselennykh punktakh Rossiyskoy Arktiki [Renewable energy sources in isolated settlements of the Russian Arctic]. World wildlife fund (WWF), 2017. – 80 p.
8. Producer of diesel generators about factors of fuel consumption https://www.comd.ru/about-company/press-center/articles/raskhod-topliva-dizelnogo-generatora/ accessed 24.11.2019.
9. Order of the Ministry of energy 30.12.2008 No. 323 [About calculation of fuel consumption of heaters and DPP].
10. Lukutin B. V., Shandarova E. B. Ways of decrease in fuel consumption of diesel power station. Tomsk: Tomsk Polytechnic University Tomsk.
11. B.V. Lukutin, E.B. Shandarova, D.L. Matukhin1, A.A. Igisenov1 and S.M. Shandarov. Simulation and optimization of wind and diesel power supply systems. Tomsk: Tomsk Polytechnic University.
12. Distributor of wind turbines in Russia, catalog https://romanov-motors.ru/katalog/vetroenergetika/vetrogenerator-vetrox.
13. Gary L. Johnson. Wind Energy Systems. Kansas State University, 2006- 449 p.
14. Sathyajith Mathew. Wind Energy Fundamentals, resource analysis and economics. 246 p.
15. J. F. Manwell and J. G. McGowan. Wind energy explained: theory, design and application. Second Edition. Department of Mechanical and Industrial Engineering,University of Massachusetts, USA, 2009, 689 p.
16. Brealey, Richard A. Principles of corporate finance / Richard A. Brealey, Stewart C.

Myers, Franklin Allen.—10th ed. 967 p.

17. Inflation in Russia https://fin-plus.ru/info/inflation_index/russia/ accessed 16.03.2020.
18. Tax code of Russian Federation, clause about depreciation: http://www.consultant.ru/document/cons_doc_LAW_28165/ad6e31e62418ce6768a1215342837d033553217e/
19. Tax code of Russian Federation, clause about depreciation: http://www.consultant.ru/document/cons_doc_LAW_28165/ad6e31e62418ce6768a1215342837d033553217e/
20. Dynamic of price for diesel fuel https://yandex.ru/news/quotes/213/20010.html accessed 17.03.2020.
21. S.V. Gatagova. The analysis of pricing dynamics for electricity in Russian Federation depending of it economical development.
22. Expenditures for transportation of wind turbines https://pecom.ru/services-are/shipping-request/ accessed 21.03.20
23. Cost and schedule of maintenance operation of the generator CTG AD- 65SD https://www.allgen.ru/ctg/4908 accessed 23.03.20
24. Distributor of UPS http://www.oc.ru/katalog/ups_online/delta/nh_plus/ accessed 30.03.20
25. Accumulator battery https://www.delta-battery.ru/catalog/gx/delta-gx-12-200/ accessed 01.04.20.
26. Explanation of term depreciation https://www.investopedia.com/terms/d/depreciation.asp.
27. Tariff for electrical energy at chosen region https://energovopros.ru/spravochnik accessed 16.04.20.
28. Sensitivity analysis https://www.investopedia.com/terms/s/sensitivityanalysis.asp accessed 24.04.20.

APPENDICES

Appendix 1. Technical parameter of wind turbine «CONDOR AIR WES 380/50-60»

Diameter of wind wheel, m	17.5
Height of blade, m	8.5
Nominal number of rotations, rotations/min	25-30
Nominal power, kW	60
Maximal power, kW	62.5
Start wind velocity, m/s	2.5
Nominal wind velocity, m/s	9
Operating wind velocity, m/s	3-20
Hurricane wind protection	Automatic
Automatic wind orientation	Yes
Tower height, m	18
Wind installation weight (without tower), kg	2400
Number of blades	3
Wind usage efficiency factor	>0.42
Generator type	Three-phase generator with permanent magnets
Generator frequency, Hz	0-50
Generator current	Alternative
Nominal voltage, V	170- 420
Nominal current, A	100
Maximal current, A	110
Inverter characteristics	Depends on system characteristics
Recommended number of batteries	40
Recommended capacity of batteries, A*h	200
Converting system efficiency	>0.85
Noise level not more, Db	65
Limit of wind velocity, m/s	35

Appendix 2. Technical Specification delta UPS DPH series 20- 80/120 V

Input parameters	
Nominal voltage	380 V/ 220 AC
Range of input voltage	208 ~ 477 V (phase- phase)
Power factor	> 0.99
Output parameters	
Voltage	380 / 220 V 3 phase
Frequency	50 / 60 Hz
Overload	≤ 125%: 10 minutes
	≤ 150%: 1 minute
Efficiency	94% Nominal mode
	97% ECO mode
Battery	
Nominal voltage, Vdc	240
Protection from deep discharge	Yes

Appendix 3. Economical model with only diesel generators

Year	**0**	**1**	**2**	**3**
Investment	-2 310 000			
Depreciation		385 000	385 000	385 000
Maintenance		546 344	578 688	612 946
Salaries		3 931 200	4 163 927	4 410 432
Fuel		7 827 176	8 343 770	8 894 458
Revenue		2 196 320	2 433 523	2 696 343
Subsidy		10 599 712	11 227 215	11 891 867
Expenses		12 689 720	13 471 384	14 302 836
EBT		106 312	189 354	285 374
Tax, 20%		21 262	37 871	57 075
CF		470 050	536 483	613 299
Real CF		443 778	478 189	516 105
NPV	-2 310 000	403 435	395 198	387 758
Year	**4**	**5**	**6**	
Investment				
Depreciation	385 000	385 000	385 000	
Maintenance	649 232	687 667	728 377	
Salaries	4 671 529	4 948 084	5 241 010	
Fuel	9 481 493	10 107 271	10 774 351	
Revenue	2 987 548	3 310 203	3 667 705	
Subsidy	12 595 865	13 341 540	14 131 359	
Expenses	15 187 254	16 128 022	17 128 738	
EBT	396 159	523 722	670 327	
Tax, 20%	79 232	104 744	134 065	
CF	701 927	803 978	921 261	
Real CF	557 674	603 051	652 402	
NPV	380 899	374 447	368 264	
Total NPV	0	COE, kW*h	21,44	

Appendix 4. Economical model with integration of diesel generators

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Investment	-31 495 200						
Depreciation		1 918 760	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760
Maintenance		125 152	132 561	140 409	148 721	157 525	166 851
Salaries		3 931 200	4 163 927	4 410 432	4 671 529	4 948 084	5 241 010
Fuel		1 793 807	1 912 198	2 038 403	2 172 938	2 316 352	2 469 231
Revenue		2 196 320	2 433 523	2 696 343	2 987 548	3 310 203	3 667 705
Subsidy		10 599 712	11 227 215	11 891 867	12 595 865	13 341 540	14 131 359
Expenses		7 768 919	8 127 446	8 508 003	8 911 948	9 340 720	9 795 852
EBT		5 027 114	5 533 292	6 080 206	6 671 466	7 311 023	8 003 213
Tax, 20%		1 005 423	1 106 658	1 216 041	1 334 293	1 462 205	1 600 643
CF		5 940 451	6 345 394	6 782 925	7 255 932	7 767 579	8 321 331
Real CF		5 608 432	5 655 912	5 707 989	5 764 761	5 826 340	5 892 844
NPV	-31 495 200	5 098 574	4 674 307	4 288 496	3 937 410	3 617 699	3 326 357
Total NPV	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Investment					-12 952 277		
Depreciation	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760
Maintenance	176 728	187 190	198 272	210 010	222 442	235 611	249 559
Salaries	5 551 278	5 879 914	6 228 004	6 596 702	6 987 227	7 400 871	7 839 003
Fuel	2 632 200	2 805 925	2 991 116	3 188 530	3 398 973	3 623 305	3 862 443
Revenue	4 063 817	4 502 710	4 989 002	5 527 814	6 124 818	6 786 299	7 519 219
Subsidy	14 967 936	15 854 038	16 792 597	17 786 719	18 839 692	19 955 002	21 136 338
Expenses	10 278 966	10 791 789	11 336 153	11 914 002	12 527 402	13 178 547	13 869 765
EBT	8 752 787	9 564 958	10 445 446	11 400 531	12 437 108	13 562 754	14 785 792
Tax, 20%	1 750 557	1 912 992	2 089 089	2 280 106	2 487 422	2 712 551	2 957 158
CF	8 920 990	9 570 726	10 275 117	11 039 185	-1 083 831	12 768 963	13 747 394
Real CF	5 964 407	6 041 171	6 123 293	6 210 939	-575 710	6 403 538	6 508 887
NPV	3 060 684	2 818 251	2 596 874	2 394 586	-201 783	2 040 364	1 885 393
Total NPV	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Investment							
Depreciation	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760	1 918 760
Maintenance	264 333	279 982	296 556	314 113	332 708	352 404	373 267
Salaries	8 303 071	8 794 613	9 315 254	9 866 717	10 450 827	11 069 516	11 724 831
Fuel	4 117 365	4 389 111	4 678 792	4 987 592	5 316 773	5 667 680	6 041 747
Revenue	8 331 295	9 231 075	10 228 031	11 332 658	12 556 585	13 912 696	15 415 267
Subsidy	22 387 609	23 712 956	25 116 763	26 603 675	28 178 613	29 846 787	31 613 716
Expenses	14 603 529	15 382 466	16 209 363	17 087 182	18 019 069	19 008 361	20 058 605
EBT	16 115 375	17 561 565	19 135 431	20 849 151	22 716 129	24 751 122	26 970 378
Tax, 20%	3 223 075	3 512 313	3 827 086	4 169 830	4 543 226	4 950 224	5 394 076
CF	14 811 060	15 968 012	17 227 105	18 598 081	20 091 663	21 719 658	23 495 063
Real CF	6 620 557	6 738 780	6 863 802	6 995 884	7 135 303	7 282 349	7 437 332
NPV	1 743 400	1 613 210	1 493 763	1 384 098	1 283 347	1 190 722	1 105 512
Total NPV	17 856 064	COE, kW*h	13,12				