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FACULTY OF ELECTRICAL ENGINEERING

Department of Economics, Management and Humanities

Hybrid Power Supply in the Koyda Village

Study Program: Electrical Engineering, Power Engineering and Management

Field of Study: Economy and Management of Power Engineering

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V PRAZE

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní program: **Electrical Engineering, Power Engineering and Management**
Specializace: **Management energetiky a elektrotechniky**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Hybrid power supply in the Koyda village

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Hybrid power supply in the Koyda village

Pokyny pro vypracování:

1) Analysis of renewable energy sources in the region.
2) Integration of renewable energy sources with diesel generators.
3) Modeling of wind turbine generator in MATLAB Simulink.
4) Techno-economic analysis of hybrid wind-diesel power plant.

Seznam doporučené literatury:

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LUKUTIN, B.V., MURAVLEV, I.O., PLOTNIKOV, I.A. Sistemielektrosnabzheniya s vetrovimiisolnechnimielektrostanciyami [Power supply systems with wind and solar power plants]. Tomsk: Tomsk Polytechnic University, 2015.

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání

Podpis studenta

Declaration:

I hereby declare that this master's thesis is the product of own independent work and that I have clearly all information sources used in the thesis according to Methodology 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 thesis is to integrate renewable energy sources in villages on the arctic side. Most of locations on the arctic side in Russia are not connected to the central network system and have expensive power supplied by diesel generators. These locations, for example, the Koyda village, have rich wind energy potential. So, integration of wind turbines with diesel power system may decrease energy cost. In this master thesis, I research renewable energy potential in the Koyda village, consider integration of wind turbines with diesel power plant, simulate the hybrid power plant in MATLAB Simulink and make techno-economic analysis. I suggest obtaining more cost efficient power plant. After analysis of diesel power plant in the Koyda village and climate conditions I decided to upgrade the power plant with two wind turbines with capacity 60 kW each. It can decrease diesel fuel consumption from 79.5 ton to 22 ton a year.

Key words

Renewable energy sources, wind turbine, hybrid power plant, MATLAB Simulink, economic analysis.

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List of Abbreviations

CF – Cash Flow

DC – Direct Current

FEC – Fuel and Energy Complex

INV – Investment

IRR – Internal Rate of Return

NPV – Net Present Value

PV – Photovoltaic

RES – Renewable Energy Sources

RPM – Rotate Per Minute

RUB – Ruble

SB – Storage Battery

WT – Wind Turbine

1. Introduction

Nowadays the environmental problems such as global warming and air pollution have a global scale. The stock of fossil fuels like gas, coal and oil is diminishing every year. These factors touch all counties in the world and because of that the “green” power engineering is developing. “Green” power engineering uses renewable energy sources: sun, wind, water flow, geothermal source and energy of bio-fuel.

Full or fractional changeover to the renewable energy sources has a range of economic and ecological advantages. According to [1] this range includes:

- Speed-down the growth of negative anthropomorphic impact on the environment and preventing climate change taking in account necessity to satisfy the growing energy needs.
- Reducing of air pollution in the way of decrease the fossil fuel burning. Therefore, there will be heath maintenance of the population, decrease breathing system diseases risk, decrease state spending on health maintenance.
- Increase the supply decentralization, therefore its safety and reliability will increase.
- Decrease costs on transmission and distribution of power and fuel and also losses in these processes [1].

In this master’s thesis, I analyze geography of the Arkhangelsk Region and the Koyda village where the power plant is proposed to be build. The geographical analysis includes:

- Evaluation of climate conditions
- Evaluation of solar energy potential
- Determining of wind power characteristics on the territory

After studying natural conditions I analyze consumers’ characteristics. Based on these characteristics I will choose the corresponding equipment for power plant. Next, I will design the hybrid power plant and analyze its economic effectiveness. The electric scheme of power plant will be modeled in MATLAB Simulink.

2. Renewable energy sources in the region

The main energy generators in Russia are thermal power plants. They generated 622.4 billion kWh of total 1073.7 billion kWh in 2017. Next are nuclear power plants with its generation billion 202.9 kWh and hydro power plants with its generation 187.4 billion kWh. The own power plants of industrial factories generated 60.3 billion kWh. The renewable power plants generated only 0.69 billion kWh in 2017 [2]. As we can see, the part of renewable energy generation takes only 0.06% of all energy when thermal power plants generate 57.97% of all energy. The fuel mining and energy producing, transmission, distribution and consuming system is called fuel and energy complex (FEC). In economy of Russia it still takes the leading position. The complex produces about 25% of industrial production in Russia. FEC includes spheres of fuel industry (oil, gas, coal, schist, peat) and electric power industry. All spheres of the complex are related with each other. To account common volume of mined fuel and energy generation, its ratio, distribution between consumers the fuel-energy balance is plotted. It shows mining ratio of different kinds of fuel and generated power and its usage in industry. To calculate the balance, the different kinds of fuel are recalculated into indicative fuel. For 1 unit of indicative unit 1 kilogram of coal that gives 7000 kcal in burning is used. The FEC structure of Russia always changes. Before the 1970s the main part took coal. In 1970–1980s the main part took oil. In 1990s the main part took natural gas [3].

Nowadays, the part of renewable energy generation in Russia is very small but it has a great potential. The outlook of cost-efficient renewable energy usage in Russia consists more than 30% of annual power consuming. However current part of renewable energy is only 0.06%. To compare, Germany generated 151.57 billion kWh with renewable power plants in 2017. It is 37.5% of all generated power [4].

Regardless of there is dramatic renewable energy potential in Russia, the government started to be interested recently in this issue. The Order of the Government of the Russian Federation in 2013 put forward the priority of increasing the volume of production and consumption of electric energy using renewable energy sources to 2.9% to 2020.

The low level of renewable energy development is due to several reasons. The main reason is Russia since 1960 developed only traditional energy sources – coal, fuel and gas. The government orientated on producing and export of traditional energy resources. There were established fundamentals of renewable energy development in conditions of 1970s energy crisis in west Europe countries-importers of energy resources. The overstock of energy resources did not induce Russia to pay attention to this issue.

Russian government plans on increasing of renewable energy part has few brakes:

1. Relatively low prices on energy resources and electricity;
2. Oil and gas priority as the main energy resource in the inside consumption;
3. The lack of ecological pressure on government from society;
4. The lack of interested in renewable energy development companies in politic and economic fields.

The government interest of renewable energy development related with necessity to develop far regions of the country. About 10% of Russian population has not access to central power and heat supply. The installation of wind power plants in the regions on Atlantic coast or PV power plants in the Altay region is more cost-effective than shipping the fuel by sea or building up network system.

2.1 Description of the Koyda village

The Koyda village is located on the north of Arkhangelsk region in the Mezenskiy district in Russia. Its population is 478 people, according to data of 2017 year [5]. Nowadays, the village receives electric energy from diesel generators only. Its total capacity is 360 kW. The fuel is shipped by sea [6]. Integration of renewable energy sources in the power supply system will help to decrease costs on fuel and will decrease CO_2 emission. The Koyda village is presented on the map and a satellite shot of the Koyda village from Google Maps in Figure 1.

Figure 1 – Location of the Koyda village [7]

There are no rivers with dramatic water flow in the Koyda village, so, next, I will analyze solar and wind energy potential in the region.

2.2 Potential of solar energy in Koyda

I take the data about Archangelsk because it is the nearest point to the Koyda village where the data exists. According to “www.solbat.su” the year insolation of Arkhangelsk is 0.815 MW/m^2. The monthly insolation data are in the Table 1.

Table 1 - Monthly insolation in Arkhangelsk [8]

Month	Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sept	Oct	Nov	Dec
Insolation, MJ/m^2	12	61	207	356	494	575	565	385	186	71	20	4
Insolation, kWh/m^2	3.3	16.9	57.5	98.9	137.2	159.7	156.9	106.9	51.7	19.7	5.6	1.1

One MJ/m^2 is equal to (1/3.6) kWh/m^2. According to [1], the photovoltaic power plant will be effective if the yearly insolation per square meter is more than 1000 kWh. If we calculate the annual insolation in the Koyda village presented in Table 1 than we will obtain 815.4 kWh/m^2. This number is less than 1000 kWh, therefore it is not efficient to install solar power plant in the Koyda Village.

2.3 Potential of wind energy in Koyda

There is monthly average wind velocity in Table 2. The data are from the website of weather schedule accessible from “www.rp5.ru”.

Table 2 – Monthly wind velocity in Koyda [9]

Month	Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sept	Oct	Nov	Dec
Wind velocity, m/s	7.19	6.47	7.08	6.53	5.98	5.31	4.23	5.05	5.52	5.25	5.75	6.00

Repetition of wind velocities is an important power characteristic. It shows how many times in a month or year the same velocity was. The data of wind potential allocation are presented in Table 3.

Table 3 – Distribution of wind velocity over time [9]

Wind velo-city, m/s	Jan, %	Feb, %	Mar, %	Apr, %	May, %	Jun, %	Jun, %	Aug, %	Sept, %	Oct, %	Nov, %	Dec, %	Year %
0-2	4.42	0.87	0.77	0.77	4.44	2.77	6.59	6.01	2.93	5.81	1.65	0.88	3.13
2-4	10.84	11.74	5.36	10.81	15.32	22.1	29.84	24.03	25.10	20.75	8.23	10.96	16.08
4-6	14.06	26.09	19.92	22.39	26.61	30.8	31.40	32.19	28.03	28.63	37.86	26.75	26.72
6-8	21.69	32.17	39.85	36.29	23.39	24.5	24.81	24.89	18.41	26.56	36.21	42.11	29.95
8-10	28.51	13.91	14.18	13.13	20.56	13.0	6.20	8.58	15.06	12.45	11.11	13.60	14.06
10-12	10.04	9.57	12.64	13.13	8.06	5.93	1.16	3.43	8.79	4.56	3.29	3.07	6.97
12-13	6.43	5.22	5.36	2.32	1.21	0.79	0	0.86	1.26	1.24	1.23	1.32	2.25
14-15	4.02	0.43	1.92	1.16	0.4	0	0	0	0.42	0	0.41	1.32	0.84

There are 8760 hours in a year. To plot the graph of wind velocity distribution it is necessary to multiply values from the last column in Table 3 by 8760. The graph is presented in Figure 2.

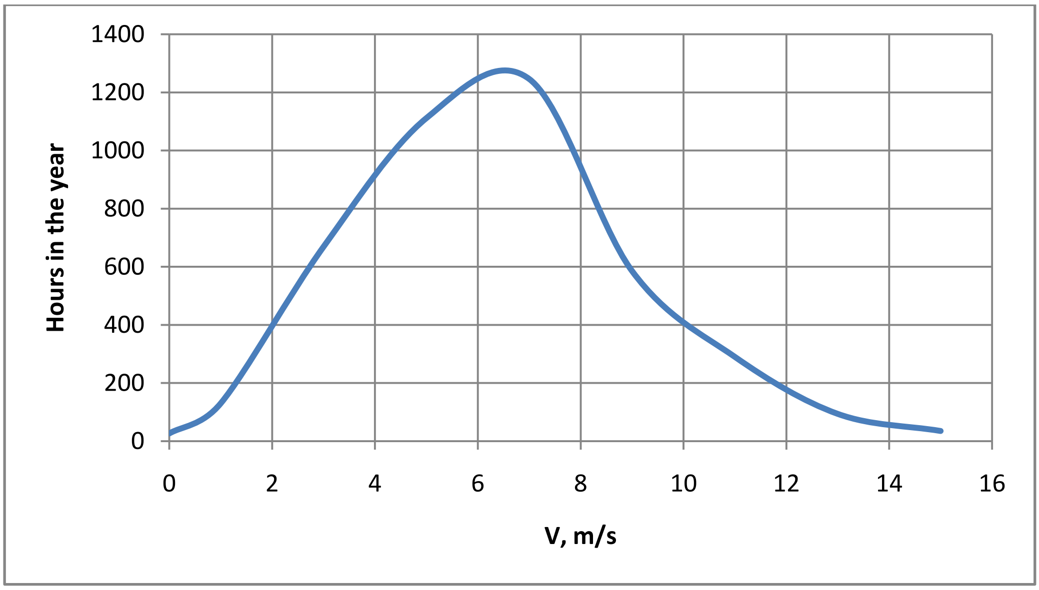

Figure 2 – Distribution of wind velocity over time

According to [1], the wind power plant will be effective if the yearly average wind velocity is more than 4 m/s. The yearly average wind velocity in the Koyda village is 5.86 m/s.

Efficiency of wind power plant also related with area landscape. Wind power plant should have a clear, smooth fetch to the prevailing wind, over open water, smooth ground or on a smooth hill [10]. The Arkhangelsk Region represents wide lowland. It has the low-hill terrain with height up to 450 meters in the east and the chain of hills with height up to 350 meters in the west [11]. The Koyda village is situated in the north. Therefore, there are no any barriers for wind and it is justified to build here a wind power plant.

3. Possible configurations of hybrid power supply

There are several configurations of hybrid power supply with renewable energy source. Most of them are a combination of renewable energy source and diesel generator. The diesel generator provides consumers with energy when there is lack of energy from RES (for example the wind is weak for wind power plant or at night for photovoltaic power plant). Also the configurations include storage battery. It keeps energy in case when the power plant generates more power than consumer needs. Next, I will describe every configuration in detail.

3.1 Stand-alone renewable power plant

Due to variable characteristics of energy consumption graphics and energy potential of RES, the configuration must include device for energy storage. The common structure of stand-alone wind and solar power plants is presented in Figure 3.

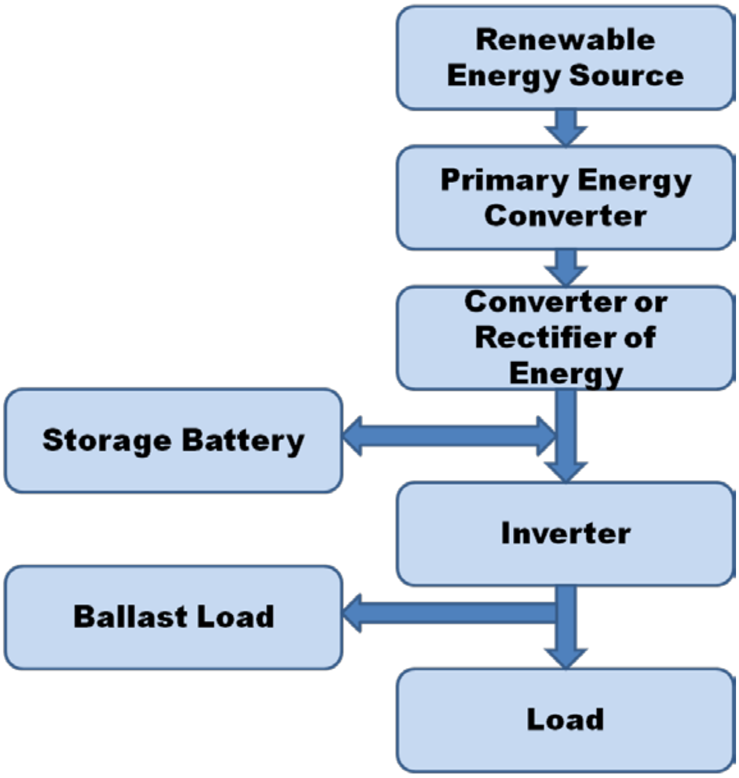

Figure 3 – Stand-alone renewable power plant [1]

Primary energy converter in this configuration is a wind turbine or a PV panel. It converts the energy of wind or the sun into electrical energy. We need the converter or rectifier of energy to make the voltage direct and equal to nominal of storage battery. The storage battery supplies the load through the stand-alone inverter. The inverter converts direct current to alternative. We need it because the most consumers use alternative current. Peak load power is determined by the power of battery and inverter. Average load power in the time period is determined by positive power balance of the battery, when its energy received from RES is more than energy transmitted to the load (taking into account efficiency coefficients and effective modes of power equipment, first of all – storage batteries). Ballast load takes extra power that the load and storage battery do not need in the current time period.

Power plant needs an intelligent control system to provide energy-effective mode for the equipment.

Power supply of decentralized districts only by RES is impossible because of dramatic daily wind and solar potential changes, those usually do not correspond to seasonal and daily changes of power consumption graphs. Field of use such configurations is limited of consumers with load less than 1 kW.

3.2 Hybrid power plant with diesel power installation

Combination of assured energy source – a diesel power installation and a non-stable renewable source let to build multipurpose power plants for decentralized object with sustainable power supply and good technical and economic characteristics.

Power plant configuration with two energy sources, every of which can supply the consumers in determined intervals of time, has maximum opportunities to change diesel energy generation to renewable energy. Reduction of diesel part work time provides the maximum fuel economy and increase time of diesel generator exploitation.

The opportunity to turn off the diesel power installation in periods when the renewable energy source has high potential is reached with complicated configuration of hybrid power plant and control algorithms of its units.

The common configuration of the hybrid power plant is in Figure 4.

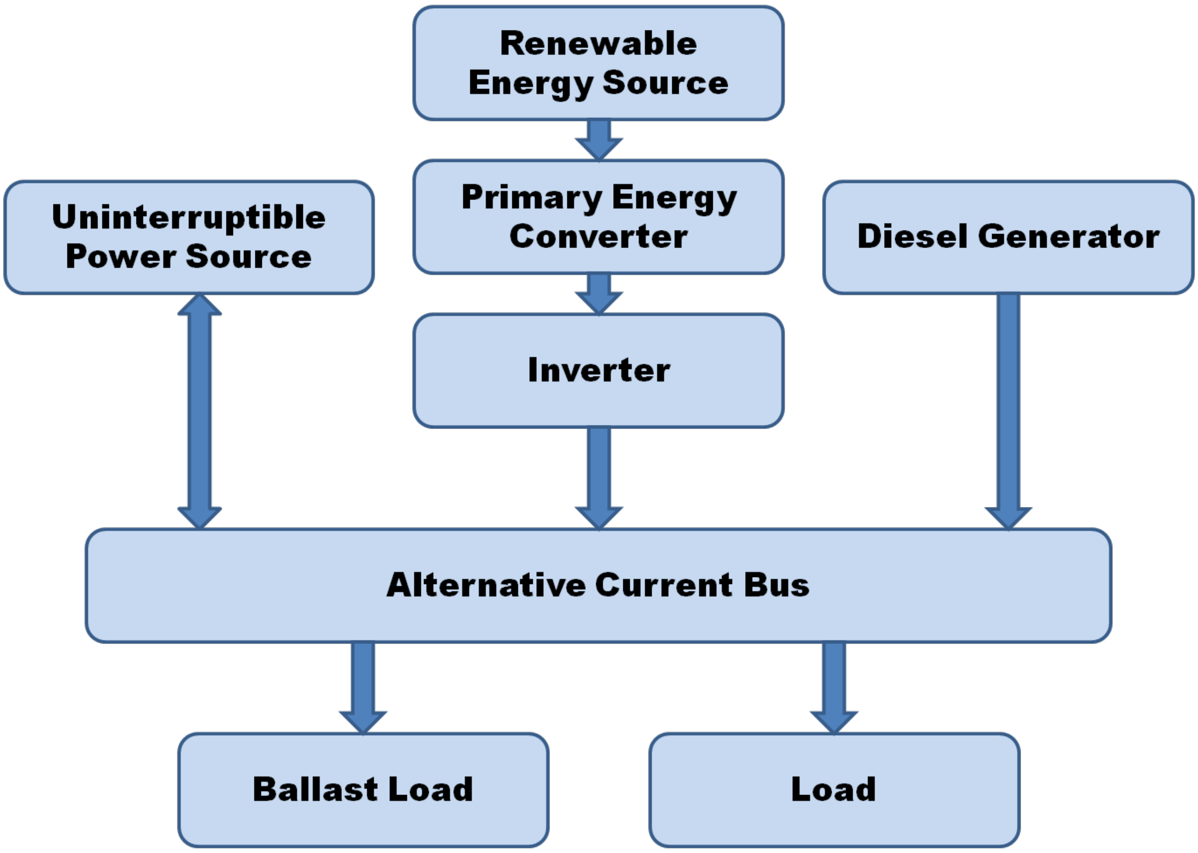

Figure 4 – Hybrid power plant with duplicate diesel power installation [1]

The shown configuration of hybrid power plant allows to combine different power sources in alternative current bus.

In period when the renewable energy source has high potential, the diesel power installation is turned off. Consumption and generation renewable energy distortion are damping by store of energy in batteries of the uninterruptible power source. It allows to decrease amount of starting the diesel power installation.

The energy sources can operate separately or in parallel with common load. It depends on relation between installed capacity of diesel and renewable power plants in hybrid complex.

That separate operation mode means relatively big installed capacity of primal energy converter for renewable energy source. Therefore, instantaneous power of wind or solar power plant can be dramatically more than nominal load. To utilize extra electric energy, there is installed ballast load.

The part of green energy in general power balance of this power supply system is usually more than 50%.

3.3 Hybrid power plant with inverter diesel power installation

In case of low capacity of renewable power plant, the load on diesel power installation increases. If there is lack of power from renewable energy source it makes sense to set parallel operation of renewable and diesel power installations. To perform such mode, it is necessary to improve the control algorithm for hybrid power plant by addition in the configuration next equipment: a multipurpose inverter, which can work as stand-alone and in parallel with network, synchronize devices. The configuration is presented in Figure 5.

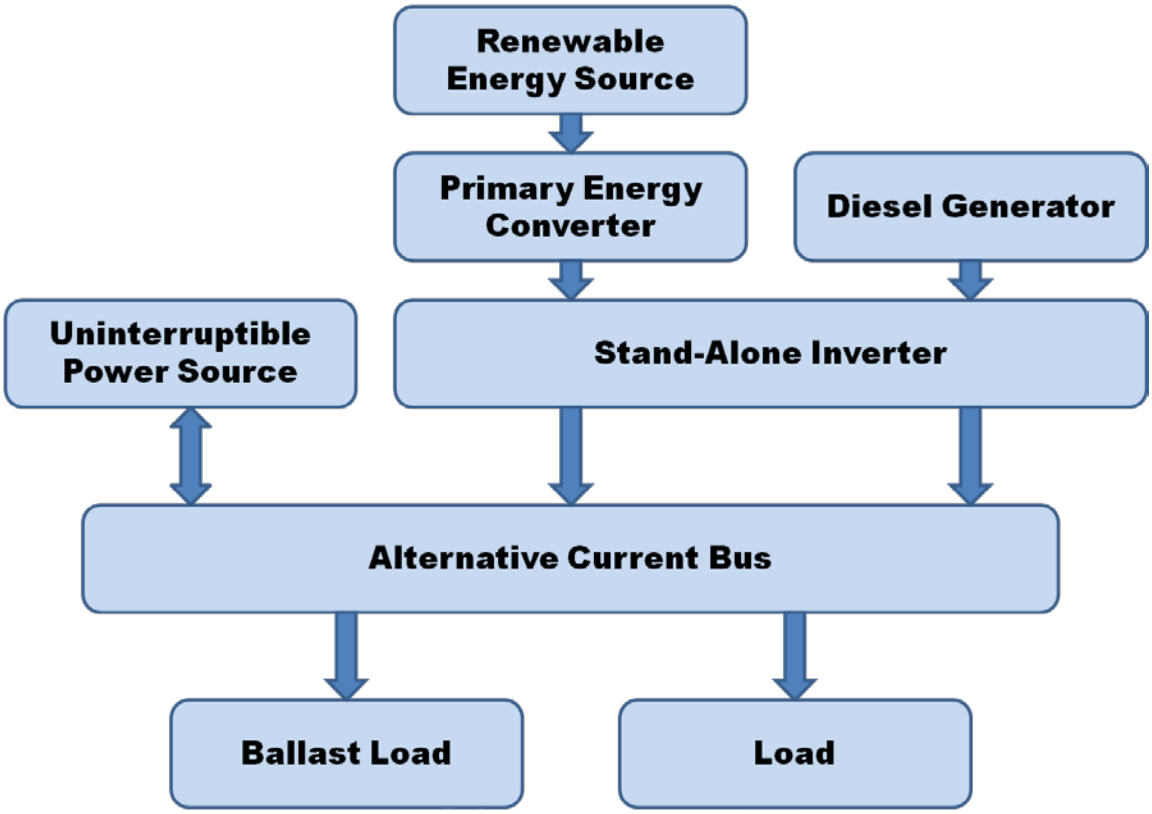

Figure 5 – Hybrid Power Plant with Inverter Diesel power installation [1]

The advantage of an inverter diesel power installation is reducing of fuel consumption during low load modes due to reducing of diesel generator rotation frequency.

3.4 Hybrid power plant with direct current bus

Usually, in hybrid power plant, the rectifying-inverting frequency converters are used as a voltage converter. The actual wind power plants include such converters. Due to this fact and generation the direct current by photovoltaic panels, it is possible to combine energy source in hybrid power plant based on direct current bus with rectifiers and voltage converters. The configuration is presented in Figure 6.

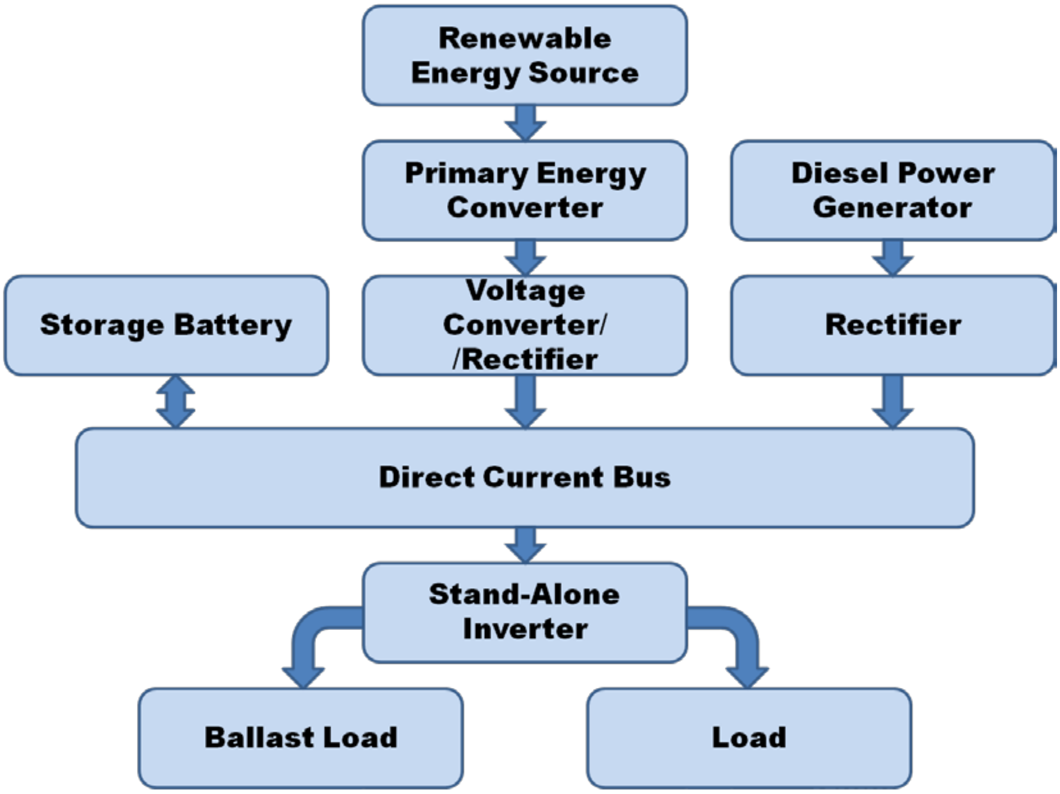

Figure 6 – Hybrid power plant with direct current bus [1]

In case if the renewable source is wind turbine, the installation needs rectifier to convert DC to AC. Rectifiers are used after wind turbine and after diesel generator. In case if the renewable source is PV panel, after panel will be installed voltage converter to convert voltage value to nominal value of storage battery.

4. Designing wind-diesel power plant

Wind energy has been used for several centuries, initially in the form of windmills used to provide power for milling grain and to drain low-lying land in the Netherlands and parts of England. These all but disappeared, however, as cheap electricity from large-scale power plants became widely available around the middle of the century. As we enter the twenty-first century wind power has made a comeback and is currently the most significant source of renewable energy [12].

In this chapter there will be description of equipment that is used in hybrid power plants. There are not only generation installations such as wind turbine and diesel generator, hybrid power plant also need specific equipment such as inverters and converters to transform the energy and distribute it between consumers. Hybrid power plant also needs storage batteries to collect extra energy and supply the consumers in periods of calm weather for wind turbines or at night for photovoltaic panels.

4.1 Wind turbines

Stand-alone wind turbine consists of generator, blades, hub, speed increaser or gear box, controller and tower. The construction of wind turbine is presented in Figure 7. The nacelle is the covering or enclosure. The output of the rotor, rotational kinetic energy, can be converted to electrical, mechanical, or thermal energy. Generally, it is electrical energy, so the conversion system is a generator [13]. General wind turbine has three blades fixed on the rotor. The spinning rotor generates three-phase alternative current that energizes the controller; next the current through the inverter converts into direct current and energizes the battery. The current charges the battery and also uses the battery as a conductor. Next, the current energizes the inverter, where it converts into one-phase current with voltage equal to 220 V and frequency equal to 50 Hz. The load is supplied by wind turbine. If there is not enough energy from wind turbine, the lack of energy is covered by storage battery.

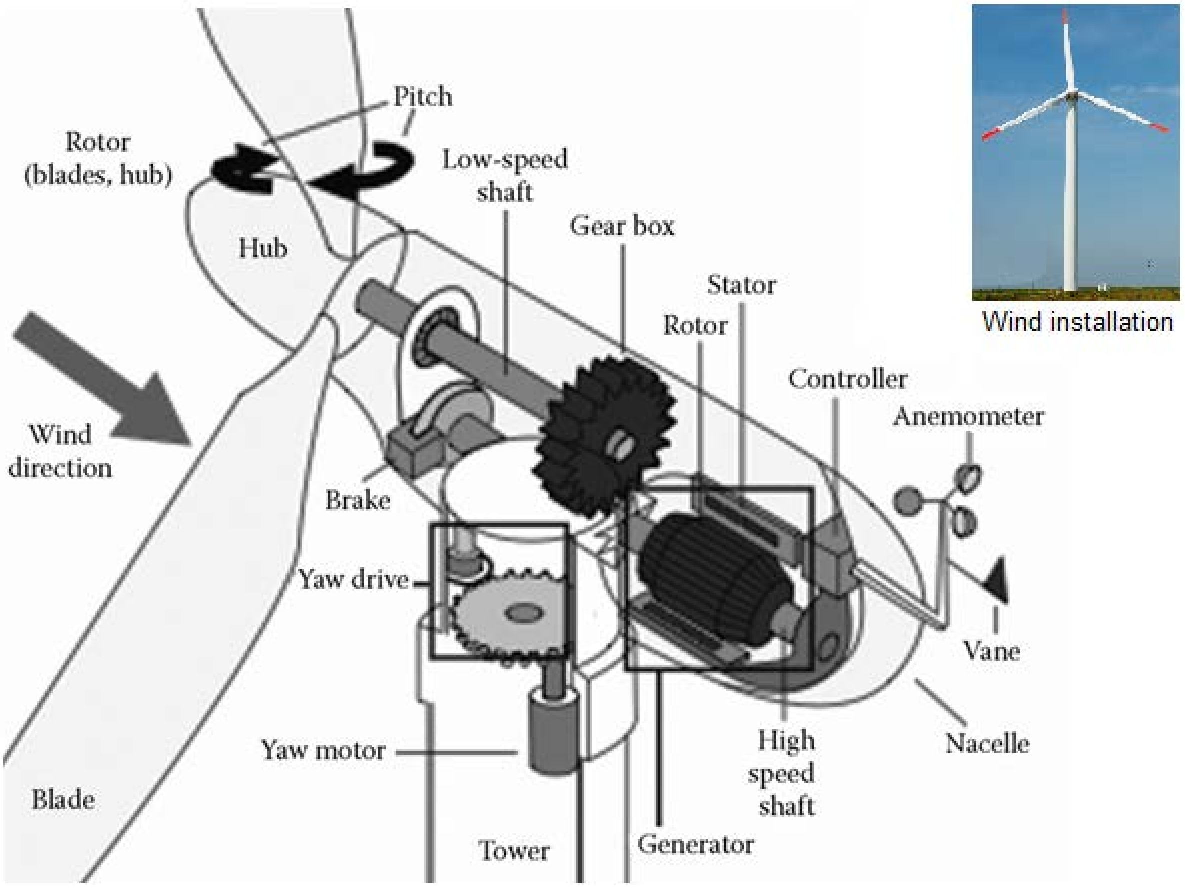

Figure 7 – Scheme of wind turbine components [13]

Cutting-edge wind turbines use the energy of wind effectively. With wind turbines we can not only provide the network with energy but solve power supply issues of local and island objects of any capacity.

Wind turbines may be classified according to following characteristics:

- Rotation axis;
- Number of blades;
- Material of blades;
- Blade pitch.

Rotation axis can be horizontal or vertical. The most widespread are horizontal wind turbines; its rotation axis is parallel to the ground. Construction of horizontal wind turbines allows to rotate the “head” in the direction of wind flow and to change the angle of blades to use weak wind.

Vertical wind turbines are less effective than horizontal. Its blades rotate parallel to the ground with any direction of wind flow. Wind turbine with such construction loses half of its power because half of its blades are rotating against wind. It dramatically reduces energy efficiency of the plant. The advantage of this installation: it is easy to install and serve because gear box and generator are located on the ground. The disadvantages: it is expensive and needs much space.

Horizontal wind turbines more correspond for producing energy in industrial scale. They are use in system of wind power plants. Vertical wind turbines are usually used for small private facilities.

Wind turbines may have different number of blades. Usually, wheel of wind turbine has two blades, three blades and 50 or more blades. The blades may be rigid or canvas. Pitch of the blades may be fixed or veriable.

Because the power in the wind increases so rapidly, all wind turbines must have a way to dump power (not capture power) at high wind speeds. The methods of control are:

1. Change aerodynamic efficiency

- Variable pitch, feather or stall

- Operate at constant RPM

- Spoilers

2. Change intercept area

a. Yaw rotor out of wind

b. Change rotor geometry

3. Brake

a. Mechanical, hydraulic

b. Air brake

c. Electrical (resistance, magnetic)

All of these methods have been used alone or in combination for control in high wind speeds and for loss of load control. There were two vertical-axis wind turbines where they actually changed the rotor geometry; one was a V shape that became flatter in high winds, and the other was a two-bladed gyro-mill where the rotor geometry changed by changing the length of the blades. A blade was designed where the length could be change as the outer part of the blade moved into the rest of the blade.

For control in high winds, most small wind turbines and farm windmills have a tail to yaw the wind turbine out of the wind, to furl the rotor. This operation is also called furling. There are some wind turbines where the rotor is rotated about the horizontal axis for the high wind speed control, rather than yawed about the vertical axis. The results are the same; the intercept area has been decreased.

A pitch control system is one method to control RPM, start up (need high torque), and overspeed. Blades are in the feather position (chord parallel to the wind) during shutdown, and when the brake is released, the feather position provides starting torque, and then the pitch is changed to the run position (pitch angle around 0°) as RPM increases. The blades are kept at the same pitch over a range of wind speeds, the run position. For high wind speeds and overspeed control, the blades are moved to the feather or stall position (blades perpendicular, negative pitch, to wind) to shut the unit down. The pitch can be changed to maintain a constant RPM for synchronous generators. For an induction generator, variable-speed generator, or alternator that operates over a range of RPM in the run position, over this range the tip speed ratio is constant, and the unit operates at higher efficiency.

For fixed-pitch blades, there are two possible operations, constant tip speed ratio (variable RPM), which is the maximum efficiency, and constant RPM. The blade has to have enough twist to produce torque for start-up, or the induction motor/generator starts the rotor at the cut-in wind speed. The constant RPM operation with induction generators means that the maximum efficiency is reached only at the design wind speed. Above rated power, the power output is controlled by the reduced aerodynamic efficiency, called stall control [13].

4.2 Inverters

Inverter is a device which converts DC voltage to AC voltage. The form of voltage can be sinusoidal, close to sinusoidal or pulsed. Inverters are used as stand-alone devices and as a part of uninterruptible power supply systems.

In the actual power converting technologies the inverter is an intermediate link and its function is to convert the voltage with transformation in high frequency (in a score of tens and hundreds kHz). In the inverters the semiconductor switches are used that can conduct currents in the score of hundreds amps, also magnetic cores with special parameters and electronic microcontrollers (including resonance controllers).

The objectives for inverters as for other power devices include: high efficiency factor, reliability, small size and weight. Also inverter must stand permissible level of higher harmonics in the input voltage and not to generate unacceptable high impulse noise for consumers.

In the systems with integrated renewable power source to apply the power directly in the network the Grid-Tie inverters are used. Grid-Tie inverters – are inverters that can perform with industrial network in synchronous mode.

When the voltage inverter works, the DC source periodically connects to the load circuit with alternating polarity. The frequency of connections and its duration is performed with control signal from controller.

The controller in inverter usually performs several functions: output voltage regulation, semiconductor switches work synchronization, protection the circuit from overload. Inverters are divided on two groups: stand-alone inverters (voltage inverters and current inverters) and dependent inverters (followed by network, Grid-Tie).

Semiconductor switches of an inverter are performed by the controller. The switches have reverse shunting diodes. Output voltage, in dependence on current load, is regulated by high-frequency converter block with automatically changing of the pulse width. In the simplest case it is pulse width modulation.

Half-waves of the output low-frequency voltage must be symmetrical so that the load circuits will not receive a significant DC component (it is especially dangerous for transformers). To perform it, pulse width of the low-frequency block is set to constant.

In the controlling of inverter output switches, the algorithm is used, providing serial changing of the power circuit mode: positive, short-circuit, negative.

The load instantaneous power magnitude on the inverter output has character of pulses with doubled frequency, because of that, the primal source must allow this mode, when it conducts pulsed current, and stand corresponding level of the noise (on the inverter output).

The first inverters were mechanical only, but nowadays there are many configuration schemes of inverters with semiconductor base. There are three typical schemes: bridge without transformer, two-cycle with zero output of the transformer, bridge with transformer.

The bridge without transformer is used in devices with capacity more than 500 VA and in the automobile inverters. The two-cycle with zero output of the transformer is used for low-capacity uninterruptible power source (for computers) with capacity up to 500 VA, where the voltage on the back-up battery is 12 or 24 Volt. Bridge scheme with transformer is used in interruptible power sources with high capacity (in score of tens kVA).

In voltage inverters with rectangle form of the signal there is the group of switches with reverse diodes which commutate in the order to provide the circulation of reactive power in the circuit in controlled mode.

Relative width of control pulses or phase shift between control signals of groups of switches provide proportionality of output voltage. In non-controlled mode of reactive power circulation the consumer influence on the form and magnitude of voltage in the output of the inverter.

In voltage inverters with stepped form in the output the initial high-frequency converter forms one-pole stepped voltage curve, roughly closed to sinusoidal form. Its period is equal to half of the period of output voltage. Next, bridge low-frequency scheme convert the stepped curve in two halves of bipolar curve that looks like rough sinusoidal curve [14].

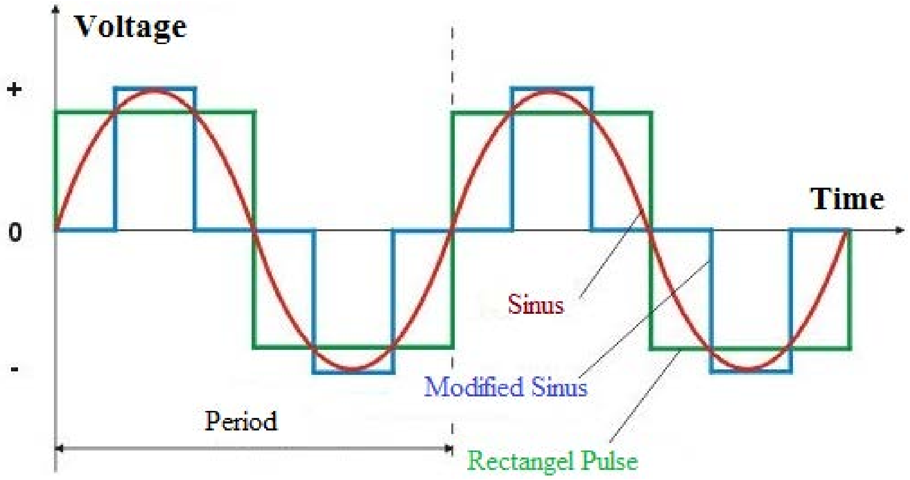

Figure 8 – Voltage in output of the inverter [14]

In voltage inverters with sinusoidal form in the output the initial high-frequency converter generates DC voltage closed in magnitude to amplitude of future sinusoidal curve in the output. Next, the bridge scheme with pulse width simulation converts DC voltage to AC voltage with low frequency: every pair of transistors in every half-period of forming sinusoidal curve switches on several times according to harmonic law. Next, low-frequency filter extracts sinusoidal signal from this form.

The simplest schemes of initial high-frequency converter in inverters are self-maintained. They are quite simple in technical implementation and effective enough with low power (up to 20 W) for supplying consumers that are not sensitive to process of power transmission. Its frequency can be up to 10 kHz.

A positive feedback in such devices is achieved by saturation of transformer core. However such schemes cannot be used for high power inverters, because the losses in the switchers increase, therefore efficiency factor decreases. Moreover, any short circuit in the output breaks auto-oscillations.

More sustainable schemes of initial high-frequency converters are: flyback (up to 150 W), two-step (Up to 500 W), half-bridge and bridge (more than 500 W) with width pulse modulation controllers, in which the frequency achieves value of hundreds kHz. Load of the consumers in the Koyda village is more than 500 W, therefore th power plant needs inverter with half-bridge or bridge scheme, which described below.

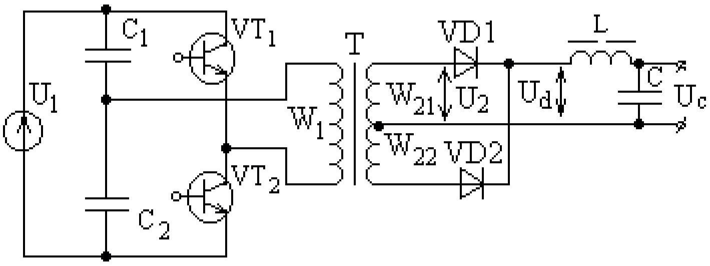

Figure 9 – Half-bridge circuit [14]

The work principle of the half-bridge scheme consists in one-at-a-time connection of transistors VT_1 and VT_2 to capacitors C_1 and C_2. Advantages of this scheme are low losses in power circuit due to commutation of one switch in every step. The capacitors keep the current balance and exclude asymmetric mode of transformer magnetizing. Moreover, in this scheme the backward voltage on the switchers is low, therefore this scheme can be used in high input voltage [14].

4.3 Batteries

Storage systems can be classified into short-term storage for a few hours or days to cover periods of bad weather and long-term storage over several months. Long-term storage is usually used in PV power plants to compensate for seasonal variations in the solar irradiation in summer and winter.

Secondary electrochemical elements are mainly used for storage over shortand medium-term periods; they are usually called batteries. For economic reasons, the lead-acid battery dominates the current market. When higher energy densities are needed due to weight considerations, for example, in laptop computers, other batteries such as nickel-cadmium (NiCd) or nickel-metal hydride (NiMH) are used. Other batteries such as sodium-sulphur (NaS) have been tested for use in electrical (battery-powered) vehicles but are no longer being developed. Table 4 summarizes the data for various types of rechargeable battery.

Lead-acid battery

Today, the most common battery for electricity storage is the rechargeable lead-acid battery. The main reason is cost. The car industry, especially, prefers lead-acid batteries. So called solar batteries have a slightly modified structure compared with car batteries and achieve longer lifetimes. However, the principle structure of the solar battery is similar to the car battery. It has two electrodes. In the charged state, the positive electrode consists of lead dioxide (PbO_2) and the negative electrode of pure lead (Pb). A membrane embedded in a plastic box separates the two electrodes.

Battery self-discharge, which causes additional losses, reduces the system efficiency. The self-discharge rate increases with the temperature and is about 0.3% per day or 10% per month at temperatures of 25°C. However, some battery types provide lower self-discharge rates.

Table 4 – Data for various types of rechargeable batteries [15]

	Lead-acid	NiCd	NiMH	NaS
Positive electrode	PbO_2	NiOOH	NiOOH	S
Negative electrode	PbO	Cd	metals	Na
Electrolyte	$H_2SO_4+H_2O$	$KOH+H_2O$	$KOH+H_2O$	β-Al_2O_3
Energy density (Wh/l)	10–100	80–140	100–160	150–160
Energy density (Wh/kg)	25–35	30–50	50–80	100
Cell voltage (V)	2	1.2	1.2	2.1
Charge/discharge cycles	500–1500	1500–3000	about 1000	about 1500
Operating temperature (°C)	0–55	-20 to 55	-20 to 45	290–350
Self-discharge rate (%/month)	5–15	20–30	20–50	0
Wh efficiency	70–85%	60–70%	60–85%	80–95%

The rechargeable battery should be protected against deep discharge or overcharging. If the battery is totally empty, crystalline lead sulphate is created. This type of lead sulphate is difficult to reconvert and some material will remain in the crystalline form. This damages the battery permanently. Therefore, deep discharge should be avoided in any case. This can be achieved in most cases by switching off the load at about 30% of the remaining capacity. At common operating conditions, this is equivalent to a battery voltage of about 11.4 V. Lower voltages for ending discharge can be chosen for higher discharge currents above $I_{10\%}$. In addition, if the battery is not used for a long time, damage as a result of deep self-discharge is possible. The battery should be recharged from time to time to minimize the risk of damage.

If the lead-acid battery is continuously charged, it starts to produce gas at a voltage of 14.4 V; the electrolysis decomposes the water within the electrolyte into hydrogen and oxygen and these gases escape from the battery. Therefore, the battery must be refilled with water from time to time. Continuous strong gassing can damage a battery. To protect the battery, charging should be stopped at voltages between 13.8 V and 14.4 V. However, it is advisable to charge lead-acid batteries until they begin gassing from time to time to mix the electrolyte thoroughly. The batteries should be placed in a dry room at moderate temperatures. Battery gassing can produce explosive oxyhydrogen, so good ventilation of battery rooms is essential [15].

Airproof lead-acid batteries

The main difference from lead-acid batteries is that batteries do not extract gas. However airproof batteries are more sensitive to discharging voltage, because it is impossible to ventilate them, except of extreme cases (which can be reason of unfixable damage). Airproof batteries much more sensitive to high temperatures and can not be discharged for a long time in compare with lead-acid batteries. Therefore, charging of airproof batteries should be strictly controlled. Sometimes airproof batteries need additional regulator with temperature compensation [1].

Other rechargeable batteries

Other more expensive rechargeable battery types such as NiCd or NiMH are used in addition to the lead-acid battery. They have the advantages of higher energy density, fast charging capability and longer lifetime.

Nickel-cadmium (NiCd) batteries have the following advantages compared with lead-acid batteries:

- higher cycle number
- larger temperature range
- possibility of higher charge and discharge currents
- fewer problems with deep discharge.

On the other hand, NiCd batteries have the disadvantages of higher costs and the so called memory effect. If charging of a NiCd battery is stopped before the full capacity is reached, the capacity decreases. Repeated full charging and discharging partly counteracts the capacity reduction; however, the memory effect is one of the most important problems for this type of battery. Materials used in the production of NiCd batteries are the metals nickel and cadmium.

The nominal voltage of a NiCd cell of 1.2 V is lower than that of a lead-acid battery cell. NiCd batteries are mainly used as household batteries as well as for laptops or electric cars. One major disadvantage of NiCd batteries is the use of environmentally problematic materials. It surely cannot be avoided that constituent materials of disposed batteries are released into the environment after the end of the battery’s useful life. Cadmium accumulates in the food chain, and in human bodies, because it is excreted only partially. High cadmium contamination can cause organ damage or cancer.

Nickel-metal hydride (NiMH) batteries are much less environmentally problematic. Applicable metals are nickel, titanium, vanadium, zirconium or chrome alloys. However, small amounts of toxic materials are also used for these batteries. The electrolyte is diluted potash lye, the same as for NiCd batteries. Besides good environmental compatibility, NiMH batteries have further advantages compared to NiCd batteries such as higher energy density and the absence of the memory effect. Disadvantages are the smaller temperature range and the high self-discharge rate (about 1% per day). Since the cell voltage of 1.2 V is the same as for NiCd batteries, NiMH batteries can easily replace NiCd batteries.

Estimation of the state of charge for NiCd and NiMH batteries is more complicated compared with lead-acid batteries. The temperature influence is greater and the voltage of a fully charged NiCd or NiMH battery even decreases a little.

Other rechargeable battery types such as sodium-sulphur (NaS) batteries promise advantages of higher energy densities; however, problems with high operating temperatures and dangerous materials such as sodium have not yet been resolved fully. Because only prototypes of these batteries exist, they are not discussed in detail [15].

4.4 Diesel generators

Diesel generators – sometimes called generating sets or “gensets” – are relied upon by many businesses and other organizations to supply the electrical power they need during cuts, brownouts, or any other interruption to mains power. There are many different types and configurations of generators, but they all work essentially the same way, and have the same core components.

Engine

This is typically a diesel engine, much like that in a large vehicle, the bigger the source of mechanical energy, the more electrical power can come out ‘the other end’.

Alternator

This is the part which turns the mechanical energy (the rotation of the shaft) into electrical power through induction. The ‘how’ of the alternator is one of the most fascinating parts of a generator. Faraday discovered (or at least described) the process of “electromagnetic induction” in the early 1830s. This principle holds that if you move a wire (or any electrical conductor) through a magnetic field, an electric current is ‘induced’ in the wire. The same is true if the wire is still and the magnetic field moves. Simply moving through a magnetic field causes the electrons to flow through the wire. If the wire moves North-South, the electrons flow one way, and if it moved back south-north, they flow into the other. The stronger the field and the longer the wire, the greater the amount of current induced. Modern generators work by placing several large, powerful magnets in a cluster around a central, rotating shaft. This is called the ‘rotor’ or ‘armature’. The magnets might be permanent magnets or electromagnets, but the point is that they produce a magnetic field, which the engine causes to turn. The other important sub-component of the alternator is the ‘stator’, which is essentially a series of tightly bundled coils of wire, all packed closely around the rotor. When an outside force (such as a diesel engine) turns the central shaft, the rotor constantly moves the north and south poles of its magnetic field(s) across the bundles of wire that surround them. This causes a great deal of electrical current to flow back and forth through the wires – what we call “alternating current” or “AC” mains power.

Fuel System

This is typically the diesel fuel supply for the engine. The most obvious part is a tank holding enough fuel for at least 6-8 hours of operation. This tank may be inside the generator housing for smaller, or portable units, or it may be a separate external structure for larger, permanently installed units. Other parts of the fuel system involve pipe-work to get the fuel to the engine, a fuel pump similar to the one in most vehicles, a fuel filter, and a ventilation pipe or valve for the fuel tank, preventing overpressure or vacuum inside. There will also be an overflow connection ensuring that if the tank is overfilled, the fuel is channeled away, and not simply splashed over the surface of the engine or alternator.

Voltage Regulator

This is a fairly complex but important component. Without it, the voltage and amperage of the AC current provided would vary according to the speed of the engine. As modern electrical equipment relies on a very steady power supply, something is required to level it out. The workings of a voltage regulator are quite ingenious and are beyond the scope of this article. It is probably enough to know what it does, for now.

Cooling System

Just like in a vehicle, the engine produces a great deal of waste heat in addition to mechanical energy. The power flowing through the alternator also produces heat via the electrical resistance of the wires themselves. Again, like in your car, this heat is soaked up by a coolant fluid, often but not necessarily water, which then runs through a heat exchanger, dumping its heat typically into the air, or sometimes into a secondary coolant fluid.

Exhaust System

All internal combustion engines produce exhaust gases. These are toxic and must be directed away from the engine itself and any nearby people. Exhaust gases are typically channeled through pipes, and vented into the outside air. There are typically health and safety regulations about how and where exhaust systems must be channelled, so consult these carefully before installing a new generator.

Lubrication (Oil) System

Any engine requires lubrication, and this is handled by an oil pump and reservoir attached to the engine itself.

Starter & Battery System

Again, just like in a car or lorry, the diesel motor relies on a small electrical motor to start running. This electrical starter motor is powered by a battery, which is charged by either a separate charger or the generator output itself.

Control Panel

The control panel is where the generator is operated. Typical controls & outputs included on most control panels are:

- Start / shutdown controls (manual, automatic, or both)
- Phase selector switch
- Frequency switch
- Engine mode switch
- Engine fuel
- Engine oil
- Engine speed
- Coolant temperature
- Battery charge
- Generator output voltage

- Generator output current (amperage)

- Generator Output in kVA

- AC power frequency

Frame or Housing

The genset will either be contained in a weatherproof housing, an open structural frame, or a transportable unit. All of these function to keep the components together and solidly attached. It also ensures that all electrical components are safely grounded [16].

5. Technical analysis of wind-diesel power plant

The weather conditions and landscape of the Koyda village were evaluated. The results show that it is a good place for wind power plant. The required equipment for hybrid power plant was determined and now I am going to design a wind-diesel power plant. Wind turbines can be directly connected to consumers but usually generating power and consuming power are not equal. Therefore, the wind turbines will be connected to consumers through batteries and power control boxes which are also connected with diesel generator.

5.1 Determination of consumers' load

Before selection of the equipment for power plant, we need to determine load graph of the consumers. There is no any information about an accurate load graph of the Koyda village, but we can calculate it with usage of typical load graph for decentralized objects [1] and information about installed diesel capacity that I mentioned above. Its capacity is 360 kW (P_{inst}) [6]. According to [1], capacity of diesel installation must be equal to 1.25 of maximum load (P_{max}). If we know the capacity we can calculate maximum load:

$$P_{max} = \frac{P_{inst}}{1.25} = \frac{360}{1.25} = 288\ kW \quad (1)$$

To plot typical load graph, we estimate load in approach of multiplying capacity of the power plant by coefficients. There are coefficients for months and hours in winter and summer period. The coefficients are presented in Tables 5 and 6.

Table 5 – Month coefficients

Month	Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sept	Oct	Nov	Dec
Coefficient	1	1	0.8	0.8	0.8	0.7	0.7	0.7	0.9	0.9	0.9	1

Table 6 – Hour coefficient for winter and summer period

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Winter period	0.25	0.25	0.25	0.25	0.25	0.35	0.5	0.6
Summer period	0.15	0.15	0.15	0.15	0.175	0.21	0.28	0.31
Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Winter period	0.4	0.3	0.3	0.35	0.4	0.3	0.3	0.3
Summer period	0.28	0.21	0.21	0.21	0.24	0.21	0.21	0.21
Hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Winter period	0.4	0.7	1	0.95	0.7	0.5	0.35	0.3
Summer period	0.21	0.21	0.25	0.28	0.5	0.7	0.42	0.18

All load data are presented in Appendix 1 and according to this data we plot a daily load graph:

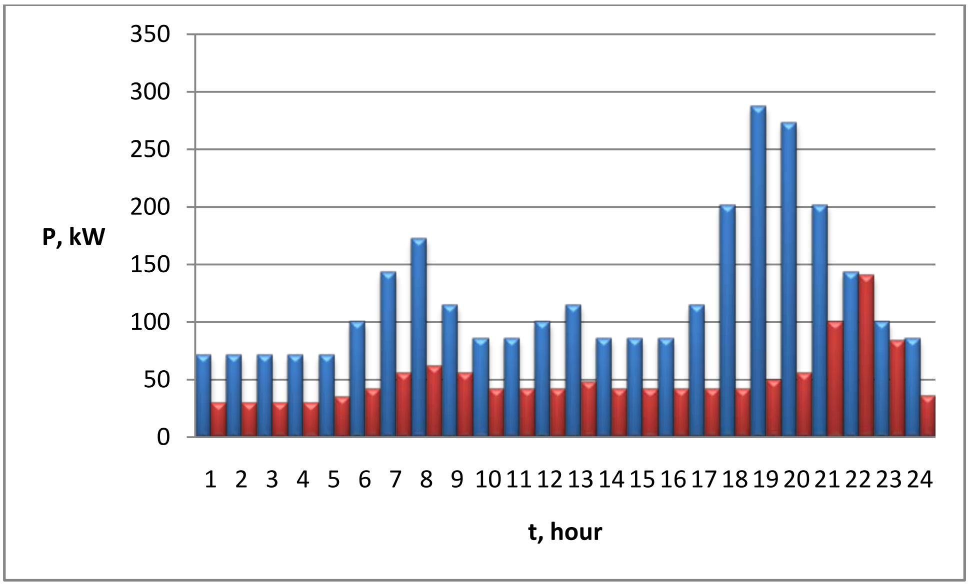

Figure 10 – Daily load graph of the Koyda village (blue is for winter period, red is for summer period)

Also plot yearly load graph:

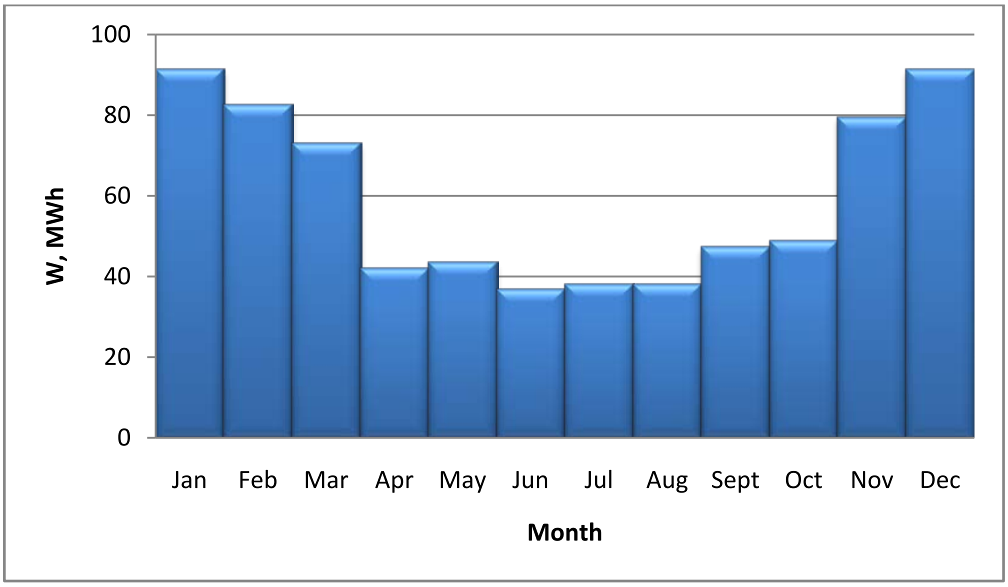

Figure 11 – Yearly load graph of the Koyda village

All data for consumers have been determined. Next step is selection of the equipment.

5.2 Determination of wind turbine characteristics

Now we can select wind turbine. I consider several variants: two, three or four wind turbines “CONDOR AIR WES 380/50-60”; eight, eleven or fifteen wind turbines “Falcon Euro” (20 kW); or combination of these turbines: three turbines CONDOR and two turbines Falcon. Its technical parameters are presented in Appendix 2. The wind turbine characteristics are presented in below.

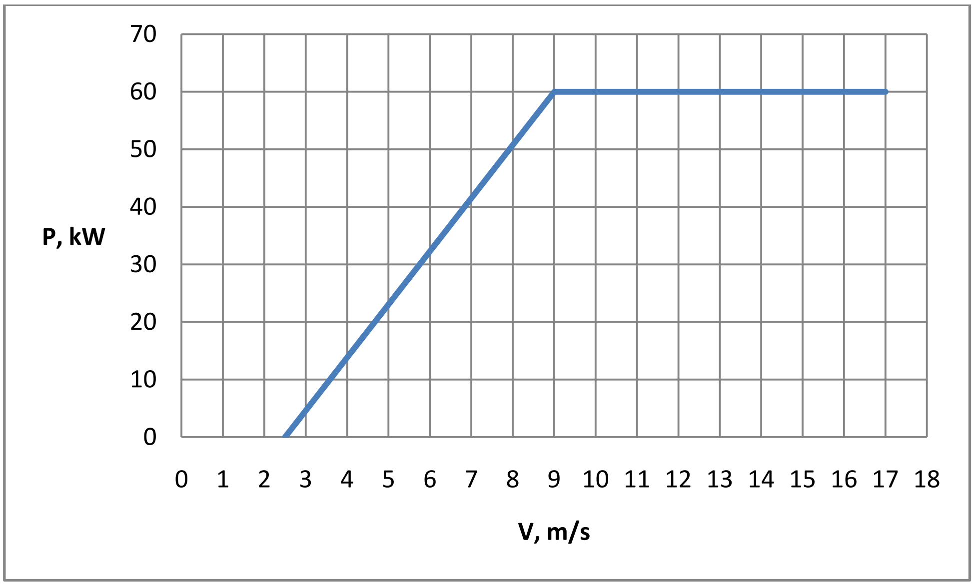

Figure 12 – Wind turbine characteristic for “CONDOR AIR WES 380/50-60” [18]

This characteristic show how the power generation changes in dependence on wind velocity. As we may see, turbine CONDOR operates with maximum efficiency with wind velocity 9 or more. Turbine Falcon operates with maximum efficiency with wind velocity 9 or more.

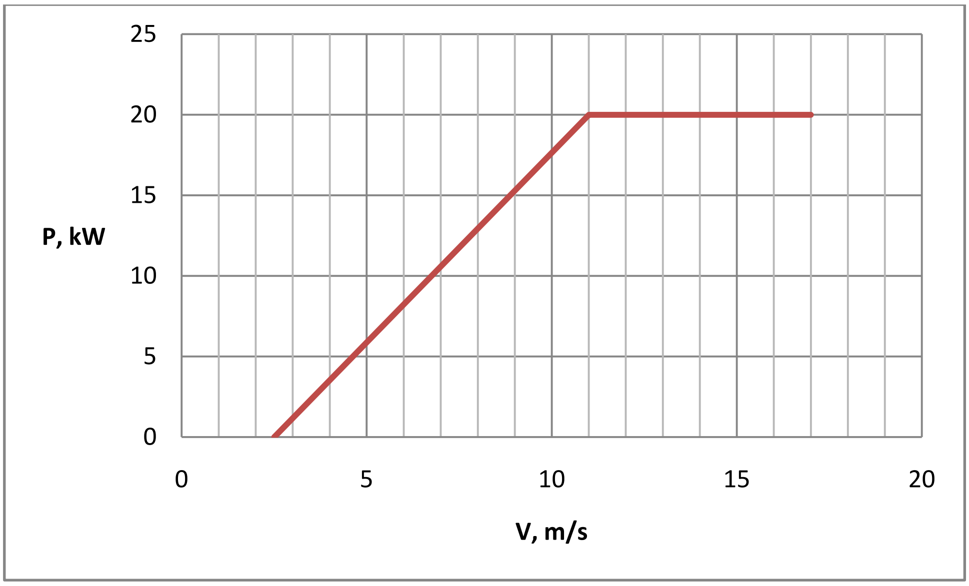

Figure 13 – Wind turbine characteristic for “Falcon Euro” (20 kW) [18]

According to Figure 13, turbine Falcon operates with maximum efficiency with wind velocity 11 or more. Turbine Falcon operates with maximum efficiency with wind velocity 11 or more.

We need to calculate how much load the wind turbine can cover. To calculate this, we need wind velocity and loads of every month. The wind velocities are already calculated and the results are presented in Table 2. Plot the graph according to Table 2:

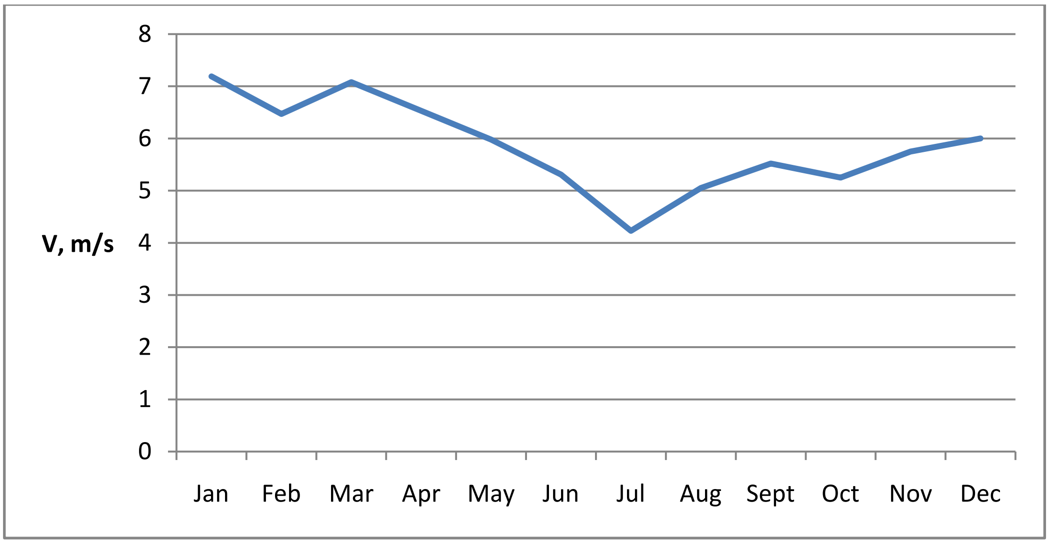

Figure 14 – Average month wind velocities

Now we can calculate how much electricity the wind turbine produces. All data are presented in Table 7.

Table 7 – Electricity produced by wind turbine “CONDOR AIR WES 380/50-60”

Month	Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sept	Oct	Nov	Dec
1 turbine produces per 1 hour, kWh	43.3	36.6	42.3	37.20	32.12	25.94	15.97	23.54	27.88	25.38	30.00	32.31
1 turbine produces per 1 month, MWh	32.2	24.6	31.4	26.78	23.9	18.68	11.88	17.51	20.07	18.89	21.6	24.04
Load graph coverage (1 turbine), %	35.2	29.8	42	63.47	54.81	50.58	31.14	45.90	42.28	38.50	27.10	26.27
Load graph coverage (2 turbines), %	70.4	59.6	85.9	126	109.6	101.2	62.28	91.80	84.56	77.00	54.20	52.53
Load graph coverage (3 turbines), %	106	89.4	129	190.4	164.4	151.7	93.4	137.7	126.8	115.5	81.3	78.8
Load graph coverage (4 turbines), %	141	119	172	254	219	202	125	184	169	154	108	105

According to Table 7, the more turbines will be installed the more will be coverage of the load by wind turbines. However the more wind turbines, the more extra energy is generated.

It is necessary to make the same calculations for wind turbine “Falcon Euro” (20 kW). All data are presented in Table 8.

Table 8 – Electricity, produced by wind turbine “Falcon Euro” (20 kW)

Month	Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sept	Oct	Nov	Dec
1 turbine produces per 1 hour, kWh	11	9.34	10.8	9.48	8.19	6.61	4.07	6.00	7.11	6.47	7.65	8.24
1 turbine produces per 1 month, MWh	8.21	6.28	8.02	6.83	6.09	4.76	3.03	4.46	5.12	4.81	5.5	6.13
Load graph coverage (1 turbine), %	8.97	7.59	11	16.2	14	12.9	7.94	11.7	10.8	9.81	6.91	6.70
Load graph coverage (8 turbines), %	70.4	59.6	85.9	126	109.6	101.2	62.28	91.80	84.56	77.00	54.20	52.53
Load graph coverage (11 turbines), %	106	89.4	129	190.4	164.4	151.7	93.4	137.7	126.8	115.5	81.3	78.8
Load graph coverage (15 turbines), %	141	119	172	254	219	202	125	184	169	154	108	105

It is also necessary to make calculations for combination of different turbines. The data are in Table 9.

Table 9 – Electricity, produced by wind turbines “Falcon Euro” (20 kW) and “CONDOR AIR WES 380/50-60”

Month	Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sept	Oct	Nov	Dec
Load graph coverage (3 CONDOR+2 Falcon turbines), %	124	105	151	223	192	178	109	161	148	135	95	92

If coverage of the load is more than 100% there is extra energy and it is consumed by ballast load.

5.3 Calculation of diesel fuel consumption

Diesel generator is already installed in the Koyda village but there is no information about diesel generator model. The only data available is its capacity – 360 kW. However, it is possible to take analogue, for example diesel power station Green Power GP505A/P (360 kW). Its rated fuel consumption is equal to 0.27 liters per kWh or 232 gram per kWh.

Except for rated fuel consumption there is real fuel consumption which depends on load and can be calculated with the following formula [1]:

$$G_1 = K_{nl} G_r + (1 - K_{nl}) G_r \frac{P_1}{P_r}, \tag{2}$$

Where

G_1 – real fuel consumption;

G_r – rated fuel consumption;

K_{nl} – no load fuel consumption coefficient (K_{nl}=0.3);

P_1 – load on the generator;

P_r – rated capacity of the generator (P_r =360 kW).

If we know rated fuel consumption for respective load mode and volume of generated energy, we can calculate volume of consumed fuel for the period of time with following formula [1]:

$$Q_f = G_1 W, \tag{3}$$

Where

W – energy, generated in day, month or year.

A summary of load data in Appendix 1 are used in formulas (2) and (3). Then, we obtain that 79504 kg of fuel the diesel generator consumes a year to satisfy consumer needs.

As example, take two wind turbines “CONDOR AIR WES 380/50-60”. I summarize data of load in Appendix 1 and data of load coverage by wind turbines in Table 7 and put in formulas (2) and (3) we obtain 16500 kg of fuel the diesel generator consumes a year to satisfy consumer if the power plant is upgraded with two wind turbines. Fuel consumption for other variants is presented in Table 10.

Table 10 – Fuel consumption in a year

Variant of wind installation composition	2 WT CONDOR (60 kW)	3 WT CONDOR (60 kW)	4 WT CONDOR (60 kW)	8 WT Falcon (20 kW)	11 WT Falcon (20 kW)	15 WT Falcon (20 kW)	3 WT CONDOR (60 kW) + 2 WT Falcon (20 kW)
Fuel consumption, t/year	16.5	3.6	0	16.5	3.6	0	0

It is not obviously, which composition is the most efficient. From one side we can save money on fuel if we upgrade the power plant with wind turbines. From the other side we have to spend money for new installation. To decide, I analyzed the projects with AGREPREF method. The detailed analysis is presented in the next section.

5.3 Determination of optimal capacity for wind installation with AGREPREF method

AGREPREF method is based on an aggregation of partial preferences of particular solutions. Method uses two thresholds during ordering process – indifference threshold and preference threshold. Indifference threshold is defining the minimum sum of criteria weights, according to which two solutions (*x*, *y*) are indifferent, to consider whole *x R y* relation as indifferent. Preference threshold represents the desired difference between the sum of the criteria weights, according to which the solution *x* is outranking solution *y*, and the sum of the weights according to which the solution y outranks solution *x*. Values of both thresholds are within the range (0, 1). There is one more threshold – Δ. It is determined by decision maker. When we compare two projects, and its difference less than Δ, the projects are equal [19].

I decided to analyze variants with three criteria:

- Money for the project – should be minimized (weight – 0.45);
- Coverage of the load by wind turbines – should be maximized (weight – 0.35);
- Extra energy – should be minimized (weight – 0.2).

I take money for the project as investment multiplied by annuity payment factor plus costs for duel. Actually, there are more inputs but for primal analysis it is enough. Detailed economic analysis is presented in Section 7. Annuity payment factor can be calculated with following formula [23]:

$$a_t = \frac{(1+r)^T \cdot r}{(1+r)^T - 1}, \quad (4)$$

Where

r – Discount rate, equal to 0.0847 (its calculation is presented in Section 7);

T – Lifetime of the project, equal to 20 years.

$$a_t = \frac{(1+0.0847)^{20} \cdot 0.0847}{(1+0.0847)^{20} - 1} = 0.1057 \quad (5)$$

Data for price of equipment I take from next catalogues: EDS Group [18], Optimal communications [19], Storage batteries shop [20].

According to [28], one ton of fuel costs 47000 RUB and its shipping is 26000 RUB per ton. Therefore, total cost for one ton of fuel is 73000 RUB. I summarize data of Tables 7-10 and the information above and write it down Table 11.

Table 11 – Initial table for AGREPREF method

Variant	**Wind power installation**	**Investment·a_t + Fuel costs, RUB (MIN)**	**Coverage, % (MAX)**	**Extra Energy, % (MIN)**
V1	2xCondor	2 482 624	74	2
V2	3xCondor	2 179 987	93.6	20.5
V3	4xCondor	2 556 249	100	52
V4	8xFalcon	3 232 249	75	2.6
V5	11xFalcon	3 050 955	91.2	15.5
V6	15xFalcon	3 802 029	100	45.4
V7	3xCondor + 2xFalcon	2 460 624	98.5	35
Δ		200 000	5	15
Weight		0.45	0.35	0.2

Level of indifference is equal to 0.65. Level of preference is equal to 0.45. The solution matrices are presented in Appendix 3. According to these matrices we can plot tree of preferred variants and determine the best one. The tree is presented in Figure 15.

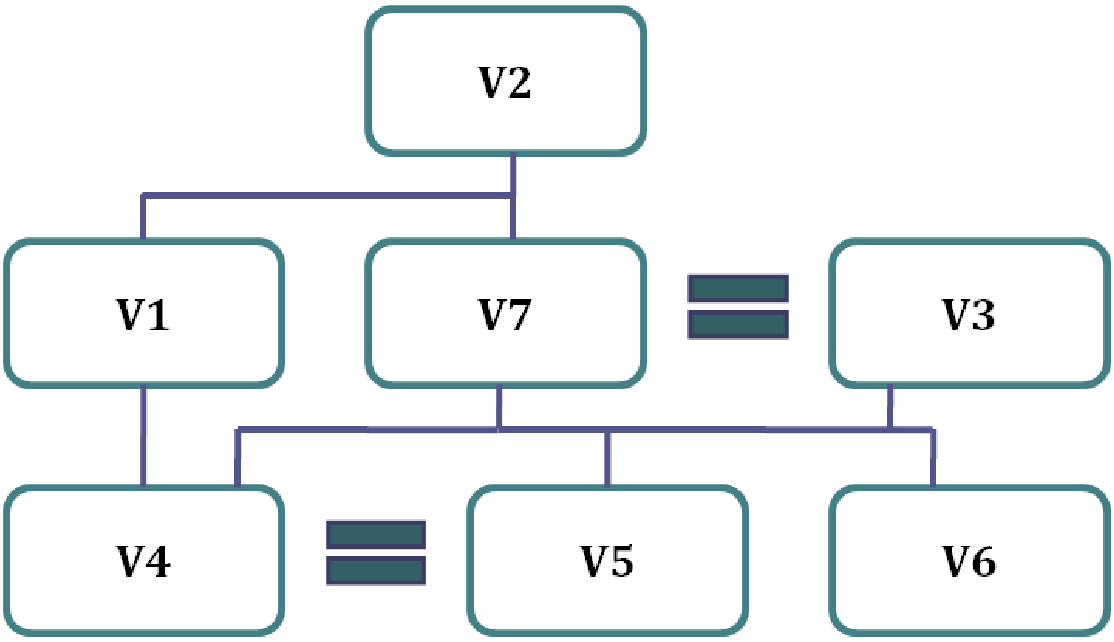

Figure 15 – Tree of preferred variants

According to Figure 15, the most efficient project is V2. In other words – three wind turbines “CONDOR AIR WES 380/50-60”.

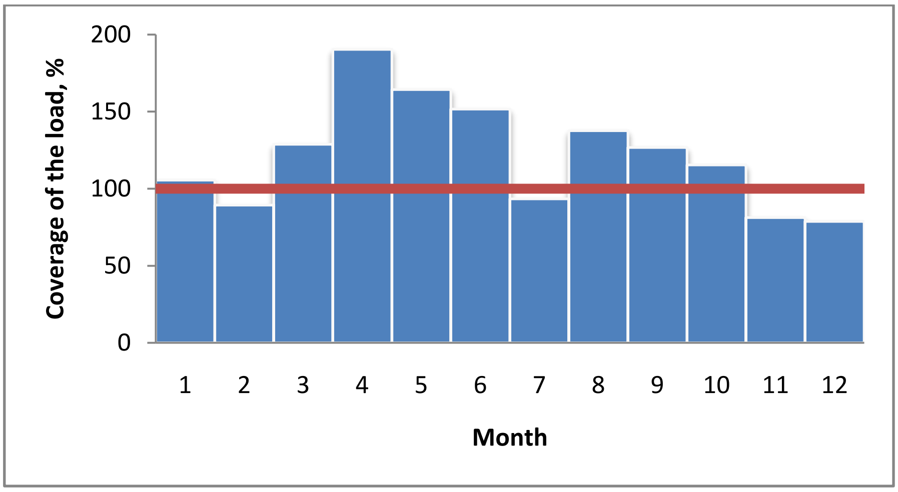

Figure 16 – Load coverage by wind turbines

According to graph in Figure 16, the average load coverage by wind turbines is 93.6%, minimum – 78.8% in December and maximum – 190.42% in April. The extra energy will be consumed by the ballast load. The lack of energy is 45593 kWh. This energy will be supplied by diesel generators.

5.4 Configuration of wind-diesel power plant

Purpose of designing the wind-diesel power plant is to generate power with wind installation and thus decreasing of fuel consumption. Diesel-generator compensates the lack of energy from wind turbines. To perform this, the diesel-generator should have an automatic transfer switch system sensitive to changing of load. Generation and peak load coverage in transient modes are performed with power blocks “Delta” NH PLUS 20 kVA (3-phase - 3-phase) and storage batteries.

Power block “Delta” is and uninterruptible power source. Storage batteries “Delta” GX12-200 have a buffer function. Power blocks “Delta” are installed in special power control boxes.

In case when there is lack of energy from wind turbines, power block starts diesel generator. When there is enough energy from wind turbines, the diesel-generator switches off. Automatic transfer switch changes the network of wind turbines and diesel-generator. While diesel-generator works, the storage batteries charge.

Below, configuration of the wind-diesel power plant is presented:

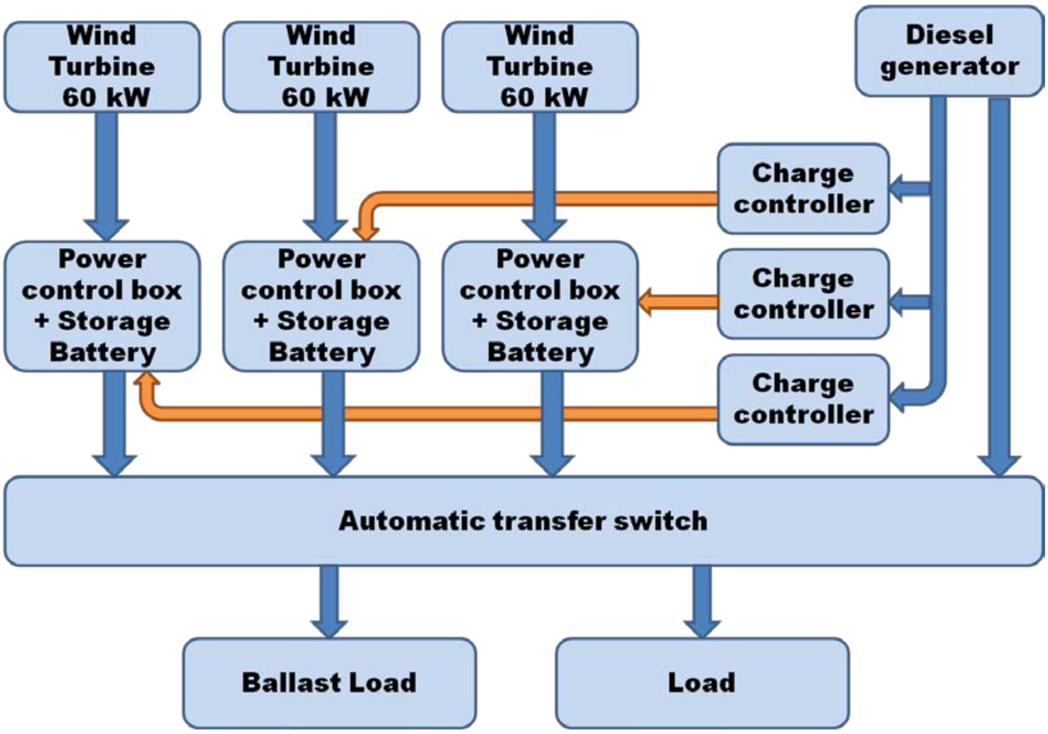

Figure 17 – Configuration of wind-diesel power plant

Wind velocity always changes in time. Therefore, torque of wind turbine wheel changes. It may be the cause of voltage deviation. To avoid it, the power plant needs uninterruptible power source, which will control the voltage value [17]. Uninterruptible power sources “Delta” provide supply for load from wind turbines through rectify-inverter converter and extra energy is collected in the storage batteries. In periods of calm weather, the load is supplied from storage battery. The diesel-generator starts in case of low charge of batteries. It supplies consumers and charges batteries through charge controllers “EDS60”.

All equipment of the power plant that we need to buy and install is presented in Table 12.

Table 12 – Equipment in the wind-diesel power plant

Equipment	**Amount**	**Lifetime, years**	**Price, RUB**	**Total price, RUB**
Wind turbine CONDOR AIR WES 380/50-60, 60 kW [18]	3	20	3 150 000	9 450 000
Power block “Delta” NHPLUS 20 kVA [20]	12	20	214 400	2 572 800
Power control box “Delta” for NHPLUS up to 80 kVA [20]	3	20	556 800	1 670 400
Lead-acid airproof storage batteries “Delta” GX12-200, 12V, 200Ah, size: 522x238x218, weight: 65kg [21]	80	12	42 400	5 088 000
Charge controller “EDS60” [20]	3	20	201 300	402 600
Automatic transfer switch [20]	1	20	478 800	478 800
Total cost	19 662 600 RUB			

5.5 Carbon emission calculation

To estimate annual CO_2 emission I used the following formula [23]:

$$E = M \cdot K_1 \cdot TNV \cdot K_2 \cdot \frac{44}{12}, \tag{6}$$

Where

M – real fuel consumption (t/year);

K_1 – carbon oxidation coefficient (0.99);

TNV – thermal net value (43.02 GJ/t);

K_2 – carbon emission coefficient (19.98 t/TJ);

44/12 – coefficient of recalculation carbon into CO_2.

The designed wind-diesel power plant consumes 3600 kg of fuel annually. Power plant without wind turbines consumes 79 504 kg. Now it is possible to calculate carbon emission by both power plants. Calculation for diesel power plant:

$$E = 79.504 \cdot 0.99 \cdot 43.02 \cdot \frac{19.98}{1000} \cdot \frac{44}{12} = 249.1\ t \tag{7}$$

Calculation for wind-diesel power plant:

$$E = 3.6 \cdot 0.99 \cdot 43.02 \cdot \frac{19.98}{1000} \cdot \frac{44}{12} = 11.3\ t \tag{8}$$

Therefore, with wind turbines we can decrease carbon emission in the atmosphere by 237.8 t a year or by 95%. The suggestion of using three wind turbines “CONDOR AIR WES 380/50-60” will allow polluting less the environment.

6. Modeling of wind turbine generator in MATLAB Simulink.

Before installation of the equipment for wind-diesel power plant, it is worth to create a computer model and look how it performs. MATLAB Simulink is a good tool for designing model of electric part in wind-diesel power plant.

Model of wind turbine consists of two parts: mechanical part of wind turbine and synchronous generator with permanent magnets. The schemes are presented bellow.

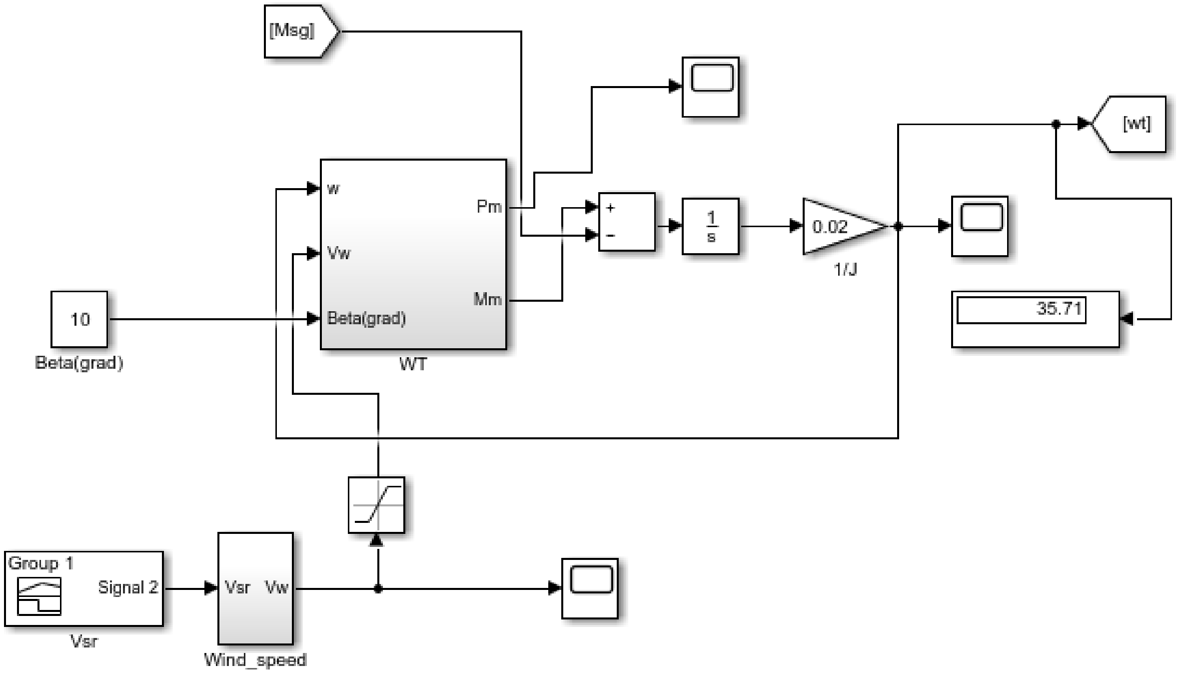

Figure 18 – Scheme of mechanical part of wind turbine

The scheme in Figure 18 has three inputs and two outputs. The inputs are: w – rotation speed, rad/s; Vw – wind speed, m/s; Beta(grad) – angle of blade, deg. The outputs are: Pm – mechanical power of the turbine, W; Mm – mechanical moment, N·m. To calculate mechanical power of the turbine, the model uses the following formula [23]:

$$P_{WT} = C_p \cdot \frac{\rho A}{2} \cdot V^3, \qquad (9)$$

Where

C_p – wind using efficiency factor;

ρ – air density, kg/m^3; ω

$A = \pi R_{wt}^2$ – square, covered by wind turbine wheel, m^2;

R_{wt} – radius of the blade, m;

V – extensional part of velocity of wind flows through the wind turbine, m/s.

Mechanical moment on the turbine shaft can be determined with following formula [23]:

$$M_{WT} = P_{WT}/\omega_{wt} \ , \tag{10}$$

Where

ω_{wt} – radial torque frequency of the turbine.

Radial torque frequency of the turbine can be determined with following formula [23]:

$$\omega_{WT} = \frac{\pi n_{wt}}{30}, \tag{11}$$

Where

n_{wt} – torque frequency.

Tourque frequency can be determined with following formula [23]:

$$n_{WT} = \frac{30\lambda V}{\pi R_{wt}}, \tag{12}$$

Where

λ – specific speed of the turbine;

V – extensional part of velocity of wind flows through the wind turbine, m/s;

R_{wt} – radius of the blade, m.

Wind using efficiency factor can be determined with following formula [23]:

$$C_p = c_1 \left(\frac{c_2}{\gamma} - c_3\beta - c_4\right) e^{-\frac{c_5}{\gamma}} + c_6\lambda \, , \tag{13}$$

Where

$c_1, c_2, c_3, c_4, c_5, c_6$ – coefficients, determined in empiric way, usually the next values are used respectively: 0.5176; 116; 0.4; 5; 21; 0.007;

γ – supplementary parameter, related with angle of blade.

Supplementary parameter can be determined with following formula [23]:

$$\frac{1}{\gamma} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{14}$$

Where

β – angle of blade, deg.

Block WT is required to calculate wind using efficiency factor. Scheme of block WT is presented in Figure 19.

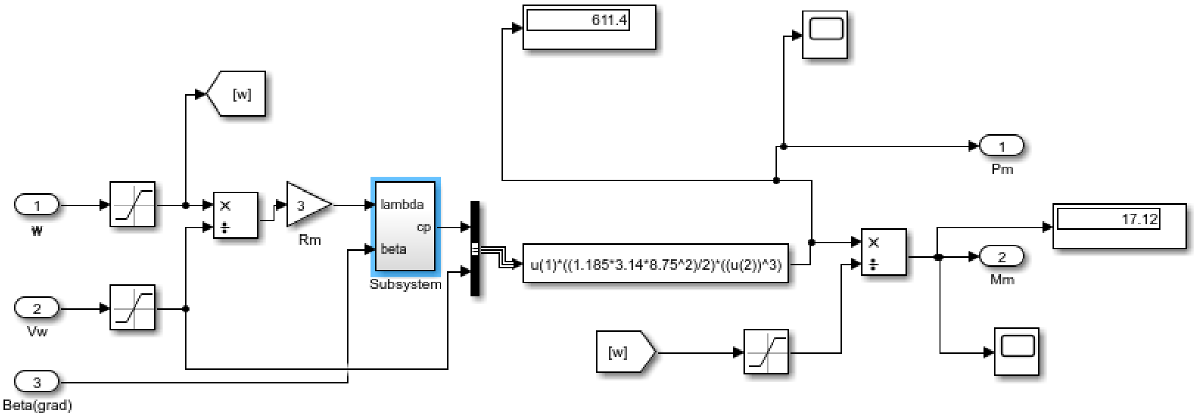

Figure 19 – Scheme of block WT

Block WT is a subsystem for main scheme and it has one more subsystem. I made these subsystems to make scheme more structured and not so complicated. The subsystem of block WT is presented in Figure 20.

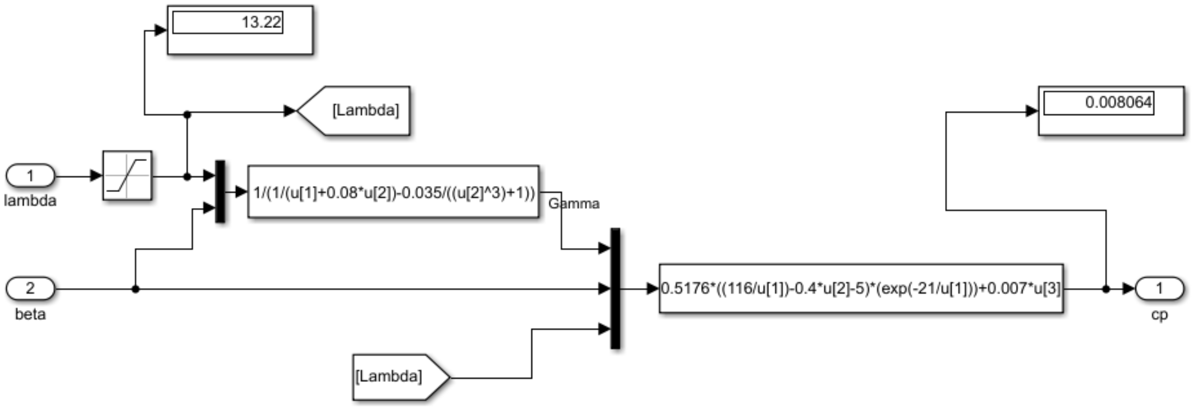

Figure 20 – Subsystem of block WT

Next part of the model is synchronous generator. The scheme is presented in Figure 21.

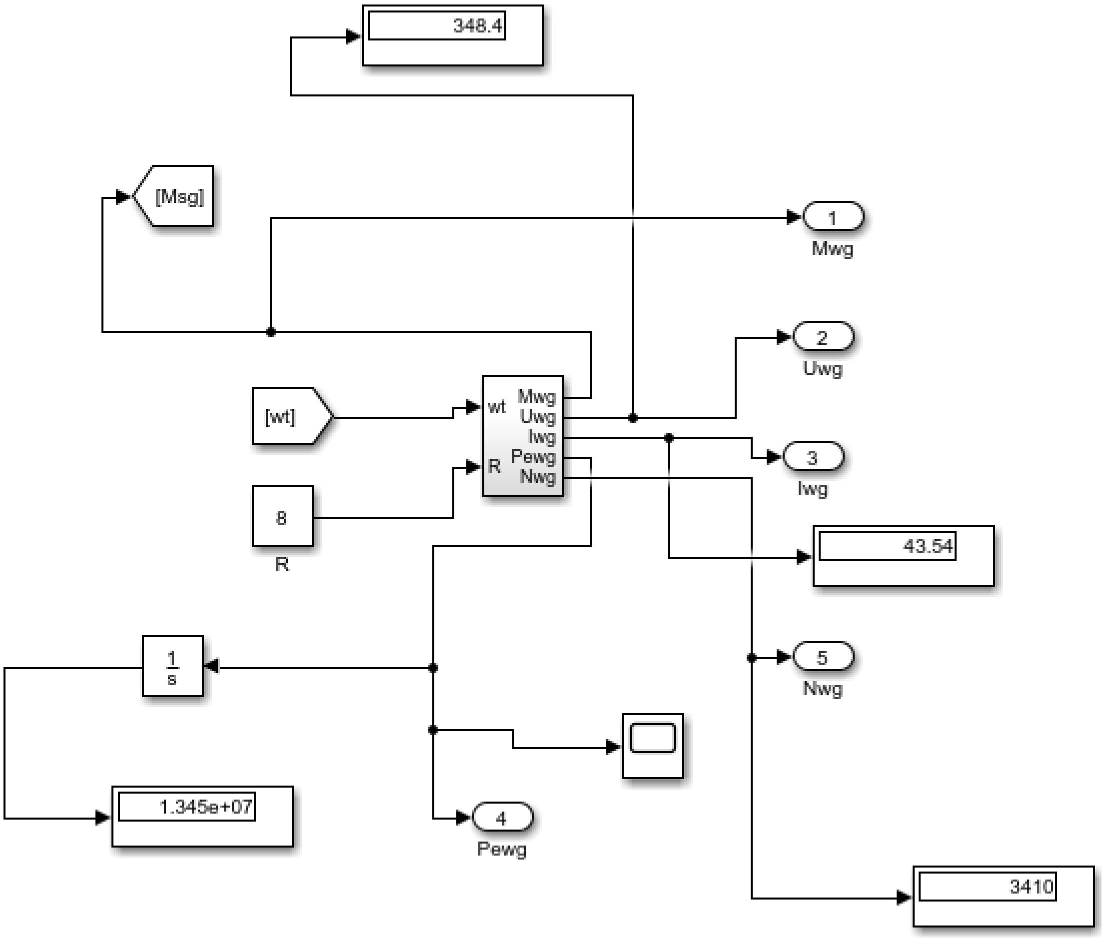

Figure 21 – Scheme of synchronous generator

The scheme of synchronous generator has two inputs and five outputs. The inputs are: wt – rotation speed, rad/s; R – resistance of the load, Ohm. The outputs are: Mwg – mechanical moment, N·m; Uwg – phase voltage, V; Iwg – phase current, A; Pewg – electric power, W; Nwg

– shaft rotation frequency, RPM. The subsystem of synchronous generator scheme is presented in Figure 22.

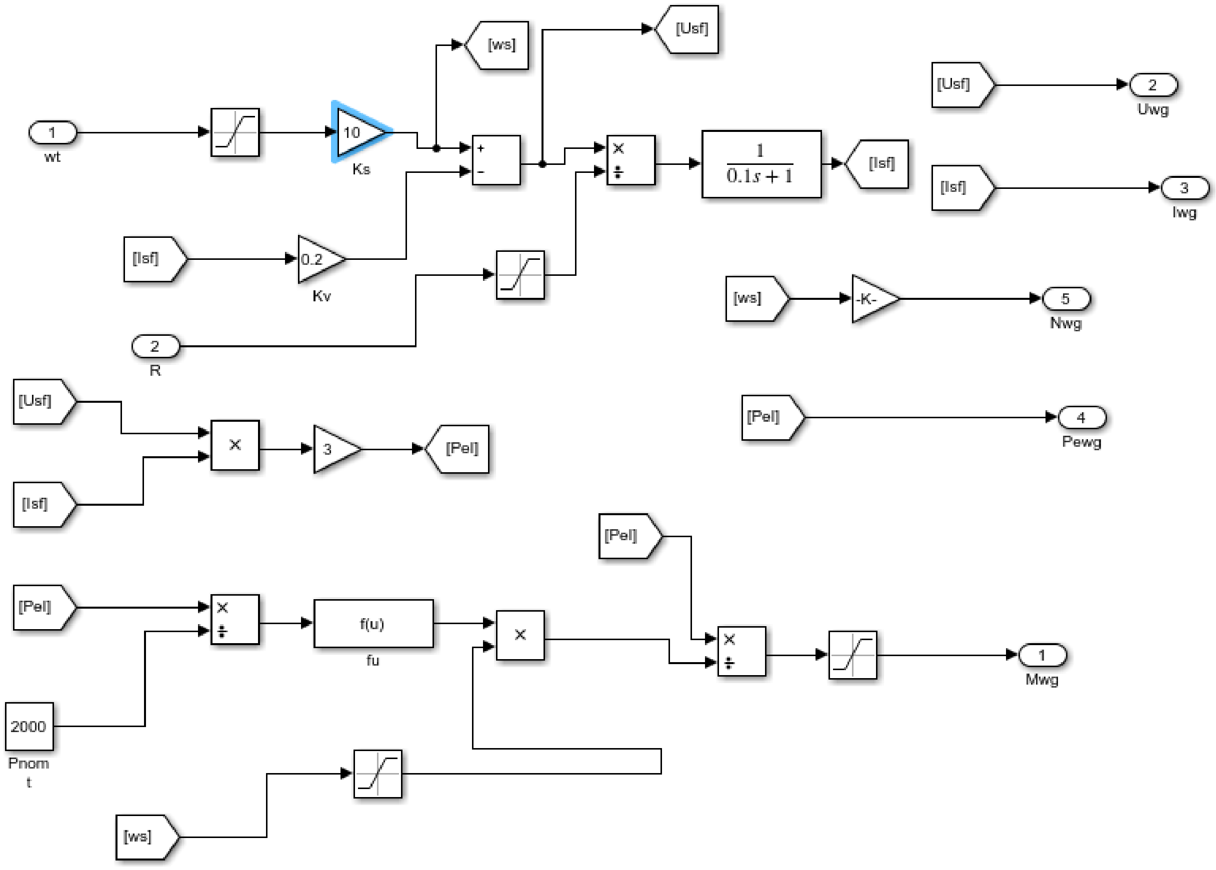

Figure 22 – Subsystem of synchronous generator scheme

Output phase voltage of the synchronous generator (root mean square value) is determined with following formula [23]:

$$U_{sf} = K_w \omega_{wt} - K_L I_{sf}, \qquad (15)$$

Where

K_w, K_L – coefficients depend on construction parameters of electric machine, can be determined in experimental way;

ω_{wt} – radial torque frequency of the turbine;

I_{sf} – root mean square value of synchronous generator phase current.

Root mean square value of synchronous generator phase current is determined with following formula [23]:

$$I_{sf} = \frac{U_{sf}}{R}, \quad (16)$$

Where

R – resistance of the load.

Electric power, which the synchronous generator generates, is determined with formula [23]:

$$P_{el} = 3U_{sf}I_{sf}\ , \quad (17)$$

Resistance moment that electric machine makes on the shaft of wind turbine can be determined with formula [23]:

$$M_{sg} = \frac{P_m}{\omega_{wt}} = \frac{P_{el}}{\eta\omega_{wt}}, \quad (18)$$

Where

P_m – mechanical power;

η – efficiency factor of electric machine, which dramatically depends on load mode of the synchronous generator.

ω_{wt} – radial torque frequency of the turbine.

Dynamics of wind turbine is determined with next differential equation:

$$(J_{WT} + J_{SG})\frac{d\omega_{wt}}{dt} = M_{WT} - M_L\ , \quad (19)$$

Where

J_{WT} – inertia moment of wind turbine;

J_{SG} – inertia moment of synchronous generator;

ω_{wt} – radial torque frequency of the turbine;

M_{WT} – aerodynamic moment of wind turbine;

M_L – load moment on the shaft of the turbine.

Sum of inertia moment of wind turbine and inertia moment of synchronous generator can be approximately determined with following formula [23]:

$$J = \frac{1}{9} m_{wt} R_{wt}^2 \ , \tag{20}$$

Where

m_{wt} – mass of wind wheel;

R_{wt} – radius of the blade, m.

It is also necessary to create model of wind flow to simulate the model of wind turbine. Main block in the model of wind flow is “signal builder”. Also, there is noise generator in the scheme, because in real life velocity of wind is not a constant.

Take, for example, first of February in 2017, one day of the coldest month in the year. There were three measurements during the day according to [9]. Wind velocities were: 6, 10 and 8 m/s. Wind flow simulation is presented in Figure 23.

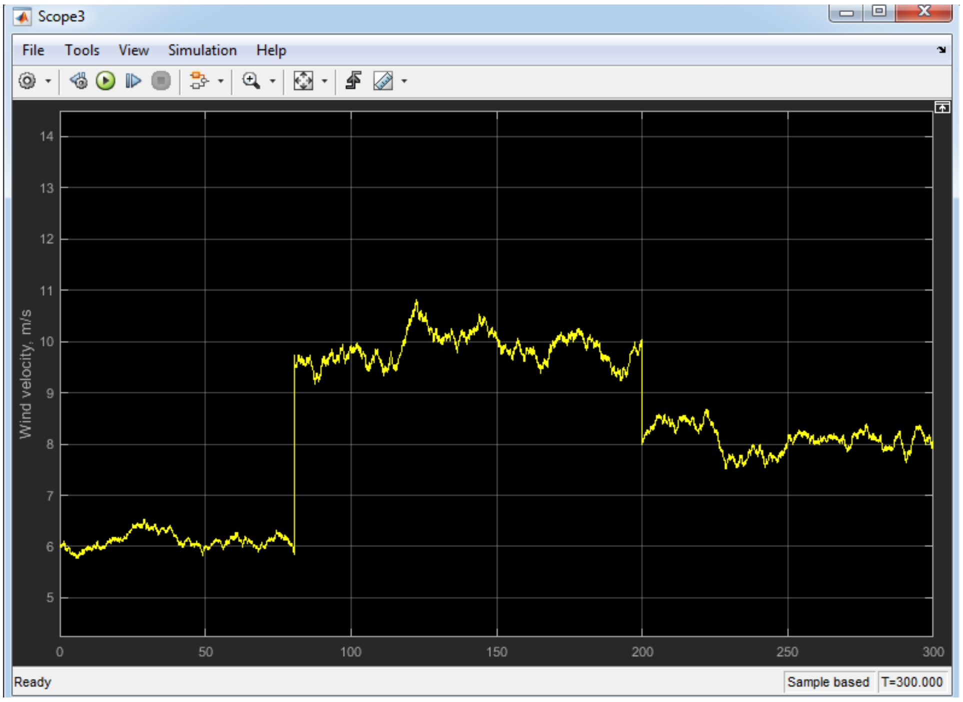

Figure 23 – Simulation of wind flow

The simulation was performed only for 5 minutes due to restrictions of the program. It does not influence on final results because form of the graph is the same and when I will calculate generated energy during the day I will multiply the result by 120.

Next step is simulation of power generation. The graph is presented in Figure 24.

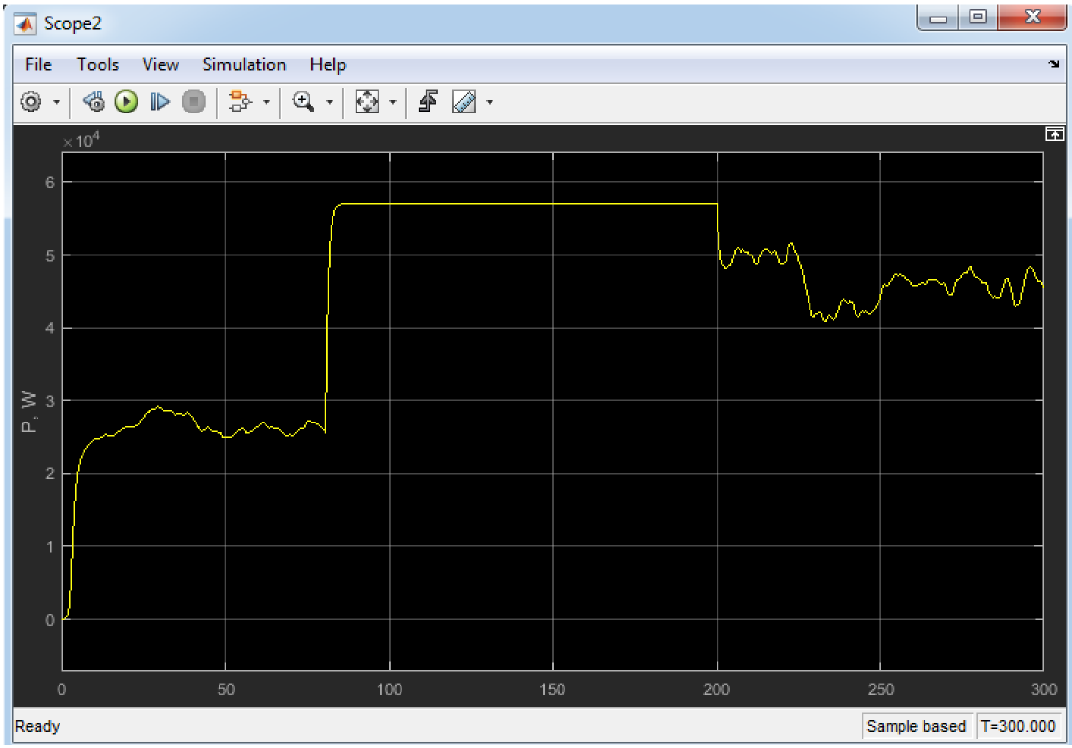

Figure 24 – Simulation of power generation

In the graph in Figure 25 we may see that in the period when wind velocity was 10 m/s the wind turbine generate almost nominal power (60 kW). According to wind turbine characteristic in Figure 9, the nominal wind velocity for turbine is 9 m/s. Therefore, even if wind velocity more than nominal, the turbine will not generate more than nominal power. Wind turbine generated 1613 MWh during the day.

Next, combine winter load graph in Figure 10 with graph of power generated by three wind turbines during the day. Load coverage in the coldest day by wind turbines is presented in Figure 25. The most time it is enough energy from wind turbine, and the lack of energy will be supplied by diesel generator. The lack of energy is in 19 and 20 hours and from.

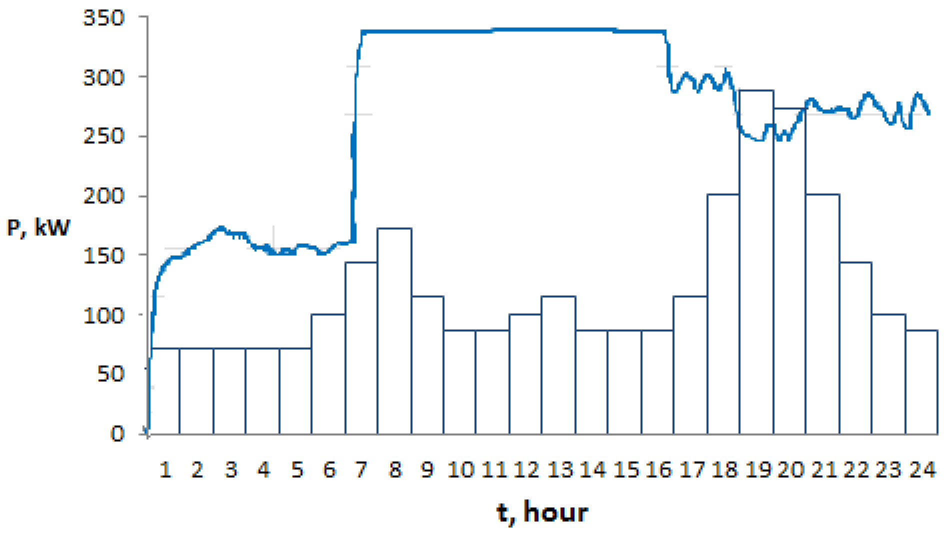

Figure 25 – Load coverage in the coldest day by wind turbines

Next, combine summer load graph in Figure 10 with graph of power generated by three wind turbines during the day. Load coverage in the hottest day by wind turbines is presented in Figure 26.

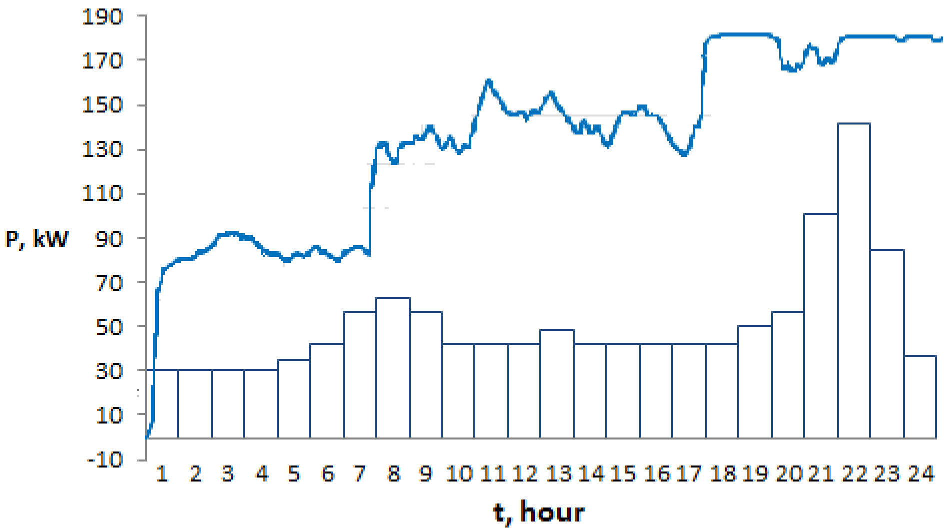

Figure 26 – Load coverage in the hottest day by wind turbines

Wind turbines cover whole load. Extra energy will be consumed to charge the batteries and the rest will be consumed by ballast load.

7. Economic analysis

The step after designing hybrid power plant is its economic evaluation. In this chapter I will estimate volume of the investment to build the wind-diesel power plant, costs and revenues. Next, relying on these data, I will calculate Net Present Value and evaluate is it project profitable or not.

7.1 Theoretical background

To realize the project it is necessary to estimate volume of investment, supposed costs and revenues and analyze the project with main economic criterions. Here is a list of main economic criterions:

- Net Present Value;
- Payback Period;
- Profitability Index;
- Internal Rate of Return.

Bellow, I will describe what do criterions mean and how to calculate them.

Net Present Value

Net Present Value (NPV) is a sum of discounted cash flows minus investment in the initial period. It may be written as a following formula:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - INV, \tag{21}$$

Where

CF_t – cash flow in the period t;

r – discount rate;

INV – initial investment in the project;

t – number of time periods;

T – lifetime of the project.

NPV is a very important criterion, usually it is calculated first before investing into project. It shows how much profit the project will yield. If NPV is more or equal to zero, it is worth to invest into the project. The greater NPV the better [24].

Payback Period

One more important criterion is payback period. It is a number of time period when total profit from the project is more than total costs and investment or our NPV becomes more or equal to zero. Payback period may be presented with following formula:

$$\sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - INV = 0, \tag{22}$$

Where

CF_t – cash flow in the period t;

INV – initial investment in the project;

r – discount rate;

T – Payback period [24].

The shorter payback period the better

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 following formula:

$$\sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - INV = 0, \tag{23}$$

Where

CF_t – cash flow in the period t;

INV – initial investment in the project;

T – lifetime of the project;

r – Internal Rate of Return (discount rate) [24].

The greater IRR the better.

Profitability Index

Profitability index shows relation between Net Present Value and investment. Formula for profitability index is presented below:

$$Profitability\ index = \frac{NPV}{INV} + 1, \tag{24}$$

Where

NPV – Net Present Value;

INV – initial investment in the project [24].

Project is considered as successful if the profitability index is greater than one. This follows from:

$$\frac{NPV}{INV} + 1 = \frac{1}{INV}\sum_{1}^{t}\left(\frac{CF_t}{(1+r)^t}\right) - \frac{INV}{INV} + 1 = \frac{1}{INV}\sum_{1}^{t}\left(\frac{CF_t}{(1+r)^t}\right) \tag{25}$$

7.2 Economic parameters

Inflation

Inflation shows average increasing of prices on products in the country during the year. To estimate inflation of the next years it is necessary to analyze inflation for last 10 years. The data is presented in Table 13.

Table 13 – Inflation in Russia for 10 years

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Inflation, %	8.8	8.78	6.1	6.58	6.45	11.36	12.91	5.38	2.52	4.27
Average inflation, %	7.32									

Using date of Table 13, plot a graph:

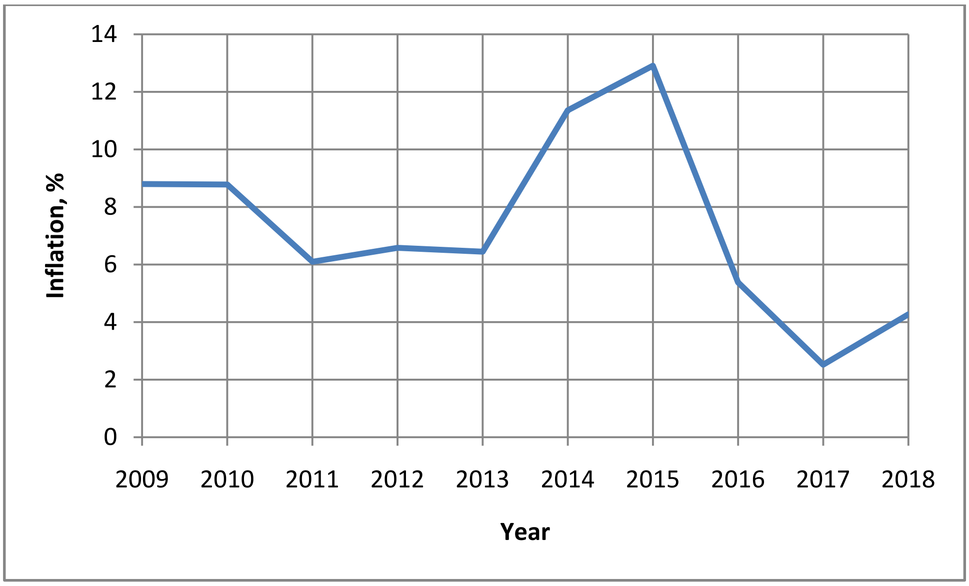

Figure 27 – Inflation in Russia

Taxes

According to the tax law of Russia, corporate tax rate is equal to 20% [25].

Depreciation

In Russia depreciation may be calculated in two methods: straight-line and method of decreasing residue. According to Russian laws, the firm has a right to select the method for calculation of depreciation. The easiest is straight-line but usually it is more profitable for firms to depreciate the equipment in the beginning of its exploitation.

Method of decreasing residue supposes unbalanced depreciation during whole lifetime. Method of decreasing residue gives an opportunity to realize accelerated depreciation with acceleration coefficient. The owner can set the coefficient from one to two and half. Coefficient for leased equipment can be taken up to three. That means the firm depreciates the most part of the costs on equipment when the equipment is relatively new yet [25].

The formulas for both methods are bellow.

Straight-line depreciation:

$$D = \frac{INV}{T}, \tag{26}$$

Where

INV – Investment;

T – Lifetime of the product.

Method of decreasing residue for year “t”::

$$D_t = S \cdot K \cdot K_a, \tag{27}$$

Where

S – residual value of the unit;

K – depreciation coefficient;

K_a – acceleration coefficient. Determined by the firm, according to the law - not more than two and half;

t – number of the period.

Formula for depreciation coefficient:

$$K = \frac{1}{T}, \tag{28}$$

Where

T – lifetime of the project.

Discount rate

It is necessary to calculate discount rate to evaluate risk of the project. To calculate discount rate I used Capital Assets Pricing Model (CAPM) [24]:

$$ER_i = R_f + \beta\left(ER_m - R_f\right), \tag{29}$$

Where

R_f – risk-free rate, equal to federal bonds rate in Russia (7.25%) [25];

β – stock volatility of the company, in sector of power generation it is about 0.544;

ER_m – market risk premium in Russia (9.43%).

$$ER_i = R_f + \beta\left(ER_m - R_f\right) = 7.25\% + 0.544(9.43\% - 7.25\%) = 8.44\% \qquad (30)$$

Escalation

Costs of goods every year increase or escalate. Average escalation can be taken according to inflation. In this case escalation is equal to 7.32%.

7.3 Inputs for economic model

To create an economic model it is necessary to determine all the inputs. Inflation, risk-free rate, tax rate and discount rate were determined in the previous subchapter.

Investment

According to Table 12 the project needs to invest 19 662 600 rubles. Also we need to install the equipment in which we invest. According to [1], cost of installation is equal to 20% of the equipment price. So, it will be:

$$19662600 \cdot 20\% = 3932520\,RUB \qquad (31)$$

But it is not an investment it is costs for first year of operation.

Lifetime of the project is 20 years but lifetime of the batteries is 12 years. Therefore, in the end of 12th year it is necessary to buy new batteries. Initial price for batteries is 5 088 000 RUB. This value should be discounted for 12th year:

$$5088000 \cdot (1 + escallation)^{12} = 5088000 \cdot (1 + 7.32\%)^{12} = 11877227\,RUB \qquad (32)$$

Therefore, we have investments in first and in the twelfth year and it is equal to 19 662 600 RUB and 5 553 370 RUB respectively. After 20 years, batteries will have residual value for the rest four years. Therefore, in the end of the project we can sell the batteries with price of its residual value, which is calculated below:

$$Residual\ value = 5553370 \cdot \frac{4}{12} = 3959075\,RUB \qquad (33)$$

This revenue will be accounted in the cash flow of 20th year.

Costs

Hybrid power plant with wind turbines generates 668 560.67 kWh by wind turbines and the rest load covered by diesel generator. The consumers need more 45 593.07 kWh a year. This volume will be covered by diesel generator and it needs 3600 kg of fuel a year.

Price for one ton of diesel fuel in Russia is 47 000 RUB. Also it is necessary to pay for shipping. We can use service of “Trader-Oil” company and its price is 26 000 RUB for shipping of one ton of fuel [28]. Therefore, annual cost for fuel is:

$$Fuel\ cost = 3.6 \cdot (47000 + 26000) = 262800\ RUB \tag{34}$$

The power plant need two specialists to service it. Average salary for specialist in Arkhangelsk Region is 31 122 rubles a month. Therefore, annual cost for stuff in the power plant is:

$$Stuff\ cost = 31122 \cdot 2 \cdot 12 = 746928\ RUB \tag{35}$$

The equipment should be serviced and repaired. According to [1], costs for repair and maintenance are equal to 1% of the equipment price. The price for wind installation has been already calculated but hybrid power plant also has diesel installation. There is no information about diesel generator model in the Koyda village but it is possible to take analogue, for example diesel power station Green Power GP505A/P (360 kW) which costs 3 730 385 RUB [27]. Therefore, costs for repair and maintenance are:

$$Repair\ and\ maintenance\ cost = (19662600 + 3730385) \cdot 1\% = 233930\ RUB \tag{36}$$

According to [29], price for 1 kWh in the Arkhangelsk Region is 5.65 RUB. Minimal price will be calculated in the next chapter.

All inputs were determined and now it is possible to create an economic model.

7.4 Creating of economic model

In this Section I will create an economic model with using of criteria which were described in the Section 7.1.

Net Present Value

In calculation was used real price for electricity in the Arkhangelsk Region (5.65 RUB/kWh) [29] and straight-line depreciation. NPV of the project is -12 372 219 RUB. NPV is negative and it can be explained that the Koyda village is supplied by the state company, so people have subsidies and pay for electricity less than it costs.

NPV of the power plant if we will do nothing and power will be generated only by diesel generator is -385 632 819 RUB. It is even less than in previous case. Therefore, if the power plant will be upgraded with wind turbines, we can save 373 260 601 RUB. The calculations have been done in Excel and presented in Appendices 4-7.

Minimal electricity price

To calculate minimal price it is necessary to make NPV equal to zero. Therefore, minimal price for 1 kWh in case of wind-diesel power plant is equal to 7.03 RUB/kWh. Therefore, to make the project at least lossless, we need subsidies in amount of (7.03 – 5.65) = 1.38 RUB for 1 kWh. Minimal price for 1 kWh in case of diesel power plant is 37.90 RUB.

Depreciation

Next I will calculate the NPV with another depreciation method – with decreasing residual method. In this case the equipment is depreciated in the beginning. The graph of dependence NPV on acceleration coefficient is presented below:

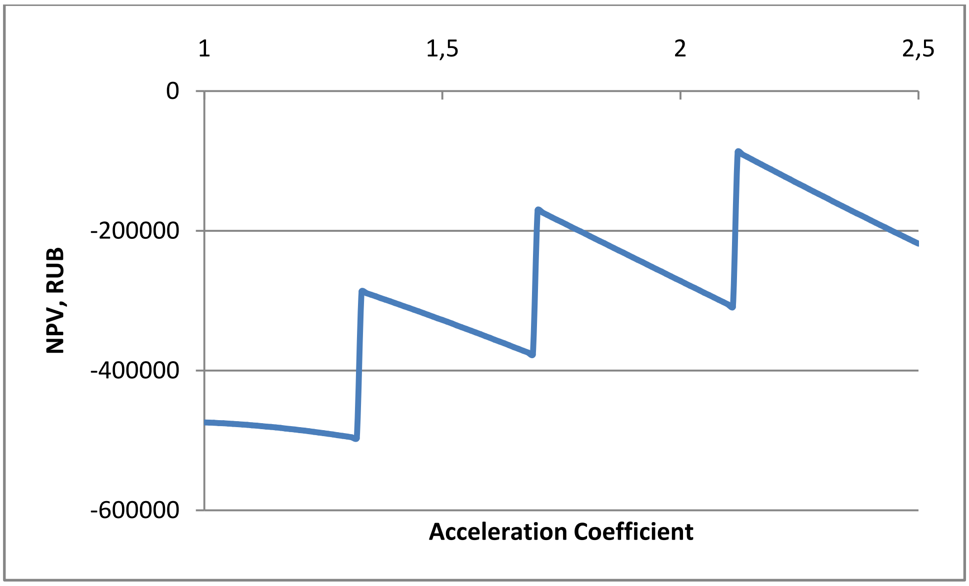

Figure 28 – Dependence of NPV on Acceleration Coefficient

According to graph in Figure 28, there is no sense to use method of decreasing value. We can take any acceleration coefficient but the result will be worse than in case with straight-line depreciation.

Taxes

In case with price 5.65 RUB/kWh and straight-line depreciation we start pay taxes in the eighth year, because in the first year we have negative profit, therefore we have tax shield. Also the depreciation decreases the taxes. In case with piece 7.03 RUB/kWh we start pay taxes in the third year.

IRR

In case with price 5.65 RUB/kWh internal rate of return is equal to 4%. In case with price 7.03 RUB/kWh internal rate of return is equal to calculated discount rate – 8.44%.

It is impossible to calculate Payback Period, because NPV is negative.

7.5 Sensitivity analysis

Sensitivity analysis of the project can show how different parameters influence on NPV. After sensitivity analysis it is possible to make conclusions which factors have more or less influence on NPV. In sensitivity analysis I use the real price equal to 5.65 RUB/kWh.

Here is a list of parameters which will be used in sensitivity analysis of NPV:

- Percentage of load coverage by wind turbines;
- Discount rate;
- Electricity price;
- Escalation.

Percentage of load coverage by wind turbines

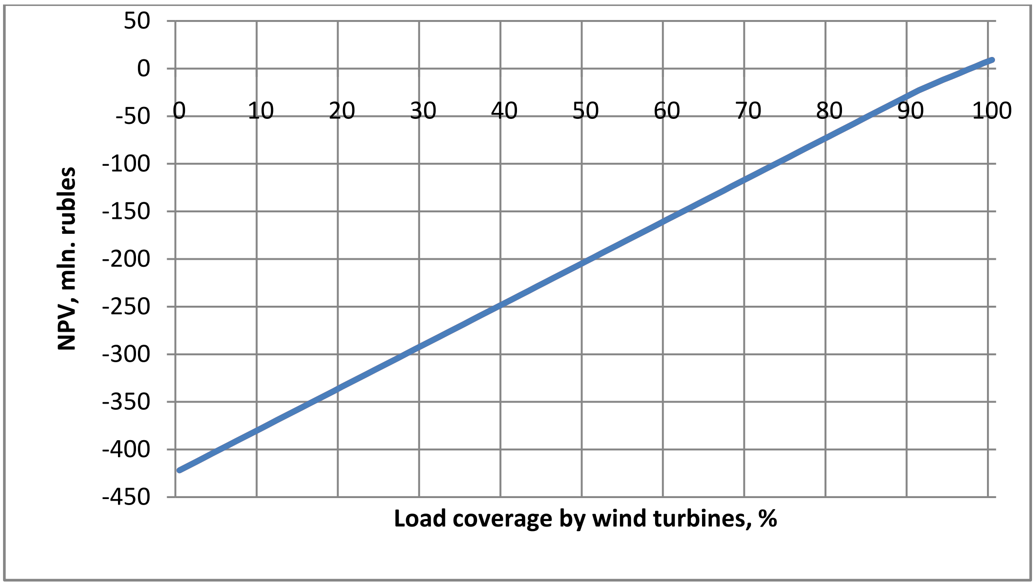

Figure 29 – Dependence of NPV on load coverage by wind turbines

The graph in Figure 29 has linear characteristic. According to the graph, NPV becomes positive when wind turbines generate 98% of required power for consumers or more.

Discount rate

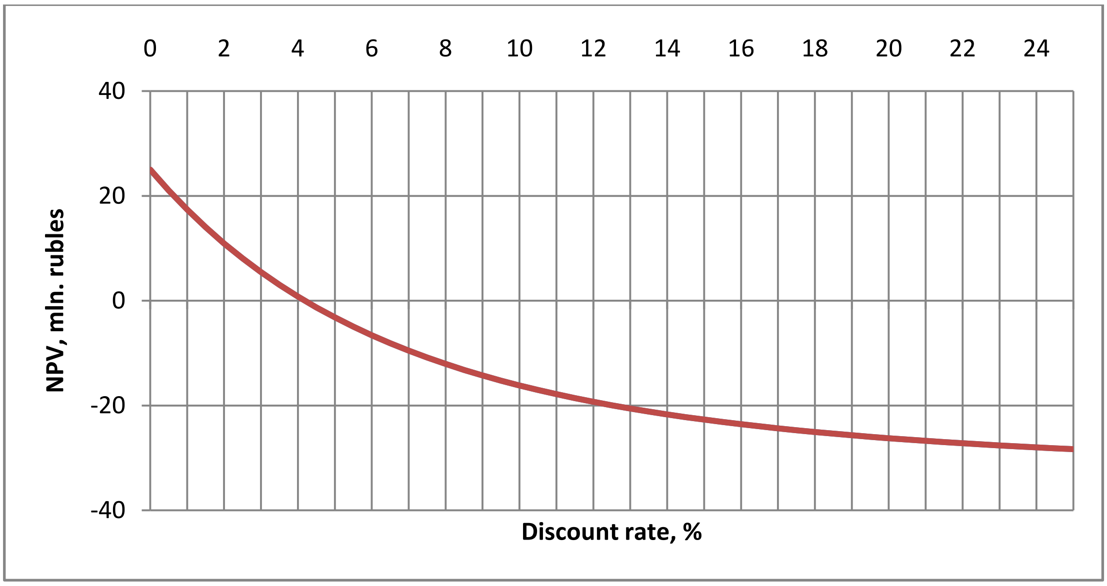

Figure 30 – Dependence of NPV on discount rate

The graph in Figure 30 has exponential characteristic. According to the graph, NPV becomes positive if discount rate is 4% or less. The greater the discount rate the less NPV.

Electricity price

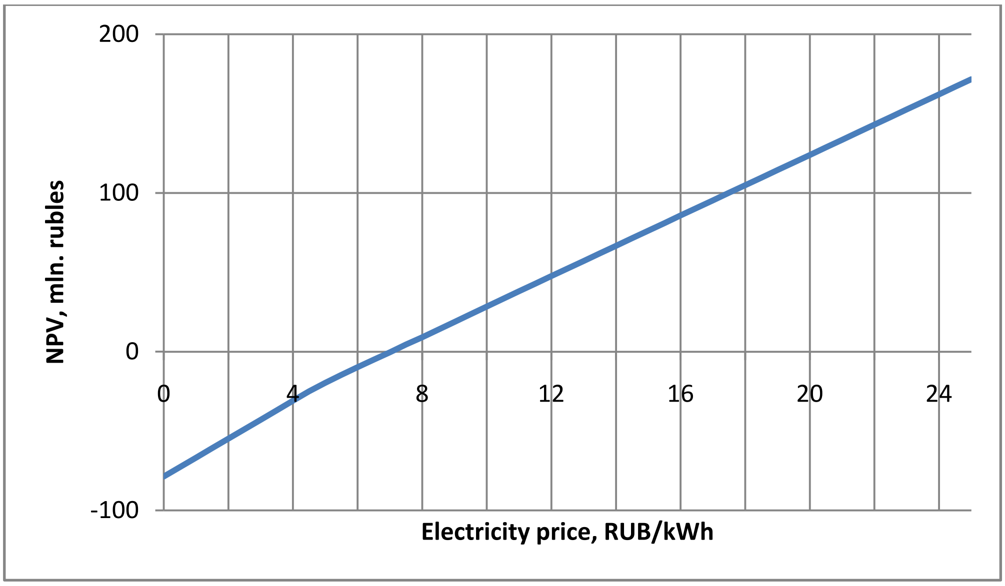

Figure 31 – Dependence of NPV on electricity price

The graph in Figure 31 has linear characteristic. According to the graph, the more electricity price the more NPV. NPV becomes positive when price is more than 7.04 rubles.

Escalation

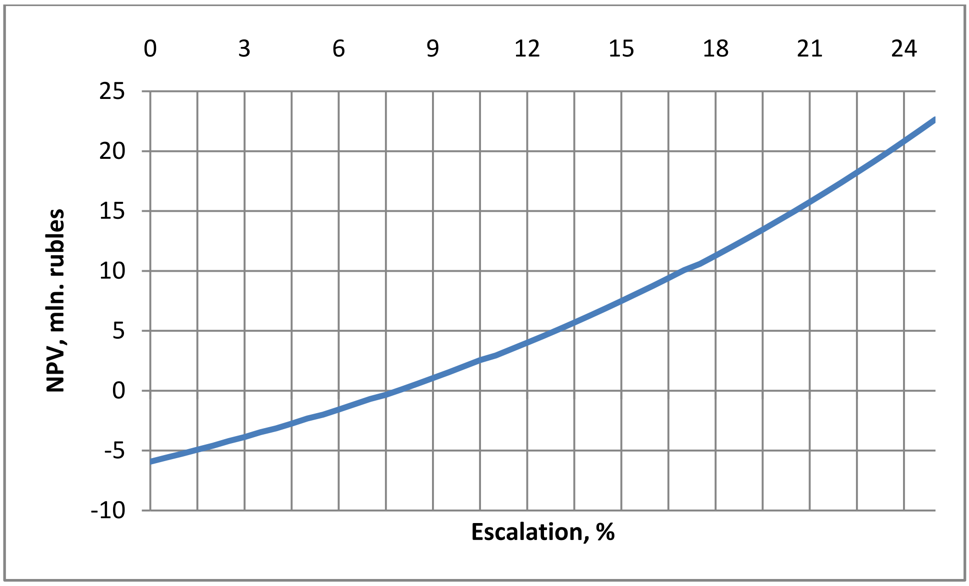

Figure 32 – Dependence of NPV on escalation

The graph in Figure 32 has exponential characteristic. According to the graph, NPV becomes positive if escalation is 8% or greater. The greater escalation the greater NPV.

Conclusion

There might be problems with electricity supply in the remote regions, which are not connected to central power system. Usually, in Russia in such regions consumers are supplied by diesel power plants. However it is expensive, there is harmful for the environment carbon emission and there might be interruptions in diesel fuel shipping. This paper presents how integration of renewable source of energy in diesel power plant can help to decrease fuel costs and carbon emission. Also there are more power sources in the hybrid power plant, therefore the reliability is higher.

In this paper I designed a hybrid power plant based on the diesel power plant in the Koyda village. In the beginning of the work I had to decide on which renewable energy source the hybrid power plant should be based. I analyzed the geography of the Koyda village and its weather conditions. According to the results of my analysis, value of insolation is too low to use PV panels. Average wind velocity in the region is 5.86 m/s and it is a good value for using wind turbines. Therefore, I decided it is more efficient to upgrade (that is, to combine) the diesel power plant with wind turbines.

The designed wind-diesel power plant includes three wind turbines “CONDOR AIR WES 380/50-60”, capacity of each is 60 kW, total capacity is 180 kW; 120 storage batteries; two power controlled boxes, charge controllers and diesel generator with capacity of 360 kW, which was already installed in the power plant before. Wind turbines cover 94% of consumers’ energy needs. The lack of energy is supplied by diesel generator.

Fuel consumption is decreased from 79.5 to 3.6 ton annually. Carbon emission is decreased by 95%. Before installation of wind turbines carbon emission was 249.1 ton a year. After the recommended use of a wind-diesel power plant, carbon emission decreased to 11.3 ton a year.

Model of wind turbine was created in program “MATLAB Simulink”. It shows how the generated energy changes in time depending on wind velocity. In Figures 24 and 25 the graphs of load coverage by wind turbines were plotted based on MATLAB model.

I made an economic evaluation of the project. I estimated costs and investments in the project and based on this data I calculated minimal price. Minimal price is 7.03 RUB/kWh. The real price for energy in the region is 5.65 RUB/kWh. The NPV of the project with energy price 5.65 RUB/kWh is -12 372 219 RUB. I also estimated minimal price and NPV of the power plant which operates only with diesel generator. Its minimal price is 37.89 RUB/kWh and its NPV is

-385 632 819 RUB. The Koyda village is supplied by state utility company, therefore people have subsidies and pay for energy less than it costs. NPV of the project is negative but it is still more efficient than diesel power plant without wind turbines. If the power plant will be upgraded with wind turbines it can save 373 260 601 RUB in 20 years. I also made sensitivity analysis of NPV. Graphs in Figures 28-31 shows how NPV depends on load coverage by wind turbines, discount rate, price for electricity and escalation.

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Appendices

Appendix 1 – Load graph of the Koyda village, kW

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Jan	90	90	90	90	90	126	180	216
Feb	90	90	90	90	90	126	180	216
Mar	72	72	72	72	72	100.8	144	172.8
Apr	43.2	43.2	43.2	43.2	50.4	60.48	80.64	89.28
May	43.2	43.2	43.2	43.2	50.4	60.48	80.64	89.28
Jun	37.8	37.8	37.8	37.8	44.1	52.92	70.56	78.12
Jul	37.8	37.8	37.8	37.8	44.1	52.92	70.56	78.12
Aug	37.8	37.8	37.8	37.8	44.1	52.92	70.56	78.12
Sept	48.6	48.6	48.6	48.6	56.7	68.04	90.72	100.44
Oct	48.6	48.6	48.6	48.6	56.7	68.04	90.72	100.44
Nov	81	81	81	81	81	113.4	162	194.4
Dec	90	90	90	90	90	126	180	216
Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Jan	144	108	108	126	144	108	108	108
Feb	144	108	108	126	144	108	108	108
Mar	115.2	86.4	86.4	100.8	115.2	86.4	86.4	86.4
Apr	80.64	60.48	60.48	60.48	69.12	60.48	60.48	60.48
May	80.64	60.48	60.48	60.48	69.12	60.48	60.48	60.48
Jun	70.56	52.92	52.92	52.92	60.48	52.92	52.92	52.92
Jul	70.56	52.92	52.92	52.92	60.48	52.92	52.92	52.92
Aug	70.56	52.92	52.92	52.92	60.48	52.92	52.92	52.92
Sept	90.72	68.04	68.04	68.04	77.76	68.04	68.04	68.04
Oct	90.72	68.04	68.04	68.04	77.76	68.04	68.04	68.04
Nov	129.6	97.2	97.2	113.4	129.6	97.2	97.2	97.2
Dec	144	108	108	126	144	108	108	108
Hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Jan	144	252	360	342	252	180	126	108
Feb	144	252	360	342	252	180	126	108
Mar	115.2	201.6	288	273.6	201.6	144	100.8	86.4
Apr	60.48	60.48	72	80.64	144	201.6	120.96	51.84
May	60.48	60.48	72	80.64	144	201.6	120.96	51.84
Jun	52.92	52.92	63	70.56	126	176.4	105.84	45.36
Jul	52.92	52.92	63	70.56	126	176.4	105.84	45.36
Aug	52.92	52.92	63	70.56	126	176.4	105.84	45.36
Sept	68.04	68.04	81	90.72	162	226.8	136.08	58.32
Oct	68.04	68.04	81	90.72	162	226.8	136.08	58.32
Nov	129.6	226.8	324	307.8	226.8	162	113.4	97.2
Dec	144	252	360	342	252	180	126	108

Appendix 2 – 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 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 3 – AGREPREF method matrices

Pij							
	V1	V2	V3	V4	V5	V6	V7
V1		0.2	0.2	0.45	0.45	0.65	0.2
V2	0.8		0.65	0.8	0.45	0.65	0.45
V3	0.35	0.35		0.8	0.8	0.45	0
V4	0	0.2	0.2		0	0.65	0.2
V5	0.35	0	0.2	0.35		0.65	0.2
V6	0.35	0.35	0	0.35	0.35		0
V7	0.35	0	0.2	0.8	0.8	0.45	

Pji							
	V1	V2	V3	V4	V5	V6	V7
V1		0.8	0.35	0	0.35	0.35	0.35
V2	0.2		0.35	0.2	0	0.35	0
V3	0.2	0.65		0.2	0.2	0	0.2
V4	0.45	0.8	0.8		0.35	0.35	0.8
V5	0.45	0.45	0.8	0		0.35	0.8
V6	0.65	0.65	0.45	0.65	0.65		0.45
V7	0.2	0.45	0	0.2	0.2	0	

Pi=j							
	V1	V2	V3	V4	V5	V6	V7
V1		0	0.45	0.55	0.2	0	0.45
V2			0	0	0.55	0	0.55
V3				0	0	0.55	0.8
V4					0.65	0	0
V5						0	0
V6							0.55
V7							

V3 = V7; V4 = V5.

Pij-Pji							
	V1	V2	V3	V4	V5	V6	V7
V1		-0.6	-0.15	0.45	0.1	0.3	-0.15
V2	0.6		0.3	0.6	0.45	0.3	0.45
V3	0.15	-0.3		0.6	0.6	0.45	-0.2
V4	-0.45	-0.6	-0.6		-0.35	0.3	-0.6
V5	-0.1	-0.45	-0.6	0.35		0.3	-0.6
V6	-0.3	-0.3	-0.45	-0.3	-0.3		-0.45
V7	0.15	-0.45	0.2	0.6	0.6	0.45	

V1 ≻ V4; V2 ≻ V1, V4, V5, V7; V3 ≻ V4, V5, V6; V7 ≻ V6.

Appendix 4 – Financial model, calculation of wind-diesel power plant NPV with electricity price 5.65 RUB/kWh with straight-line depreciation

Year		1	2	3	4	5	6
Investment	19 662 600.00						
Cost		6 595 106.41	2 857 487.74	3 066 655.84	3 291 135.05	3 532 046.13	3 790 591.91
Depretiation		728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00
D. batteries		424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00
taxes	0.2	-	-	-	-	-	-
Revenues		4 034 968.65	4 330 328.36	4 647 308.39	4 987 491.37	5 352 575.74	5 744 384.28
CF		- 2 560 137.76	1 472 840.62	1 580 652.56	1 696 356.32	1 820 529.61	1 953 792.37
Sum of CF		- 2 560 137.76	- 1 087 297.13	493 355.42	2 189 711.75	4 010 241.36	5 964 033.73
		NPV	- 12 372 218.67				

Year	7	8	9	10	11	12	13
Investment						11 877 227.38	
Cost	4 068 063.23	4 365 845.46	4 685 425.35	5 028 398.49	5 396 477.26	5 791 499.39	6 215 437.15
Depretiation	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00
D. batteries	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00
taxes	-	219 513.29	252 457.63	287 813.50	325 757.41	366 478.82	410 181.04
Revenues	6 164 873.21	6 616 141.93	7 100 443.52	7 620 195.99	8 177 994.33	8 776 623.52	9 419 072.36
CF	2 096 809.98	2 030 783.17	2 162 560.53	2 303 984.00	2 455 759.66	2 618 645.30	2 793 454.17
Sum of CF	8 060 843.71	10 091 626.88	12 254 187.41	14 558 171.41	17 013 931.07	19 632 576.37	22 426 030.54

Year	14	15	16	17	18	19	20
Cost	6 670 407.15	7 158 680.95	7 682 696.40	8 245 069.77	8 848 608.88	9 496 327.05	10 191 458.19
Depretiation	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00
D. batteries	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00
taxes	457 082.26	507 416.65	561 435.52	619 408.56	681 625.24	748 396.17	820 054.74
Revenues	10 108 548.45	10 848 494.20	11 642 603.98	12 494 842.59	13 409 465.07	14 391 037.91	15 444 461.88
CF	2 981 059.05	3 182 396.60	3 398 472.07	3 630 364.25	3 879 230.95	4 146 314.69	12 918 176.33
Sum of CF	25 407 089.58	28 589 486.19	31 987 958.25	35 618 322.50	39 497 553.45	43 643 868.14	56 562 044.47

Appendix 5 – Financial model, calculation of diesel power plant NPV with electricity price 5.65 RUB/kWh

Year	1	2	3	4	5	6
Cost	27 061 240.61	29 042 123.42	31 168 006.85	33 449 504.95	35 898 008.72	38 525 742.96
Taxes	-	-	-	-	-	-
Revenues	4 034 968.65	4 330 328.36	4 647 308.39	4 987 491.37	5 352 575.74	5 744 384.28
CF	- 23 026 271.95	- 24 711 795.06	- 26 520 698.46	- 28 462 013.58	- 30 545 432.98	- 32 781 358.67
	NPV	- 385 632 819.30				

Year	7	8	9	10	11	12	13
Cost	41 345 827.34	44 372 341.90	47 620 397.33	51 106 210.41	54 847 185.01	58 861 998.96	63 170 697.28
Taxes	-	-	-	-	-	-	-
Revenues	6 164 873.21	6 616 141.93	7 100 443.52	7 620 195.99	8 177 994.33	8 776 623.52	9 419 072.36
CF	- 35 180 954.13	- 37 756 199.97	- 40 519 953.81	- 43 486 014.43	- 46 669 190.68	- 50 085 375.44	- 53 751 624.92

Year	14	15	16	17	18	19	20
Cost	67 794 792.32	72 757 371.12	78 083 210.69	83 798 901.71	89 932 981.31	96 516 075.55	103 581 052.28
Taxes	-	-	-	-	-	-	-
Revenues	10 108 548.45	10 848 494.20	11 642 603.98	12 494 842.59	13 409 465.07	14 391 037.91	15 444 461.88
CF	- 57 686 243.87	- 61 908 876.92	- 66 440 606.71	- 71 304 059.12	- 76 523 516.25	- 82 125 037.64	- 88 136 590.39

Appendix 6 - Financial model, calculation of wind-diesel power plant NPV with electricity price 6.96 RUB/kWh with straight-line depreciation

Year		1	2	3	4	5	6
Investment	19 662 600.00						
Cost		6 595 106.41	2 857 487.74	3 066 655.84	3 291 135.05	3 532 046.13	3 790 591.91
Depretiation		728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00
D. batteries		424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00
taxes	0.2	-	-	301 088.02	340 003.63	381 767.86	426 589.23
Revenues		4 970 510.06	5 334 351.39	5 724 825.92	6 143 883.17	6 593 615.42	7 076 268.07
CF		- 1 624 596.35	2 476 863.66	2 357 082.06	2 512 744.50	2 679 801.43	2 859 086.93
Sum of CF		- 1 624 596.35	852 267.31	3 209 349.37	5 722 093.87	8 401 895.31	11 260 982.24
		NPV	64 995.80				

Year	7	8	9	10	11	12	13
Investment						11 877 227.38	
Cost	4 068 063.23	4 365 845.46	4 685 425.35	5 028 398.49	5 396 477.26	5 791 499.39	6 215 437.15
Depretiation	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00
D. batteries	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00
taxes	474 691.53	526 314.92	581 717.14	641 174.80	704 984.76	773 465.61	846 959.26
Revenues	7 594 250.89	8 150 150.06	8 746 741.04	9 387 002.49	10 074 131.07	10 811 557.46	11 602 963.47
CF	3 051 496.13	3 257 989.68	3 479 598.55	3 717 429.20	3 972 669.05	4 246 592.46	4 540 567.06
Sum of CF	14 312 478.36	17 570 468.04	21 050 066.59	24 767 495.79	28 740 164.84	32 986 757.30	37 527 324.36

Year	14	15	16	17	18	19	20
Investment							
Cost	6 670 407.15	7 158 680.95	7 682 696.40	8 245 069.77	8 848 608.88	9 496 327.05	10 191 458.19
Depretiation	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00	728 730.00
D. batteries	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00	424 000.00
taxes	925 832.65	1 010 479.57	1 101 322.64	1 198 815.42	1 303 444.68	1 415 732.80	1 536 240.40
Revenues	12 452 300.40	13 363 808.79	14 342 039.59	15 391 876.89	16 518 562.27	17 727 721.03	19 025 390.21
CF	4 856 060.60	5 194 648.27	5 558 020.55	5 947 991.69	6 366 508.72	6 815 661.19	15 782 919.00
Sum of CF	42 383 384.96	47 578 033.23	53 136 053.78	59 084 045.48	65 450 554.19	72 266 215.38	88 049 134.38

Appendix 7 – Financial model, calculation of diesel power plant NPV with electricity price 6.96 RUB/kWh

Year		1	2	3	4	5	6
Cost		27 061 240.61	29 042 123.42	31 168 006.85	33 449 504.95	35 898 008.72	38 525 742.96
Taxes		-	-	-	-	-	-
Revenues		4 970 510.06	5 334 351.39	5 724 825.92	6 143 883.17	6 593 615.42	7 076 268.07
CF		- 22 090 730.55	- 23 707 772.02	- 25 443 180.94	- 27 305 621.78	- 29 304 393.30	- 31 449 474.88
		NPV	- 369 964 826.23				

Year	7	8	9	10	11	12	13
Cost	41 345 827.34	44 372 341.90	47 620 397.33	51 106 210.41	54 847 185.01	58 861 998.96	63 170 697.28
Taxes	-	-	-	-	-	-	-
Revenues	7 594 250.89	8 150 150.06	8 746 741.04	9 387 002.49	10 074 131.07	10 811 557.46	11 602 963.47
CF	- 33 751 576.45	- 36 222 191.84	- 38 873 656.28	- 41 719 207.92	- 44 773 053.94	- 48 050 441.49	- 51 567 733.81

Year	14	15	16	17	18	19	20
Cost	67 794 792.32	72 757 371.12	78 083 210.69	83 798 901.71	89 932 981.31	96 516 075.55	103 581 052.28
Taxes	-	-	-	-	-	-	-
Revenues	12 452 300.40	13 363 808.79	14 342 039.59	15 391 876.89	16 518 562.27	17 727 721.03	19 025 390.21
CF	- 55 342 491.93	- 59 393 562.33	- 63 741 171.10	- 68 407 024.82	- 73 414 419.04	- 78 788 354.51	- 84 555 662.06