Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management and Humanities

# Autonomous hybrid power supply system based on wind generator, photovoltaic panel, and diesel generator

## Master’s Thesis

Study Program: Electrical Engineering, Power Engineering and Management

Branch of study: Management pf Power Engineering and Electrotechnics

Supervisor: Mgr. Sherzod Tashpulatov, M.A., Ph.D.

Karateev Alexander

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# MASTER‘S THESIS ASSIGNMENT

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1. Analysis of renewable energy sources and its potential in the considered settlement
2. Simulation of a hybrid power supply system using MatLab
3. Feasibility criteria of designing a hybrid power supply system
4. Economic and environmental analyses

Bibliography / sources:

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## III. Assignment receipt

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.

Date of assignment receipt

Student’s signature

**Declaration**

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

Date                                                                                                        Signature

## Abstract

This paper is devoted to renewable energy sources and their use in decentralized systems, which is relevant for current situation in Russia’s remote and decentralized regions. That is why diesel power stations supply most of these settlements. One of the main problems is related to delivery of fuel to remote settlements. It is expensive and it influences local tariffs. Introduction of a hybrid power supply system should help to decrease tariff and dependence on fuel and at the same time, it will decrease $CO_2$ emissions. This paper analyzes feasibility of a hybrid power supply system in technical and economic ways. Technical analysis represents energy potential in the region from RES. Economic model represents cost of project and possible benefit from introduction of RES. Economic analysis implemented by NPV, IRR, ROI and sensitivity analysis. Results show that introduction of HPSS is beneficial for both investor and customer, as tariff becomes less than it used to be, and project possibly can be paid off.

## Key words

Wind turbines, diesel power station, photovoltaic panel, renewable energy sources, hybrid power supply system, net present value, internal rate of return, profitability index.

## Contents

## List of abbreviations

| | |
|---|---|
| RES | Renewable Energy Source |
| HPSS | Hybrid Power Supply System |
| HAWT | Horizontal Axis Wind Turbine |
| PV | Photovoltaic |
| WT | Wind Turbine |
| DPS | Diesel Power Station |
| PPS | Photovoltaic Power Station |
| VAC | Volt Ampere Characteristic |
| MPPT | Maximum Power Point Tracking |
| AB | Accumulator batteries |
| NPV | Net Present Value |
| CAPM | Capital Asset Pricing Model |
| LEC | Levelled Energy Cost |
| IRR | Internal Rate of Return |
| ROI | Return On Investment |
| PP | Payback Period |
| PI | Profitability Index |

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## 1. Introduction

Nowadays the world faces with two important issues in the energy sphere such as environmental problem and reduction of fossil fuels consumption like oil, coal and gas. Therefore, it is very important to keep up to date and develop renewable energy sources (RES).

Autonomous power supply of remote locations is an important topic to discuss currently in Russia. To solve the problem of supplying remote objects, one can use hybrid power supply systems (HPSS). Hybrid power systems typically consist of diesel generators that run on fuel, combined with a wind generator, or a photovoltaic panel. Thus, hybrid power supply system combined with diesel generators, wind generators or solar photo panels are able to solve a number of problems essential for decentralized energy system. [1]

However, when discussing renewable energy, we also should mention its drawbacks. A significant drawback is the relatively low energy density per unit area of the installation. The second drawback is the intermittency problem of renewable energy, i.e., constantly changing wind speed or cloudy days. This means that such a plant should include either an energy storage device or a plant operating on traditional fuel in order to ensure a constant supply of energy to the consumer. These disadvantages lead to an increase in the cost of generated energy.

In Russia today, despite the high cost of energy, the use of renewable energy in particularly favorable cases may prove to be economically competitive. This applies to the territories of the country that are not connected to centralized energy supply and use expensive delivered fuel. In these cases, the use of renewable energy is also of great social importance, increasing the reliability of energy supply. For the country's recreational areas, the environmental cleanliness of renewable energy may be a decisive factor.

In my master’s thesis, I will consider settlement at the North of Russian Federation, as this settlement is decentralized. This settlement is called Karatayka with a population of approximately 500 inhabitants. [2]

In addition, it is important to develop alternative energy sources starting from small settlements, as they require minimum amount of investments. Developing of such systems is complicated and that is why we need to analyze experience of countries, which succeeded in this sphere, such as Germany or Denmark.

In this thesis, I will consider types of RES and its classification make electrical and economical calculations in order to analyze feasibility of such project.

## 2. Description of the Karatayka settlement

Karatayka settlement is located in Zapolyarny district of Nenets Autonomous Okrug 68°45′42″ N. 61°24′35″ E. Its population is 544 inhabitants [2].

Figure 1 – Location of Karatayka [3]

Karatayka’s total installed capacity is 500 kW. In case of successful integration of RES in power supply system, there is a possibility to decrease costs of fuel, and $CO_2$ emissions. On Figure 2, electric load of Karatayka at summer and winter period is presented.

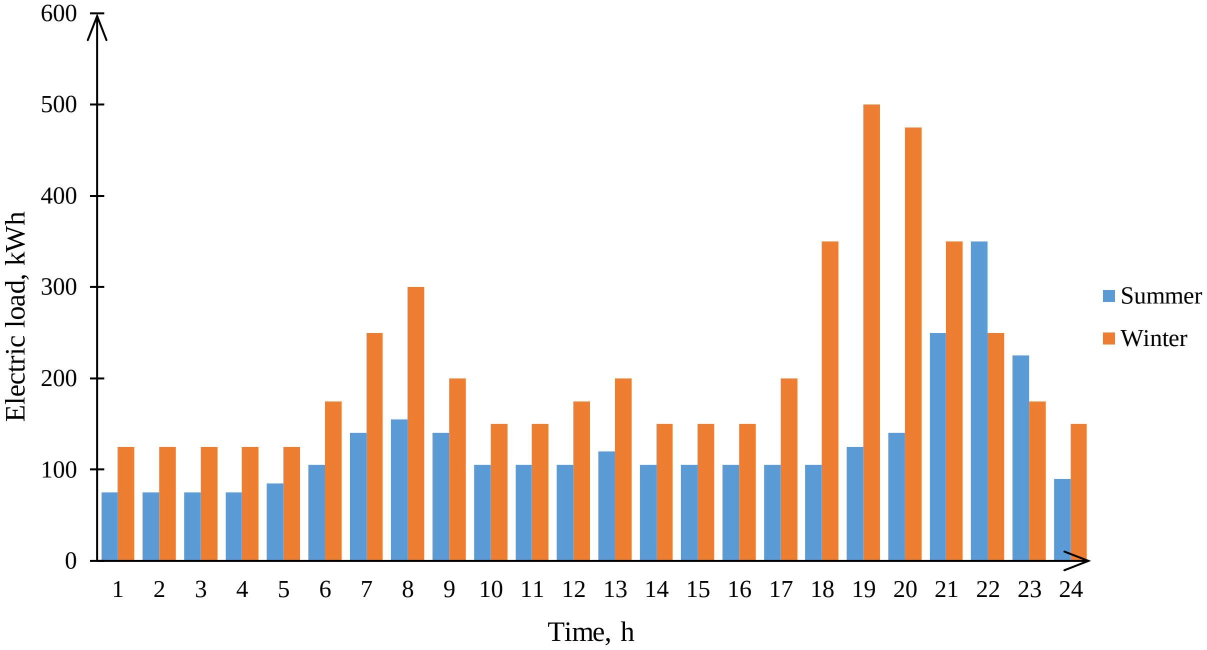


Figure 2 – Electric load of village Karatayka [4]

## 3. Overview of RES

Renewable energy sources are primarily those which are inexhaustible in nature, and which are ultimately derived from the radiant energy of the sun reaching the earth. These include the obvious examples of hydroelectric power, solar energy, and wind power, as well as some not quite so obvious examples, such as combustible renewable wastes and biomass fuels like ethanol made from grain crops [5].

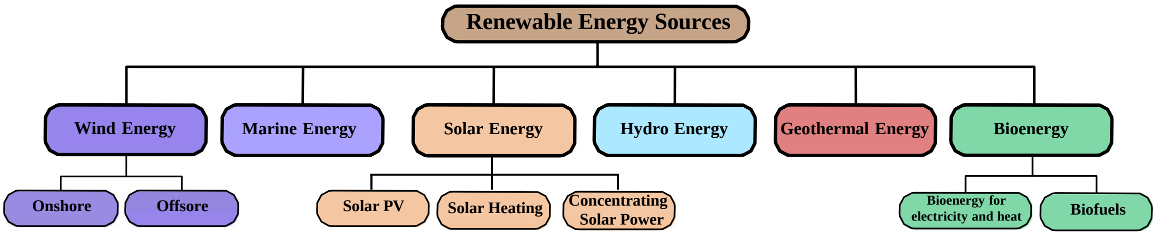


Figure 3 – Classification of RES [6]

In this chapter, I consider only solar and wind power renewable energy sources and equipment that converts it into electrical energy.

### 3.1 Wind power

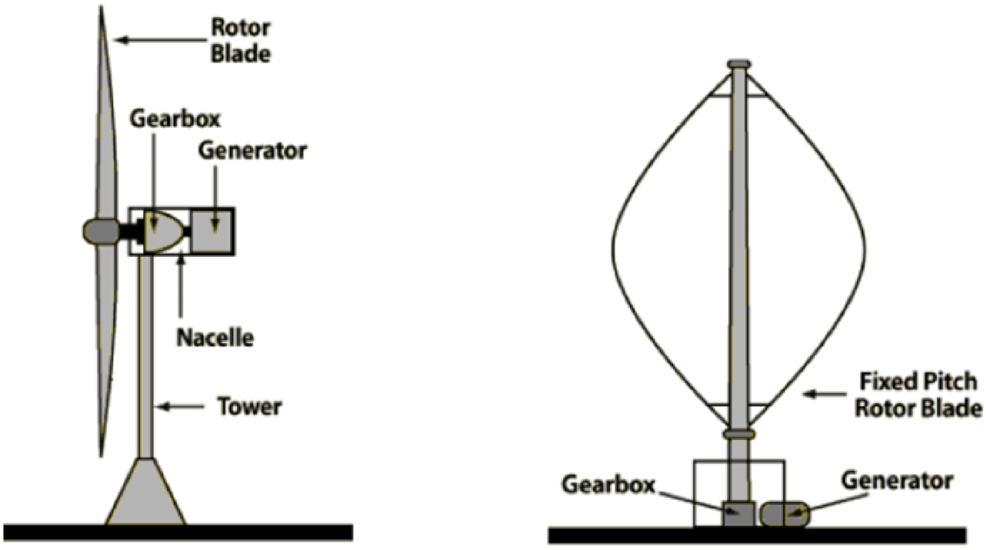
Wind is characterized by speed, which cannot be perfectly predicted. Usage of wind power can be described by following parameters [1]:

- Average annual speed
- Variability index of average speed
- Speed at different height
- Frequency of wind speed
- Energy potential of the region

Wind's seasonal and daily fluctuations are mainly function of heating of the Earth surfaces and as such they are broadly predictable. However, they cannot be forecast accurately even week ahead. Average annual wind speeds at the same site can differ up to 30%. But these changes become less important if number of wind generators is increased [7].

A wind generator or wind turbine (WT) is an equipment that converts the kinetic energy of wind into mechanical energy with further conversion of mechanical energy into electrical energy. Wind generator consists of several parts. The main nodes are the rotor and the generator. The operation principle is simple. Blades of the wind generator rotate by influence of wind. It makes rotor which is connected by the shaft to the blades revolve. Wind generators are classified based on rotation type (horizontal and vertical axis of rotation). A horizontal axis machine has its blades rotating on an axis parallel to the ground. A vertical axis machine has its blades rotating on an axis perpendicular to the ground [8].

Until the early 1970s there was no interest in developing efficient wind machines as energy producer. After 1973 interest to RES started to grow resulting in advance in technology in the late 1990s. Better turbine were designed and WT were optimized for low speeds and larger sizes [7].



Horizontal axis

Vertical axis

Figure 4 – Types of wind turbines [9]

### Horizontal axis wind turbine

Horizontal axis wind turbines (HAWT) are the most common type, which are used today. This type of wind generator is traditional and fully reflects the design described above. The main disadvantage of such wind turbines is the high speed of deterioration as well as vibration, high noise effect during operation. The main advantage of classic wind generators is their high efficiency, caused by ability to adjust angle of blades. [9]

### Vertical axis wind turbine

Vertical axis wind turbines (VAWT), however are not so commonly used. VAWT are classified into following types [9]:

- Savonius
- Darrieus wind turbine

#### *Savonius wind turbine*

Blades of Savonius rotor are designed in shape of curved half cylinders. The operation of the rotor is based on the difference in resistance that occurs when the air flows around its blades. The convex shape of the blades contributes to their movement around the axis.

The advantages of the Savonius wind generator are operation at low wind speeds, low noise, simplicity of design and maintainability.

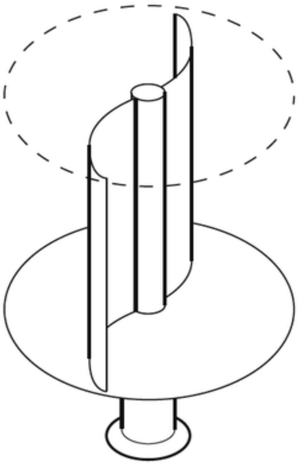


Figure 5 – Savonius wind turbine [10]

*Darrieus wind turbine*

Blades of Darrieus WT are fixed at the base and on the top of the axis of rotation. The advantage of this design is speed of rotation, thus higher energy. One of the main disadvantages of this WT is impossibility to rotate at low speed wind. In addition, rotor is vulnerable to increased aerodynamic loads, causing vibration and noise.

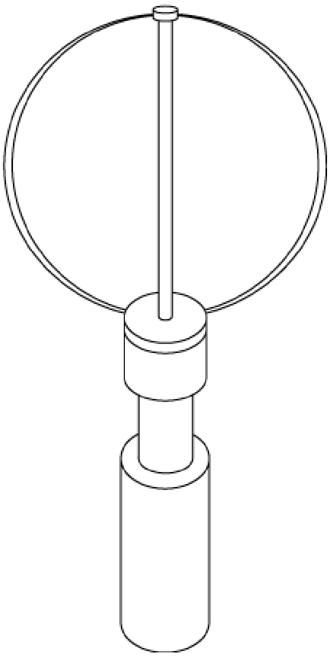


Figure 6 – Darrieus wind turbine [10]

In this paper I consider HAWT to be used in process of designing HPSS, as this WT has higher efficiency compare to others.

Finally, it its worth mentioning negative impact of WT. Those negativities are told by people who live in the proximity of WT and environmentalists. Bird strikes, noise, interference with electromagnetic waves, and the esthetic aspect of large wind turbines those are main effects. High speed of blades necessary for high efficiency of WT in the earlier models made them noisy and increased local bird mortality. Better designed WT can almost remove the noise from gearbox by insulating the nacelle and reducing the aerodynamic noise caused by blades. Appropriate exclusion zones and offshore siting are the only effective ways to deal with the noise [7].

However there is a new technology, which is called vortex technology, that allows avoid mentioned drawbacks of WT. It uses oscillations from impact of wind to generate power. There are no blades, no gear or noise. Nevertheless, this technology is not so popular in Russia that is why I do not consider implementation of this type in my project.

### 3.2 Solar power

Sun energy exists at any spot on the Earth surface. Solar radiation power at summer cloudless day is 7-9 · $10^6$ kW on the area of 10 $km^2$ [1]. Radiant energy passing through the atmosphere is scattered and absorbed. The unreflect part of the radiation is absorbed turning into heat and becoming a heat source.

Direct conversions of solar radiation harness by far the largest renewable energy resource but their efficiency and capital and operating costs have kept them from making a commercial breakthrough comparable to the one experienced by wind power since the early 1990s [7].

Photovoltaic (PV) panel is the combination of photoelectric converters, which are semiconductor devices that convert solar energy into direct current. When sunlight incidents on a photocell, electron and vacancy pairs are generated in it. Excess electrons and vacancies are partially transported through the *p-n* junction from one semiconductor layer to another. As a result, voltage appears in the external circuit. In this case, a positive pole of the current source is formed at the contact of the *p*-layer, and a negative pole at the *n*-layer. PV panels, which are connected to an external load in the form of a battery form a closed circuit. As a result, the solar panel is working, and the battery is gradually charging.

The solar power supply system includes panels, controller, batteries, inverter and transformer. The controller in this circuit protects both solar panels and batteries. On the one hand, it prevents reverse currents from flowing at night and in cloudy weather, and on the other hand, it protects batteries from excessive charge or discharge.

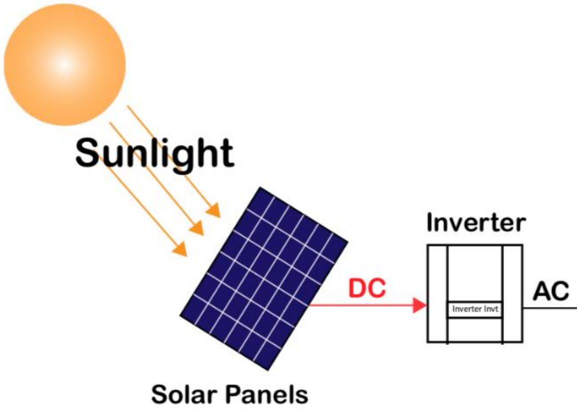


Figure 7 – Photovoltaic power supply system [11]

**Inverter**

Usually an inverter consists of power switches (transistors) and a control system. To control the power switches, special integrated control circuits, called drivers, have been developed. Drivers convert standard signals from microchips or from a microprocessor to signals that control power switches. The control is due to pulse width modulation (PWM)

Pulse width modulation is a method of encoding an analog signal by changing the width (duration) of rectangular pulses of a carrier frequency. The modulation of the width of the output pulses is achieved by comparing the positive saw tooth voltage received at the capacitor C with two control signals.

**Maximum Power Point Tracking**

Maximum Power Point Tracking (MPPT) is a technique commonly used with photovoltaic solar systems to maximize energy extraction in all conditions.

Regardless of the final destination of solar energy, the central issue considered by the MPPT is that the efficiency of energy transfer from a solar cell depends on both the amount of sunlight falling on the solar panels and the electrical characteristics of the load. When the amount of sunlight changes, the load characteristic changes, which gives the maximum power transfer efficiency, so the system efficiency is optimized when the load changes, in order to maintain power transfer with maximum efficiency. This load characteristic is called the maximum power point (MPP), and MPPT is the process of finding this point and storing the load characteristic there. The electrical circuits can be designed to represent arbitrary loads on the photovoltaic cells, and then convert the voltage, current or frequency to fit other devices or systems, and MPPT solves the problem of choosing the best load [1].

Solar cells have a complex relationship between temperature and total resistance, which leads to a non-linear output characteristic. The purpose of the MPPT system is to sample the output of the photocells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.

Operation principle of MPPT is presented on Figure B.3.

There are two types of supply system:

- On-grid system
- Off-grid system

Off-grid system will be considered further, as this system does not rely on a centralized power system.

### 3.3 Combining RES with diesel power station

First of all it is important to define and describe structure of future Hybrid Power Supply Systems **(**HPSS). Since a decentralized power supply is required for electricity consumers in decentralized zones, wind-diesel and wind-photo-diesel power plants seem to be the most suitable options for autonomous systems [12].

HPSS is a combination of different energy sources which are used in decentralized systems for power supply. Larger systems with installed capacity more than 100 kW consist of diesel generators connected to AC-bus, renewable sources, loads, and energy storage.

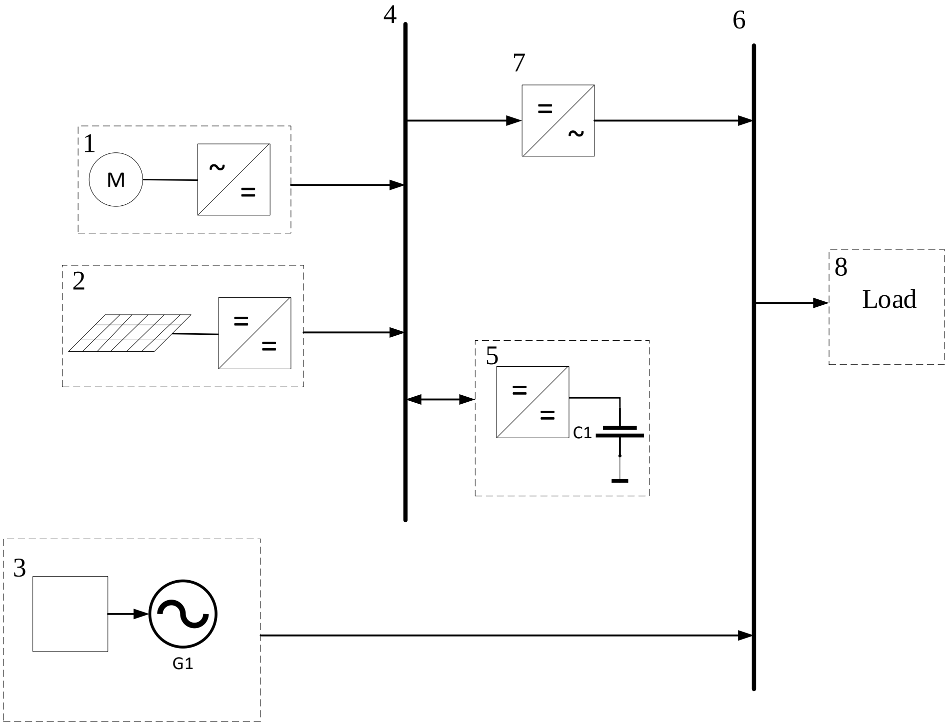


Figure 8 – Structure of HPSS [12]

1 – WT and rectifier, 2 – PV-panels and DC/DC converter, 3 – DPS, 4 – DC bus, 5 – AB, 6 – AC bus, 7 – Inverter, 8 – Electrical load (settlement).

The structure presented on Figure 8 has advantages compared to others. For instance there is no need in coordination between DPS, PV panels and WT. Moreover, due to high efficiency of power electronics, losses associated with conversion of energy are negligible.

## 4. Analysis of energy potential of the region

In order to analyze energy potential of Karatayka I use Power Data Access Viewer [13]. This web site allows to check different parameters of any region on the Earth. I evaluate wind speed, repeatability of wind speed for wind energy potential and insolation for solar energy potential.

### 4.1 Wind energy potential

Average wind speed is approximate parameter, which allows considering possibility to use WT in the region. The distribution of speeds by gradations allows to calculate the amount of energy received over a period. The repeatability of wind speed is considered as a percentage of time when we could observe given wind speed. Total wind energy potential is determined as sum of energy for each wind speed gradation.

$$W_{potential} = 0.95 \cdot (\bar{V}_{wind})^3 \cdot T \cdot \frac{S}{20},$$

where

$\bar{V}_{wind}$ – Monthly average wind speed, m/s,

$T$ – Time period, h,

$S$ – Area for WT operation, m$^2$ [1].

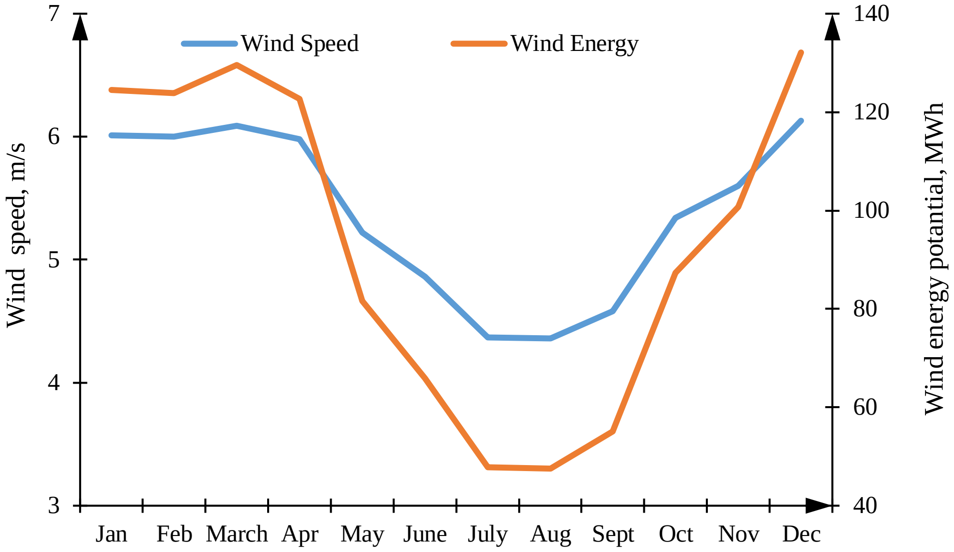


Figure 9 – Monthly average wind speed at 10 meter height [13]

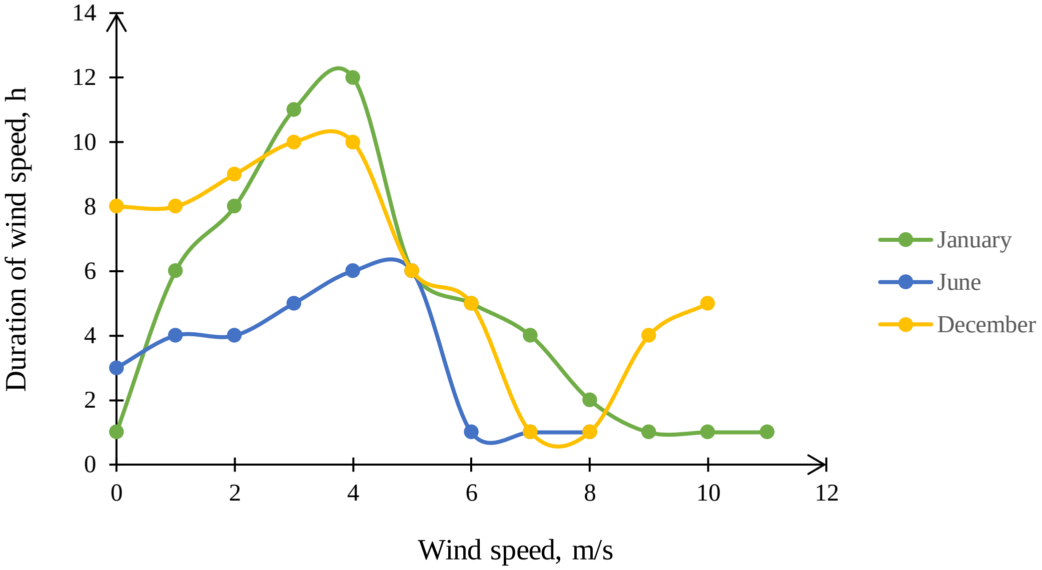


Figure 10 – Duration of wind speed [13]

It is necessary to analyze amount of energy that WT can generate at given wind speed. For this purpose, I will use power output curve [14]:

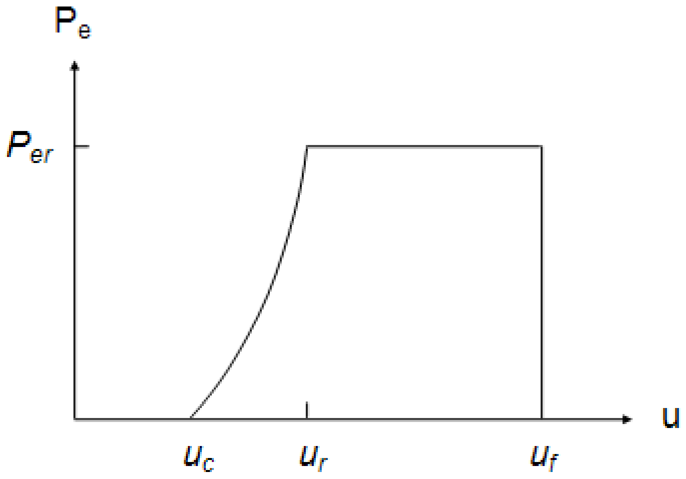


Figure 11 – Power output of wind turbine [14]

This curve shows percent of nominal power that WT could possibly generate at different wind speed. Using data presented on Figure 10 it is possible to estimate approximate power generated in the locality.

Possible energy production at known distribution of wind speeds can be determined by following formula [14]:

$$P(v)=\begin{cases}0 \ if \ v<v_c \\ (a+b\cdot v^k) \ if \ v_c<v\le v_r \\ P_r \ if \ v_r<v<v_f \\ 0 \ if \ v\ge v_f\end{cases},$$

where

$v$ – Wind speed, m/s,

$P$ – Power output of the WT, kW,

$P_r$ – Rated power of WT, kW

$v_c$ – Cut-in speed, m/s,

$v_f$ – Furling (shut down) speed, m/s,

$v_r$ – Rated wind speed, m/s,

$k$ – Weibull shape parameter.

The coefficients $a$ and $b$ are given by:

$$a=\frac{P_r\cdot v_c^k}{v_c^k-v_r^k}$$

$$b=\frac{P_r}{v_r^k-v_c^k}$$

Weibull density function is one of the functions that can be used for description of wind energy frequency. Data collected at many locations around the world can be reasonably well described by the

Weibull density function if the time period is not too short. For further calculations $k = 2$, as this value should be used if wind statistics is not well known for considered site [14].

### 4.2 Solar energy potential

Solar radiation or insolation is the main source of energy for our planet. The total power of the energy supplied to the Earth from the Sun is approximately equal to 180 TW. However, due to reflection, scattering and absorption of the surface, only half of all energy reaches. The following factors affect the intensity of solar radiation:

- Longitude
- Angle to the Earth surface
- Climate in the region
- Cloudiness
- Season of the year
- Duration of daylight hours

Figure 12 is based on data presented in Table A.1. Figures B.1 and B.2 shows additional necessary information about region. Ambient temperature is essential parameter for correct operation of PV panels. When temperature increases, panel's effectiveness decreases. That is why it is important to consider this parameter.

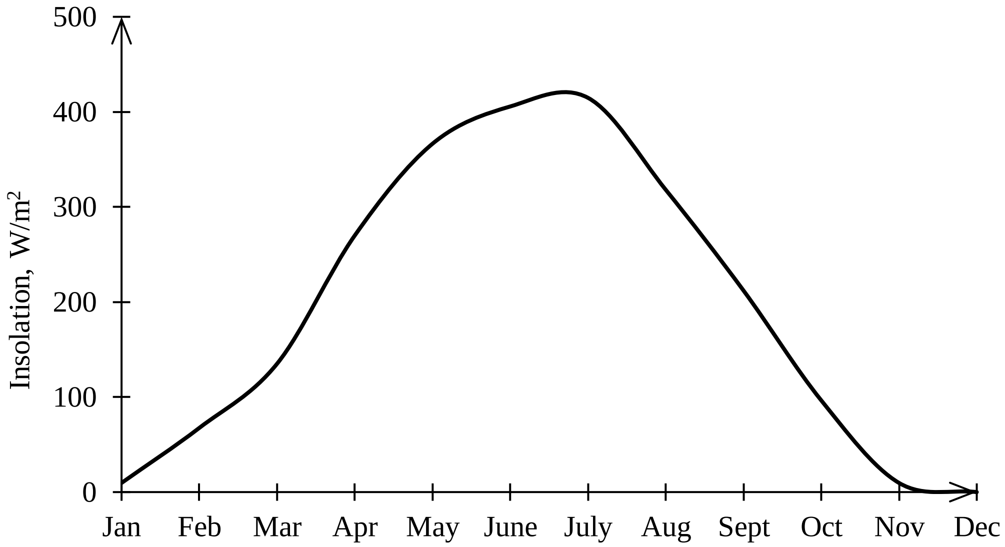


Figure 12 – Insolation during year [13]

Exact value of solar energy cannot be estimated before selection of PV panels, as value of energy depends on specific parameters of PV panel, such as area and power of panel.

Based on the obtained data it is possible to conclude, that use of wind and solar powers is feasible. Average annual wind speed exceeds minimal wind speed of 4 m/s. In addition, energy potential of the Sun is distributed evenly over surface in the region.

## 5. Specification of equipment

Before further steps, it is important to select equipment, which I will use in designing of HPSS. In this chapter, I select diesel power station, wind turbines and photovoltaic panels. DPS is chosen by several common requirements regarding to power and energy demand. WT is selected by reduced NPV analysis which does not consider mutual for alternatives parameters such as maintenance or salaries to staff. For PV panel specification energy balance is carried out.

### 5.1 Diesel power station

A diesel power station is the equipment that uses diesel engine as a mover, connected to electric generator, to produce electric energy, by using fuel.

Before starting calculation of diesel power station, we need to know total electric consumption of Karatayka village. On Figure 1, presented in Chapter 2 we can find total load.

For correct operation of diesel power station, we need to meet following requirements [8]:

- $P_{\Sigma} \geq 1.25 \cdot P_{\max} = 1.25 \cdot 500 = 625\,\text{kW}$.
- All generators that will be selected should be the same in terms of power
- Amount of selected stations should be enough to cover electric demand in case of supply failure.
- Load coefficient ($f_{load}$) should be equal to range from 0.25 to 0.8

Based on this criteria I selected five diesel power stations AD-125 YaMZ [15] with rated power $P_{DG}$=125 kW.

Figure 13 – Diesel generator AD-125 YaMZ [15]

Description of selected diesel generator is presented in Table 1 and Table 2.

Table 1 – Description of AD-125 YaMZ [15]

| Configuration | |
|---|---|
| Nominal power | 125 kW |
| Backup power | 138 kW |
| Type of current | AC. 3-phase |
| Nominal voltage | 400 V |
| Rotation speed | 1500 $\text{min}^{-1}$ |

Table 2 – Fuel consumption of AD-125 YaMZ [15]

| Fuel consumption | |
|---|---|
| 100% load | 35.9 l/s |
| 75% load | 27.3 l/h |
| 50% load | 21.7 l/h |
| Tank capacity | 300 l |

I selected this DPS as it works reliably even in the harsh conditions of the Far North, soft start-up at low temperatures - due to the unpretentious design of YaMZ engines, originally created for Russian conditions. YaMZ engines, which have a very simple fuel system, a robust design, and a mechanical fuel injection regulator, are very non-critical to fuel quality. This is especially important when operating a diesel generator in Russia, given the instability of fuel quality in various regions.

### 5.2 Wind turbine

For specifying WT to be used in HPSS, I need to consider possible alternatives. For this purpose, I use a web-catalog of WT [16]. Power of the WT and utilization coefficient are the main criteria.

Table 3 – Wind turbines and their parameters

| Wind turbine | AWP 90/18 | ADES ADES 60 | AN Bonus 150/30 | Allgaier StGW-34 | Argolabe Turbec-100 | DWP D75/15 |
|---|---|---|---|---|---|---|
| Rated power, kW | 90 | 60 | 150 | 100 | 100 | 75 |
| Height, m | 30 | 26.5 | 30 | 22.3 | 37 | 24 |
| Diameter, m | 18.6 | 29 | 23 | 34 | 22.5 | 15.3 |
| Utilization coefficient | 0.084 | 0.321 | 0.115 | 0.198 | 0.169 | 0.042 |
| Price, RUB (mln) | 3.5 | 3.15 | 5.7 | 6.5 | 5.2 | 3.1 |

In Table 3 there is a utilization coefficient, which is relation between power produced by WT in a year at average annual wind speed and rated power of WT:

$$k = \frac{P(\bar{v}_{annual})}{P_r}$$

The most important criterion to choose from is utilization coefficient. That is why I decided to compare only three wind turbines with highest utilization coefficient:

- ADES ADES 60
- Allgaier StGW-34
- Argolabe Turbec-100

Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

NPV is calculated by following formula [17]:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - A_0,$$

where

$CF_t$ – Cash flow, m.u.,

$r$ – Discount rate,

$A_0$ – Investment.

For comparison of these three wind turbines, I will use reduced NPV. It is approximate as several part of the NPV will be equal for each of the turbine. Such as maintenance, delivery, mounting at the work zone, salaries to service staff. That is why they will not be included into calculations.

In this calculation of reduced NPV, I use revenues as price for energy generation and cost or investment as price of WT.

Revenue is calculated by following formula:

$$Revenue = tariff \cdot generated\ energy$$

Tariff for electrical energy in the considered region is 3.71 RUB/kWh [18].

It is also necessary to take into account inflation for project lifetime period. Forecast inflation is presented in [19].

Final formula for preliminary NPV is:

$$NPV_{prlm} = \sum_{t=1}^{20} \frac{Revenue_t}{(1+r)^t (1+i)^t} - A_0 ,$$

where

$A_0$ – Cost of WT, m.u.,

$i$ – Inflation.

Table 4 and Figure 15 show result of optimal choice. Calculation of other alternatives are presented in Appendices B.4 and B.5.

Table 4 – Power generated by WT ADES ADES 60

| Wind speed, m/s | Days | Hours | Output, kW | Energy, MW |
|---|---|---|---|---|
| 0.25 | 0 | 0 | 0 | 0 |
| 0.75 | 1 | 0 | 0 | 0 |
| 1.25 | 4 | 0 | 0 | 0 |
| 1.75 | 10 | 0 | 0 | 0 |
| 2.25 | 14 | 0 | 0 | 0 |
| 2.75 | 25 | 0 | 0 | 0 |
| 3.25 | 28 | 0 | 0 | 0 |
| 3.75 | 35 | 840 | 2.10 | 1.76 |
| 4.25 | 38 | 912 | 6.70 | 6.11 |
| 4.75 | 31 | 744 | 11.95 | 8.89 |
| 5.25 | 32 | 768 | 17.75 | 13.63 |
| 5.75 | 18 | 432 | 24.13 | 10.42 |
| 6.25 | 30 | 720 | 31.00 | 22.32 |
| 6.75 | 22 | 528 | 38.60 | 20.38 |
| 7.25 | 25 | 600 | 46.70 | 28.02 |
| 7.75 | 12 | 288 | 55.43 | 15.96 |
| 8.25 | 19 | 456 | 60 | 27.36 |
| 8.75 | 4 | 96 | 60 | 5.76 |
| 9.25 | 7 | 168 | 60 | 10.08 |
| 9.75 | 5 | 120 | 60 | 7.20 |
| 10.25 | 3 | 72 | 60 | 4.32 |
| 10.75 | 0 | 0 | 60 | 0 |
| 11.25 | 1 | 2 | 60 | 1.44 |
| 11.75 | 1 | 24 | 60 | 1.44 |
| 12.25 | 0 | 0 | 60 | 0 |
| 12.75 | 0 | 0 | 60 | 0 |
| 13.25 | 0 | 0 | 60 | 0 |
| 13.75 | 0 | 0 | 60 | 0 |
| 14.25 | 0 | 0 | 60 | 0 |
| 14.75 | 0 | 0 | 60 | 0 |
| **Total** | **365** | **6 792** |  | **185.106** |

Firstly, it is necessary to find total annual generation for each turbine. Using power output curve presented on Figure 11 from Chapter 4.1 and data from Figure 9 we can determine power generated by WT at different wind speed. Results of calculations are presented in Table 4.

Table 5 – Comparison of considered WT

| Wind turbine | ADES ADES 60 | Allgaier StGW-34 | Argolabe Turbec-100 |
|---|---|---|---|
| NPV, RUB | 6 368 163 | 4 628 402 | 4 157 245 |
| Utilization coefficient | 0.321 | 0.198 | 0.169 |

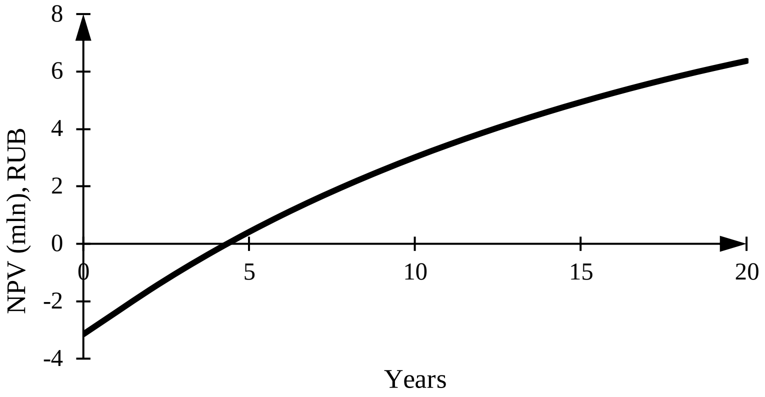


Figure 14 – Reduced NPV of ADES ADES 60 WT

After comparison I may conclude that the best choice is to select WT ADES ADES 60(AA60) for following designing of HPSS.

Complete analysis of NPV of whole project, including WT, DPS and PV panels is presented in Chapter 7.

In order to finish specification it is important to determine amount of WT for energy supplying. For this purpose I need to analyze daily data of wind speed, using [13] and calculate average power, which WT generates.

Table 6 – Energy coverage of one turbine

| Month | Energy, MWh | Coverage, % |
|---|---|---|
| Jan | 25.19 | 16.38 |
| Feb | 16.29 | 10.60 |
| March | 23.19 | 15.09 |
| Apr | 19.93 | 12.96 |
| May | 16.72 | 10.88 |
| June | 12.78 | 13.90 |
| July | 3.50 | 3.81 |
| Aug | 13.61 | 14.80 |
| Sept | 8.82 | 5.74 |
| Oct | 9.91 | 6.45 |
| Nov | 23.25 | 15.12 |
| Dec | 24.35 | 15.84 |

Clearly one turbine cannot cover all the demand, that is why I should increase amount of turbines. Exact number of WT are defined by economic analysis.

Table 7 – Energy coverage of different amount of turbines

| Month | 5 Turbines | | 6 Turbines | |
|---|---|---|---|---|
| | Energy, MWh | Coverage, % | Energy, MWh | Coverage, % |
| Jan | 125.94 | 81.91 | 151.12 | 98.29 |
| Feb | 81.47 | 52.99 | 97.77 | 63.59 |
| March | 115.97 | 75.43 | 139.17 | 90.52 |
| Apr | 99.65 | 64.81 | 119.58 | 77.78 |
| May | 83.60 | 54.38 | 100.32 | 65.25 |
| June | 63.92 | 69.52 | 76.71 | 83.42 |
| July | 17.52 | 19.05 | 21.02 | 22.86 |
| Aug | 68.05 | 74.00 | 81.65 | 88.80 |
| Sept | 44.12 | 28.69 | 52.94 | 34.43 |
| Oct | 49.56 | 32.23 | 59.47 | 38.68 |
| Nov | 116.25 | 75.61 | 139.50 | 90.73 |
| Dec | 121.77 | 79.20 | 146.13 | 95.04 |

Figure 15 is plotted based on data from Table 7.

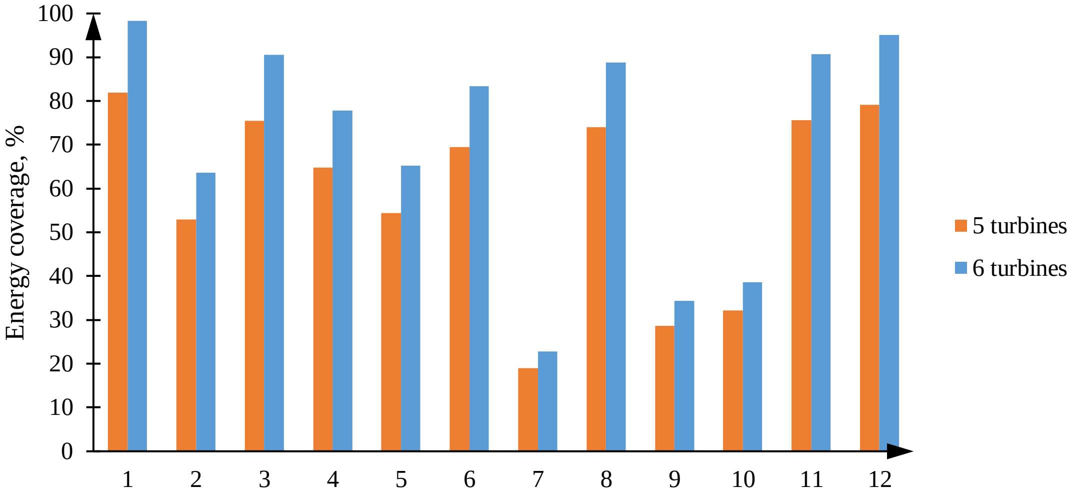


Figure 15 – Energy coverage of wind turbines

Wind turbine AA60 is the best choice for considered region according to reduced economic analysis. However, in several months there is a lack of energy, thus I need to use other sources of energy, i.e. DPS and PV panels.

### 5.3 Photovoltaic panels

Before specification of PV panels I need to select them. I came up with several criteria, which are price, power and amount of energy generated by one panel per year. The most important criterion is energy generated by one panel. This energy can be calculated by following formula [20]:

$$E = S \cdot \eta \cdot PR \cdot \lambda ,$$

where

$S$ – Total solar panel Area, $m^2$,

$\eta$ – Solar panel yield or efficiency, %,

$PR$ – Performance ratio,

$\lambda$ – Solar insolation in the region, kWh/m$^2$.

Table 8 – Comparison of PV panels

| PV-panel | Price, RUB | Power, W | Energy, kWh |
|---|---|---|---|
| SLN-60Poly-260 | 16 316 | 260 | 339.12 |
| FSM-100P | 5 100 | 100 | 147.82 |
| Delta BST 330-24 | 13 600 | 330 | 475.82 |
| E-Power 100 | 10 738 | 80 | 104.35 |
| ALM-140P | 9 975 | 140 | 182.61 |
| FE Modul Mono-310 | 14 200 | 310 | 404.34 |

PV panel Delta BST 330-24 [21] generates more energy than others. Thus it is used in this project, and further calculations are carried out for this PV panel.

Finally, there is a necessity to determine amount of PV panels for photovoltaic power station (PPS). For this purpose energy balance should be carried out [8].

Table 9 – Energy balance of PPS

| Month | Insolation, kWh/m | $W_1$, kWh | $W_{300}$, kWh | $W_{load}$, kWh | Δ, kWh |
|---|---|---|---|---|---|
| Jan | 0.08 | 2.18 | 196.99 | 153 750 | -153 553 |
| Feb | 1.07 | 29.27 | 2 634.8 | 153 750 | -151 115 |
| Mar | 3.47 | 94.94 | 8 544.62 | 153 750 | -145 205 |
| Apr | 6.76 | 184.95 | 16 646 | 153 750 | -137 104 |
| May | 9.87 | 270.04 | 24 304 | 153 750 | -129 446 |
| June | 11.6 | 317.37 | 28 564.15 | 91 950 | -63 385.8 |
| July | 10.68 | 292.2 | 26 298.72 | 91 950 | -65 651.3 |
| Aug | 7.85 | 214.77 | 19 330 | 91 950 | -72 619.9 |
| Sept | 4.56 | 124.76 | 11 228.67 | 153 750 | -142 521 |
| Oct | 1.78 | 48.7 | 4 383.12 | 153 750 | -149 367 |
| Nov | 0.25 | 6.84 | 615.6 | 153 750 | -153 134 |
| Dec | 0 | 0 | 0 | 153 750 | -153 750 |
| **Total energy, MWh** | | | **142.75** | **1 659.6** | **-1 516.85** |

I suggest using 300 PV panels in the PPS. It is clear that annual supply is not feasible, that is why I suggest seasonal supply from April to September, as these months with the highest generation. From this analysis I may conclude that amount of 300 PV panels is enough for seasonal energy supply.

More than that, I should consider additional equipment which are integral parts of any HPSS:

- Charge controller
- Accumulator batteries (AB)
- Invertor

Charge controller does not require any selection as manufacturer of PV panels recommends using charge controller ECO-MPPT Pro 200/60. That is why it will be used in further designing of HPSS.

### 5.4 Accumulator batteries

I will consider the battery pack for the case when it is necessary to cover peak loads or when the main sources discussed earlier do not generate energy. The calculation of the battery capacity will be performed according to the following formula [20]:

$$C = \frac{P_{load} \cdot t}{U_{AC} \cdot k_{discharge}},$$

where

$P_{load}$ – load power, kW

$t$ – Battery lifetime, s,

$U_{AC}$ – Battery voltage, V,

$k_{discharge}$ – Battery discharge ratio (depends on battery mode).

$$C = \frac{P_{load} \cdot t}{U_{AC} \cdot k_{discharge}} = \frac{500\,000 \cdot 2}{48 \cdot 0.75} = 41\,666 \text{ Ah}$$

Considered HPSS requires energy storage with capacitance of 42 kAh.

Storage batteries should meet several requirements, such as resistance to deep discharge, and work efficient when deep cycling occurs often. Also AB should withstand large amount of cycles.

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 [20].

Acid-lead AB are the best choice for purposes of this project, as they are common in the market, they have higher efficiency and prices of acid-lead AB are lower than prices of other types. Finally, recycling of acid-lead batteries is the most successful comparing to others. However acid-lead AB have disadvantages such as toxicity and low lifetime.

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 [20].

AB Trojan J185H-AC [22], with capacity of 225 Ah, is optimal choice as this accumulator have high capacity, tolerance to deep cycling and designed directly for HPSS.

Amount of AB:

$$n = \frac{C}{C_{AB}} = \frac{42\,000}{225} = 187$$

This HPSS requires 187 AB.

### 5.5 Miscellaneous power electronics

By miscellaneous power electronics I mean DC/DC converters, invertor that coverts DC from DC bus to AC for load and rectifier.

**Rectifier**

Rectifiers are used for conversion of AC to DC in power systems. In considered HPSS it is connected to WT on the input and to DC-bus on the output.

Rectifier Schneider Electric AFE VW3A7276 is optimal choice for this HPSS, as it can withstand high load and designed for corresponding purposes. Its power is 540 kW and operating voltage is in range from 0 to 690 V [23].

**DC/DC converter**

DC/DC converters are used for stepping down voltage and stabilization of load and whole system. Usually it is used in pair with solar panels.

CONV-DCDC-30KW is the best choice for this project as it has MPPT algorithm available, it is optimized for high currents and it is designed for industrial power supplies [24].

**Inverter**

For this project only one inverter is required. Its power should be equal to sum of powers of all connected to DC bus installations.

$$P_{inv} = \sum_{n=1}^{300} P_{PV_n} + \sum_{m=1}^{6} P_{WT_m} = 300 \cdot 0.33 + 6 \cdot 60 = 460 \text{ kW}$$

Inverter SX 500 kW ND has enough power to operate efficiently [25].

## 6. Calculation of diesel power station parameters

Using data from Chapter 5.1 we can determine number of diesel power stations required for energy supply and load coefficient $f_{load}$ using following formula [8]:

$$f_{load_i} = \frac{P_i}{n_i \cdot P_{DG}},$$

where

$P_i$ – Electric load, kW,

$n_i$ – Amount of diesel power station,

$P_{DG}$ – Power of diesel generator, kW.

e.g.

$$f_{load_1}^{summer} = \frac{P_1}{n_1 \cdot P_{DG}} = \frac{75}{2 \cdot 125} = 0.30.$$

Also, it is necessary to calculate fuel consumption per summer and winter day, depending on load percentage.

Table 10 – Calculated fuel consumption of AD-125 YaMZ

| Passport fuel consumption, l/h | | Calculated fuel consumption, l/h | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 50% | 75% | 30% | 35% | 40% | 45% | 55% | 60% | 65% | 70% |
| 21.7 | 27.3 | 16.9 | 18.1 | 19.3 | 20.5 | 22.5 | 23.7 | 24.9 | 26.18 |

Now it is necessary to calculate mass of fuel per year, in order to do this we need to calculate specific fuel consumption and amount of generated energy.

Specific fuel consumption [8]:

$$G_i = K_{idle} \cdot G_{nom} + (1 - K_{idle}) \cdot G_{nom} \cdot \frac{P_i}{P_{DG}} ,$$

where

$G_i$ – Current fuel consumption, g/kWh

$G_{nom}$ – Nominal fuel consumption (for chosen diesel power station $G_{nom}$=214 g/kWh),

$P_i$ – Actual power of diesel power station, kW,

$P_{DG}$ – Nominal power of diesel power station, kW,

$K_{idle}$ – Idle mode coefficient (fuel consumption at idle mode $K_{idle}$=0.3).

e.g.

$$G_1 = K_{idle} \cdot G_{nom} + (1 - K_{idle}) \cdot G_{nom} \cdot \frac{P_1}{P_{DG}} = 0.3 \cdot 214 + (1 - 0.3) \cdot 214 \cdot \frac{138}{125} = 229.7 \text{ g/kWh}$$

Table 11 – Calculation for diesel generators

| Initial data | | | Calculations | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time, h | P, W | | $K_{load}$ | | n | | g, l/h | |
| | Summer | Winter | Summer | Winter | Summer | Winter | Summer | Winter |
| 1 | 75 | 125 | 0.3 | 0.5 | 2 | 2 | 33.8 | 43.4 |
| 2 | 75 | 125 | 0.3 | 0.5 | 2 | 2 | 33.8 | 43.4 |
| 3 | 75 | 125 | 0.3 | 0.5 | 2 | 2 | 33.8 | 43.4 |
| 4 | 75 | 125 | 0.3 | 0.5 | 2 | 2 | 33.8 | 43.4 |
| 5 | 85 | 125 | 0.34 | 0.5 | 2 | 2 | 36.2 | 43.4 |
| 6 | 105 | 175 | 0.42 | 0.7 | 2 | 2 | 36.2 | 43.4 |
| 7 | 140 | 250 | 0.56 | 0.66 | 2 | 3 | 45 | 67.5 |
| 8 | 155 | 300 | 0.62 | 0.48 | 2 | 5 | 45 | 108.5 |
| 9 | 140 | 200 | 0.56 | 0.53 | 2 | 3 | 45 | 67.5 |
| 10 | 105 | 150 | 0.42 | 0.6 | 2 | 2 | 41 | 47.4 |
| 11 | 105 | 150 | 0.42 | 0.6 | 2 | 2 | 41 | 47.4 |
| 12 | 105 | 175 | 0.42 | 0.7 | 2 | 2 | 41 | 52.2 |
| 13 | 120 | 200 | 0.48 | 0.8 | 2 | 2 | 43.4 | 54.6 |
| 14 | 105 | 150 | 0.42 | 0.6 | 2 | 2 | 41 | 47.4 |
| 15 | 105 | 150 | 0.42 | 0.6 | 2 | 2 | 41 | 47.4 |
| 16 | 105 | 150 | 0.42 | 0.6 | 2 | 2 | 41 | 47.4 |
| 17 | 105 | 200 | 0.42 | 0.53 | 2 | 3 | 41 | 65.1 |
| 18 | 105 | 350 | 0.42 | 0.56 | 2 | 5 | 41 | 112.5 |
| 19 | 125 | 500 | 0.5 | 0.8 | 2 | 5 | 43.4 | 136.5 |
| 20 | 140 | 475 | 0.56 | 0.76 | 2 | 5 | 45 | 136.5 |
| 21 | 250 | 350 | 0.4 | 0.56 | 5 | 5 | 96.5 | 112.5 |
| 22 | 350 | 250 | 0.56 | 0.5 | 5 | 4 | 112.5 | 86.8 |
| 23 | 225 | 175 | 0.45 | 0.35 | 4 | 4 | 82 | 72.4 |
| 24 | 90 | 150 | 0.36 | 0.6 | 2 | 2 | 36.2 | 47.4 |
| **Total** | **3 065** | **5 125** | | | | | **1 129.6** | **1 617.4** |

Using obtained data we can calculate total volume of fuel per year.

Volume of fuel:

*Summer period*

$$g_{month} = 30 \cdot g_{day} = 30 \cdot 1129.6 = 33\,888 \text{ l/h}$$

*Winter period*

$$g_{month} = 30 \cdot g_{day} = 30 \cdot 1\,617.4 = 48\,522 \text{ l/h}$$

Total volume of fuel per year:

$$g_{total} = 3 \cdot g_{summer} + 9 \cdot g_{\text{winter}} = 538\,362 \text{ l/h}$$

## 7. Economic criteria of feasibility for designing a hybrid power supply system

Economic analysis will help to define whether project feasible or not. For successful analysis I need to determine costs, investments and possible revenues. More than that it is important to conduct sensitivity analysis for proper evaluation of the project.

An investor will finance a production if he or she believes that the plant will earn profit over its lifetime. Moreover this profit produced by the plant should be higher than the cost of establishing this plant. More than that, revenue should exceed profit that investor could realize by any other venture with a similar risk. To make such an investment decision, investor must compute the long-run marginal cost of the plant and forecast the price at which the output of this plant might be sold [26].

### 7.1 Economic methodology

In this chapter I describe essential criteria, which will be used in further analysis. These essential criteria are Net Present Value, Internal Rate of Return, Return on Investment, Specific energy cost, Profitability Index, Payback Period and discount rate. They help investor to evaluate projects attractiveness and make a decision whether project is worth investment or not.

**Net Present Value**

Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

NPV is calculated by following formula [17]:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - A_0,$$

where

$CF$ – Cash flow, m.u.,

$r$ – Discount rate,

$A_0$ – Investment.

**Internal Rate of Return**

The internal rate of return (IRR) is a criterion used in capital budgeting to estimate the profitability of potential investments. The IRR is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero [27].

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+IRR)^t} - A_0 = 0$$

I will use IRR to compare projects. The higher IRR the more desirable project is.

**Return on Investment**

Return on Investment is another criterion used for economic analysis. Basically it shows efficiency of investments made. As ROI is measured as percentage it can be used for comparison with other projects.

ROI is calculated by following formula [28]:

$$ROI = \frac{\frac{\sum_{t=0}^{T} CF_t}{T}}{|CF_0|},$$

where

$T$ – Number of periods, years,

$CF$ – Annual cash flow, m.u.,

$CF_0$ – Investment, m.u..

There also can be a situation when ROI is negative, which mean that project is not profitable.

**Specific energy cost**

One of the criterion of economic feasibility is specific energy cost per 1 kWh, which can be calculated by following formula [20]:

$$LEC = \frac{A_0 + p_n \cdot C}{W},$$

where

$p_n$ – Profitability ratio, year$^{-1}$,

$C$ – Annual expenses, RUB,

$A_0$ – Investments, RUB,

$W$ – Generated energy, kWh.

This cost is also called the levelled electricity cost (LEC). LEC is total amount of money per kWh that investor will receive from selling the energy. This criterion can be used as tariff.

Essential inputs in the calculation of LEC are operating and maintenance cost, fuel costs and lifetime of the project. LEC can be expressed in nominal values or real values. In addition if is worth mentioning that LEC will increase over time, because with inflation [29].

**Profitability Index**

Profitability index (PI) describes relation between the initial investment and benefit from it for a considered project. PI can be calculated by following formula [30]:

$$PI = \frac{PV(CF)}{A_0},$$

where

$PV(CF)$ – Present value of future cash flow, RUB.

PI of 1.0 is the lowest acceptable value of PI, as lower values show that generated profit is lower than initial investment. With increase of PI, attractiveness of the project rises. PI also shows value of money generated per each investment unit.

**Payback Period**

Payback period (PP) simply shows the amount of time it takes to pay off an investment. The lower PP is the more attractive for investor project is. PP can be determined from the NPV(t) dependence [30]. PP of alternatives is determined in Chapter 7.4.

### Discount rate

Discount rate is an opportunity cost, as it is the return that can be received by investing in the project, rather than investing in financial markets [30].

For this paper it is essential to determine value of discount rate. I use capital asset pricing model or CAPM. CAPM describes relations between risk and expected return. Discount rate can be calculated by following formula [30]:

$$r = r_f + \beta_L \cdot MRP,$$

where

$r$ – Discount rate, %,

$r_f$ – Risk-free rate, %,

$\beta_L$ – Sensitivity to market changes,

$MRP$ – Market risk premium.

The $\beta_L$ of a potential investment is a sign of how risky investment is. If $\beta_L$ is more than one, it means that risk is higher. In addition, it dependent on industry and for RES $\beta_L$=1.07. *MRP* shows the difference between expected return on an investment and the risk free rate. *MRP* of Russia is 10.04% [31]. Also Central Bank of Russia states that risk free rate of governmental bonds for 20 years is $r_f$= 6.54% [32].

$$r = r_f + \beta_L \cdot MRP = 0.0654 + 1.07 \cdot 0.1004 = 0.173$$

Discount rate for this project is 17.3%

### 7.2 Definition of cost

When conducting economic analysis of any project it is important to determine its cost, as it is the first step to further analysis. For this project total cost is calculated out of investment to the project, annual expenses and overhaul which takes place once lifetime of equipment is over.

Investment consists of total price for equipment, delivery and installation at the operation spot. Annual expenses consist of wages for operational staff, fuel for the DPS, depreciation and annual maintenance of generation equipment. In further analysis I will consider several alternatives, as number of WT is not determined. Each alternative have different investment cost, these costs are presented in Table A.2.

Table 12 – Cost of equipment

| Item | Name | Amount | Lifetime, years | Price per item, RUB | Price, RUB |
|---|---|---|---|---|---|
| Diesel power station | YaMZ-125 | 5 | 5 | 1 200 000 | 6 000 000 |
| Wind turbine | AA60 | 5-7 | 20 | 3 150 000 | |
| PV-panel | Delta BST 330-24 | 300 | 20 | 13 600 | 4 080 000 |
| DC/DC converter | CONV-DCDC-30KW | 1 | 20 | 1 123 532 | 1 123 532 |
| Inverter | SX 500 kW ND | 1 | 20 | 3 976 380 | 3 976 380 |
| Rectifier | Schneider Electric AFE VW3A7276 | 1 | 20 | 1 311 788 | 1 311 788 |
| Charge controller | ECO-MPPT Pro 200/60 | 1 | 20 | 36 500 | 36 500 |
| Accumulator batteries | Trojan J185H-AC | 187 | 10 | 39 200 | 7 330 400 |
| Mount plates for PV | | 90 | - | 1 260 | 113 400 |

**Cost of fuel**

Specific fuel price (SFP) per 1 liter is provided by State Statistical Service [33] and estimated to be 53.35 RUB/l at the end of 2019.

Cost of fuel:

$$C_{fuel} = g_{total} \cdot SFP = 538\,362 \cdot 53.35 = 23\ 399\ 502\ \text{RUB}$$

Also it is important to take into account delivery of fuel. In calculations I consider that Delivery Company will transport fuel at the price 33.29 RUB/l [34]. Moreover I consider escalation of price for fuel. For this purpose I analyzed changing of price in previous 9 years [33] and estimated that approximate growth of fuel price will be 4.9% per year. Changing of price for fuel is presented on Figure B.6.

Fuel cost is an important and major component of LEC for traditional energy generation. However for most of RES fuel costs are insignificant and in fact are often equal to zero [29].

**Annual expenses**

First of all I need to decide number of workers who will maintain HPSS, I suggest that 4 workers will operate HPSS. Average salary in the considered industry is 53 626 RUB/month [35].

Then it is essential to estimate cost of maintenance of WT, PV panels and DPS. It can be calculated via following formula [36]:

$$C_{maintenance} = C_{operating} + C_{repair}$$

where

$C_{operating}$ – Operating expenses, RUB,

$C_{repair}$ – Cost of repair, RUB.

$$C_{operating} = 36 \cdot Minimum\ Wage = 36 \cdot 12\,130 = 436\,680 \text{ RUB}$$

$$C_{repair} = k_{rep} \cdot p_n (A_0 + k_p \cdot C_{mount}),$$

where

$k_{rep}$ – Coefficient of repair,

$k_p$ – Installation cost ratio,

$C_{mount}$ – Mount cost of installation, RUB.

Cost of repair is different for each installation. Often annual expenses are divided into fixed and variable components.

**Depreciation**

Depreciation is a method of allocating the cost of equipment over its lifetime [37]. There are several types of depreciation, but I will use straight-line depreciation. It demands equal distribution of cost for each following year. Straight-line depreciation is calculated by following formula [37]:

$$D = \frac{A_0}{T},$$

where

$A_0$ – Cost of the equipment, m.u.,

$T$ – Lifetime of the equipment, years.

Furthermore, following calculations should take into account annual growth of costs, which is equal to predicted inflation rate [19], growth of salaries and possible growth of tariff. I suggested that growth of salaries will be equal to inflation rate. Another important parameter that will be used in further calculations is taxes. Income tax is equal to 20% [38].

### 7.3 Calculations for economic analysis

This chapter contains calculations of important criteria, mentioned in previous sub-chapters. Initially calculations will be conducted for energy supply from DPS only, and then with combination of RES.

**Diesel power station is the only source of supply**

Firstly I consider case when electric energy supply is performed by DPS. In this case annual and investment costs are consist of total price of DPS, maintenance of DPS, cost of fuel and fuel delivery. Values of mentioned costs are presented in Table A.3.

$$LEC_{DPS} = \frac{A_0 + p_n \cdot C}{W} = \frac{31\,200\,000 + 0.05 \cdot 41\,000\,000}{1\,682\,650} = 19.76 \text{ RUB/kWh}$$

As there is no clear information about tariff in considered decentralized region I assume that it is equal to value of $LEC_{DPS}$. This value will be used for further comparison with RES based alternatives.

**Combination of DPS with RES**

Next step is to combine DPS with RES. Theoretically introduction of RES will decrease amount of consumed fuel, thus it will decrease annual cost and tariff for consumers. In Table 13 LEC depending on number of WT is presented.

Table 13 – Values of specific energy cost

| Number of wind turbines | LEC, RUB/kWh |
|---|---|
| 5 | 10.07 |
| 6 | 9.51 |
| 7 | 7.31 |

Results confirm that usage of RES decreases LEC.

Before calculating NPV and other criteria I need to calculate depreciation of the equipment for each alternative.

*5 wind turbines:*

$$D_{DPS} = \frac{A_0}{T} = \frac{6}{5} = 1.2 \text{ RUB (mln)}$$

$$D_{AB} = \frac{A_0}{T} = \frac{7.3}{10} = 0.73 \text{ RUB(mln)}$$

$$D_{WT} = \frac{A_0}{T} = \frac{15.75}{20} = 0.78 \text{ RUB(mln)}$$

$$D_{PV} = \frac{A_0}{T} = \frac{4.08}{20} = 0.204 \text{RUB(mln)}$$

*6 wind turbines:*

$$D_{DPS} = \frac{A_0}{T} = \frac{6}{5} = 1.2 \text{ RUB(mln)}$$

$$D_{AB} = \frac{A_0}{T} = \frac{7.3}{10} = 0.73 \text{ RUB(mln)}$$

$$D_{WT} = \frac{A_0}{T} = \frac{18.9}{20} = 0.945 \text{ RUB(mln)}$$

$$D_{PV} = \frac{A_0}{T} = \frac{4.08}{20} = 0.204 \text{RUB(mln)}$$

*7 wind turbines:*

$$D_{DPS} = \frac{A_0}{T} = \frac{6}{5} = 1.2 \text{ RUB(mln)}$$

$$D_{AB} = \frac{A_0}{T} = \frac{7.3}{10} = 0.73 \text{ RUB(mln)}$$

$$D_{WT} = \frac{A_0}{T} = \frac{22.05}{20} = 1.1 \text{ RUB(mln)}$$

$$D_{PV} = \frac{A_0}{T} = \frac{4.08}{20} = 0.204 \text{RUB(mln)}$$

Following calculation of NPV will be conducted for 20 years. That is why equipment with lifetime less than 20 years will be purchased again. Time value of money will be taken into account.

Table 14 – NPV of alternatives

| Number of wind turbines | NPV, RUB (mln) |
|---|---|
| 5 | -25.51 |
| 6 | -33.62 |
| 7 | -51.98 |

Now, when NPVs for each alternative are known, IRR and minimal value of LEC can be calculated, using formulas from Chapter 7.1. For project to be profitable easiest way is to increase LEC.

Calculation also shows that annual cost of fuel decreases after introduction of RES. Consumption of fuel is calculated out of the difference between energy demand and energy generated by WT and PV panels. Cost of fuel in case of 5 WT decreases by 17.28 mln.RUB annually and in case of 6 WT cost decreases by 17.98 mln.RUB annually. Full calculations are presented in Table A.4, Table A.5 and Table A.6.

Table 15 – IRR and tariff for alternatives

| Number of wind turbines | IRR, % | Minimal tariff, RUB/kWh |
|---|---|---|
| 5 | 7.9 | 13.07 |
| 6 | 4.7 | 13.47 |
| 7 | - | 12.34 |

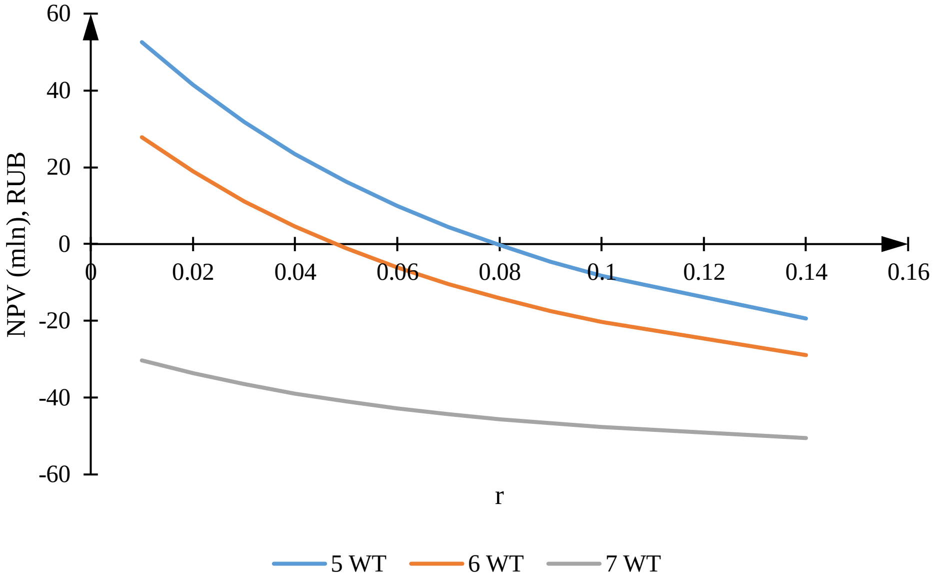


Figure 16 – IRR curves for projects

The results show that IRR of 7 WT alternative is not feasible and investment will never be paid off at discount rate of 17.3%. That is why this alternative will not be included in further analysis.

**Return of Investment**

*5 wind turbines*

$$ROI = \frac{\frac{\sum_{t=0}^{T} CF_t}{T}}{|CF_o|} = 6.13\%$$

*6 wind turbines*

$$ROI = \frac{\frac{\sum_{t=0}^{T} CF_t}{T}}{|CF_o|} = 3.38\%$$

ROI shows that both alternatives are worth to invest and alternative with 5 wind turbines is better.

**Profitability Index**

5 wind turbines

$$PI = \frac{PV(CF)}{A_0} = 0.35$$

6 wind turbines

$$PI = \frac{PV(CF)}{A_0} = 0.24$$

PI shows that at the value of tariff equal to LEC, project does not generate enough profit to be attractive in both alternatives.

Economic calculations show that at the tariff equal to LEC, project is not feasible, as most of the criteria are not satisfactory. Payback period cannot be determined, PI is lower than 1.0. In order to determine best conditions for project to be profitable I need to conduct a sensitivity analysis.

### 7.4 Sensitivity analysis

Sensitivity analysis is a way of estimating how NPV will change if certain changes in input parameters will occur. For analysis I chose as input parameters tariff, fuel price, price of WT, price of PV, price of DPS and salaries for workers. After that I study how tariff influences investment decision criteria described in Chapter 7.1.

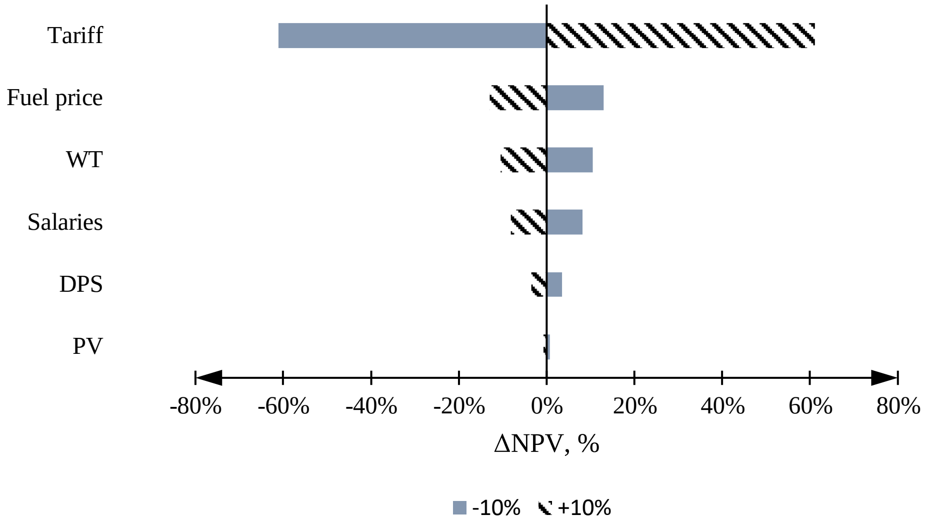


Figure 17 – Tornado diagram for 5 WT alternative

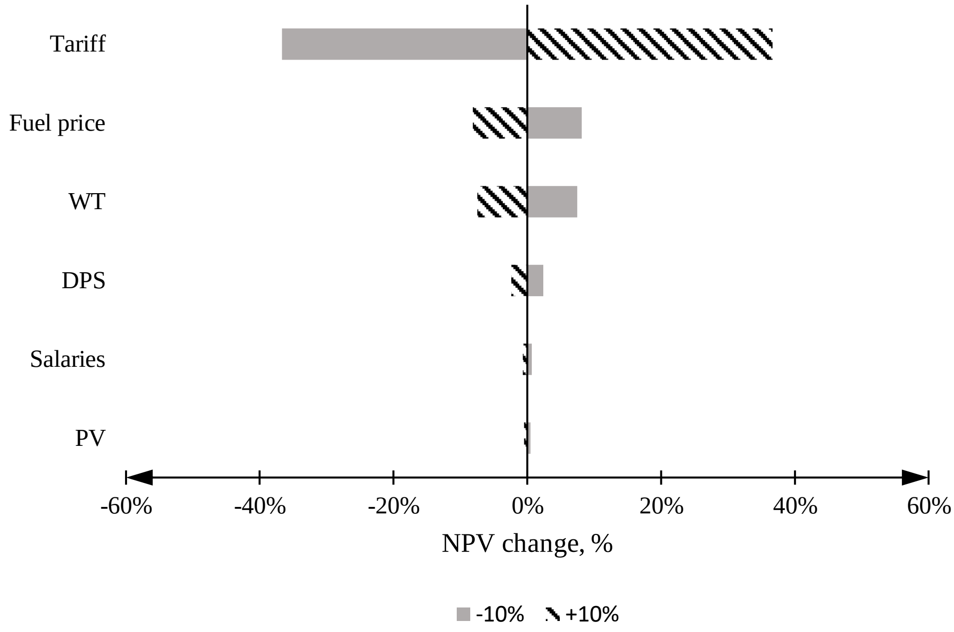


Figure 18 – Tornado diagram for 6 WT alternative

Based on the tornado diagram, we may conclude that NPV mostly depends on the value of tariff, fuel price and cost of wind turbines for both alternatives.

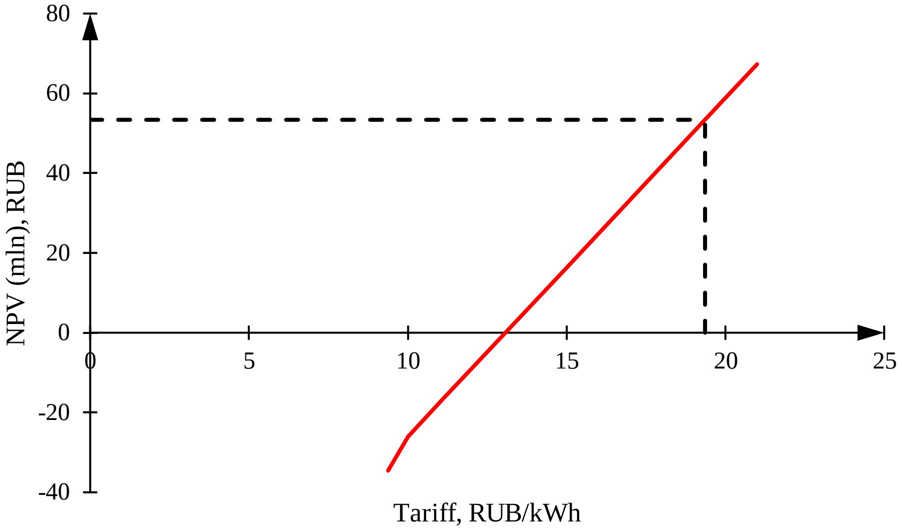


Figure 19 – NPV dependence of tariff for 5 WT alternative

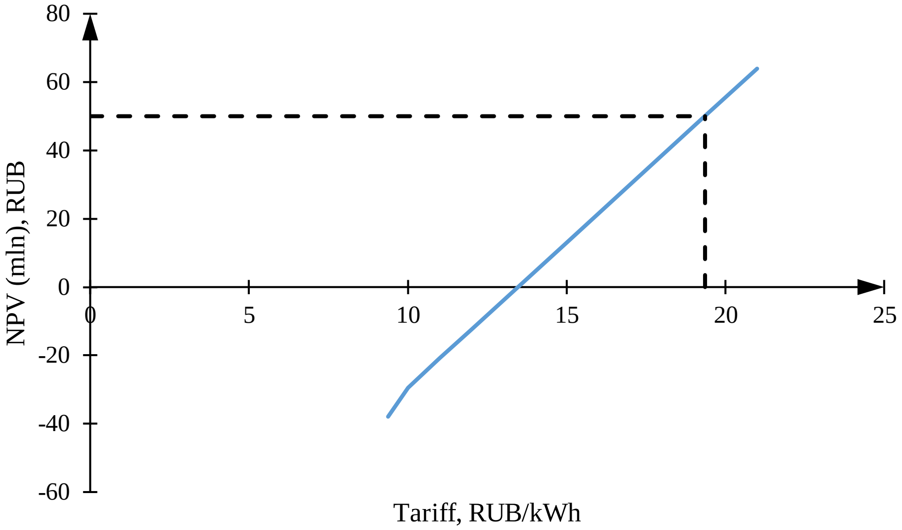


Figure 20 – NPV dependence of tariff for 6 WT alternative

Figures 17 and 18 show dependence of NPV from tariff for both alternatives. For project to be beneficial for investor tariff should be more than 13.07 RUB/kWh for 5 WT alternative and 13.47 RUB/kWh for 6 WT alternative. At the same time from customer point of view tariff should be less than 19.76 RUB/kWh.

In addition I decided to see how all investment decision criteria depends on changing of tariff, and how it influences whole project. Table 16 shows this dependence.

Table 16 – Investment decision criteria changing

| 5 wind turbines | **Tariff, RUB/kWh** | **10.07** | **12** | **15** | **19.76** |
|---|---|---|---|---|---|
| | PP, years | - | - | 10 | 5 |
| | ROI, % | 6.13 | 12.23 | 21.71 | 36.73 |
| | NPV(mln), RUB | -25.51 | -9.10 | 16.36 | 56.77 |
| | PI | 0.35 | 0.55 | 0.87 | 1.37 |
| | IRR, % | 7.90 | 14.10 | 22% | 35.40 |
| 6 wind turbines | **Tariff, RUB/kWh** | **9.51** | **12** | **15** | **19.76** |
| | PP, years | - | - | 11 | 5 |
| | ROI, % | 3.38 | 10.81 | 19.76 | 33.95 |
| | NPV | -33.62 | -12.47 | 13.00 | 53.41 |
| | PI | 0.41 | 0.46 | 0.73 | 1.15 |
| | IRR, % | 4.70 | 13 | 21.40 | 33.80 |

In order to show how tariff influences NPV let us consider case when tariff is equal to 15 RUB/kWh. This value lays in between minimal and maximum values of tariff.

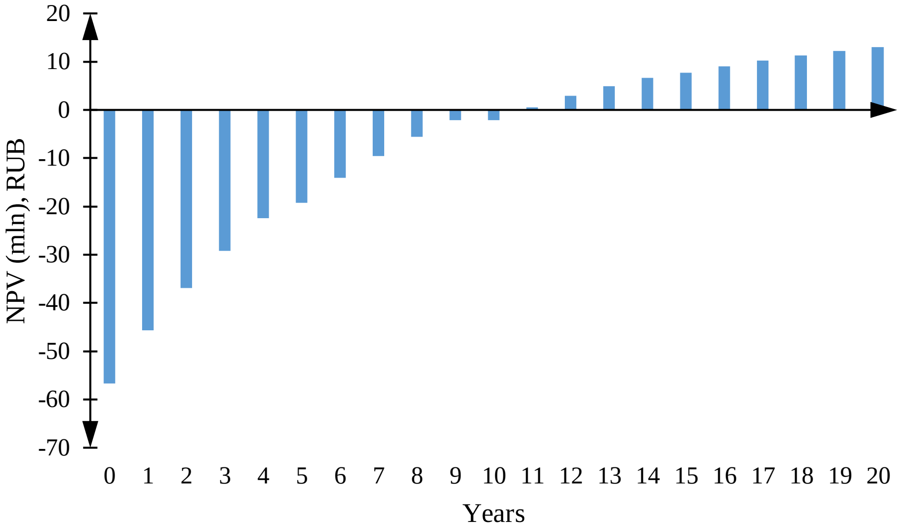


Figure 21 – Cumulative NPV of the 6 WT alternate

Figure 21 shows cumulative NPV for 6 WT alternative. We also can estimate payback period which is 11 years. After 10 years project starts to generate profit. Figure B.7 shows NPV for 5 WT alternative with tariff equal to 15 RUB/kWh.

## 8. Environmental benefits of introducing renewable energy sources

CO$_2$ contributes to air pollution in its role in the greenhouse effect, as CO$_2$ reflects heat radiation from the earth. Thus it prevents surface from cooling at night, keeping temperature constant or even increasing warming oceans. Over time this effect is compounding, resulting in climate change. What is more important is that increasing of CO$_2$ emissions effects human's health [39].

While burning fuel, there are emissions of CO$_2$ and CH$_4$ happen. These CO$_2$ emissions from burnt fuel are the result of the release of carbon. Amount of released CO$_2$ depends on type of fuel, as each type of fuel contains different amount of carbon and it does not depend on process or conditions of burning. Annual emission of $CO_2$ is calculated by following formula [40]:

$$E = M \cdot K_1 \cdot NCV \cdot K_2 \cdot \frac{44}{12},$$

where

$M$ – Annual real fuel consumption, t,

$K_1$ – Oxidation coefficient,

$NCV$ – Net calorific value, TJ/Gg,

$K_2$ – $CO_2$ emission coefficient, tC/TJ,

44/12 – Recalculation of carbon emissions.

$K_1$ takes into account incomplete fuel combustion. Average value of $K_1$ for diesel fuel is 0.99. In order to convert the consumed amount of fuel into energy units, its mass is multiplied NCV. NCV for diesel fuel is 43.02 TJ/Gg. Value of $K_2$ for diesel fuel is 19.98 tC/TJ.

**DPS energy supply**

Firstly it is necessary to determine mass of fuel in case of DPS energy supply.

*Sumer period*

Energy generated per month [8]:

$$W_{gen.sum} = P_{day} \cdot t = 3065 \cdot 30 = 91950 \text{ kWh}$$

Mass of fuel [8]:

$$M_s = G_1 \cdot W_{gen.sum} = 229.7 \cdot 91950 = 21120915 \text{ g} \sim 21 \text{ t}$$

*Winter period*

Energy generated per month [8]:

$$W_{gen.\mathrm{wint}} = P_{day} \cdot t = 5125 \cdot 30 = 153800 \text{ kWh}$$

Mass of fuel [8]:

$$M_w = G_1 \cdot W_{gen.\mathrm{wint}} = 229.7 \cdot 153800 = 35327860 \text{ g} \sim 35 \text{ t}$$

$$M_{totalDPS} = 3 \cdot M_s + 9 \cdot M_w = 378 \text{ t}$$

Before introducing RES, DPS consumes 378 t of fuel annually.

Annual $CO_2$ emissions before introducing RES:

$$E = M_{totalDPS} \cdot K_1 \cdot NCV \cdot K_2 \cdot \frac{44}{12} = 378 \cdot 0.99 \cdot \frac{43.02}{1000} \cdot 19.98 \cdot \frac{44}{12} = 1179.4 \text{ t}$$

**Combination of DPS and RES**

Now $CO_2$ emission calculations are conducted for HPSS. As it is mentioned in Chapter 7.3 fuel cost decreases. It is now possible to calculate mass of consumed fuel from its cost, and determine $CO_2$ emissions. $CO_2$ emissions are calculated for 5 WT alternative and 6 WT alternative.

*5 wind turbines*

$$M_{totalRES} = \frac{C_{fuel}}{SFP \cdot 1000} \cdot \rho_{DF} \,,$$

where

$C_{fuel}$ – Cost of fuel, RUB,

$SFP$ – Specific fuel price, RUB/l

$\rho_{DF}$ – Density of diesel fuel, kg/m$^3$.

Mass of fuel:

$$M_{totalRES} = \frac{C_{fuel}}{SFP \cdot 1000} \cdot \rho_{DF} = \frac{6\,120\,000}{53.35 \cdot 1000} \cdot 850 = 97\,510 \text{ kg}$$

Annual value of $CO_2$ emissions:

$$E = M_{totalRES} \cdot K_1 \cdot NCV \cdot K_2 \cdot \frac{44}{12} = 97.51 \cdot 0.99 \cdot \frac{43.02}{1000} \cdot 19.98 \cdot \frac{44}{12} = 304.2 \text{ t}$$

*6 wind turbines*

Mass of fuel:

$$M_{totalRES} = \frac{C_{fuel}}{SFP \cdot 1\,000} \cdot \rho_{DF} = \frac{5\;420\;000}{53.35 \cdot 1000} \cdot 850 = 86\,350 \text{ kg}$$

Annual value of $CO_2$ emissions:

$$E = M_{totalRES} \cdot K_1 \cdot NCV \cdot K_2 \cdot \frac{44}{12} = 86.35 \cdot 0.99 \cdot \frac{43.02}{1000} \cdot 19.98 \cdot \frac{44}{12} = 269.4 \text{ t}$$

Calculations of $CO_2$ emission show that emissions decreased by 74% in case of 5 WT and by 77% in case of 6 WT. It means that successful introduction of RES in power supply system has environmental benefit.

## 9. Simulation of a hybrid power supply system components

Before making a conclusion I need to check whether chosen equipment works correctly. For this reason simulation of equipment in MATLAB should be performed. I consider simulation of WT and PV-panels in order to obtain power and energy as output parameters.

### 9.1 Simulation of wind turbine

The main idea of simulation is to verify how WT will operate. I need to obtain power output characteristic mentioned in Chapter 4.1. Then comparison of simulation results and calculations conducted.

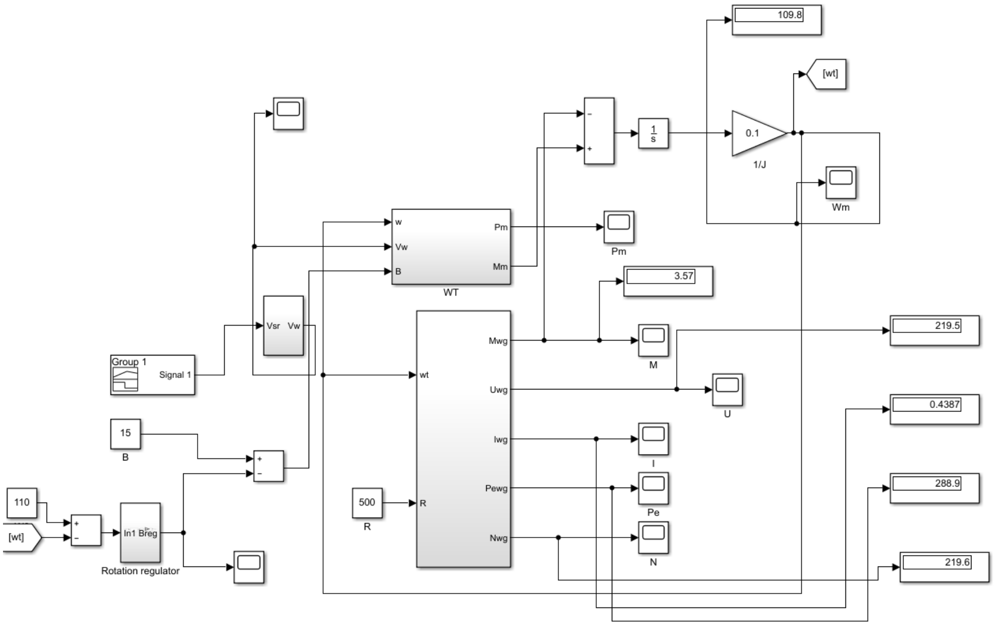


Figure 22 – Simulation model of WT

This simulation model consists of 2 main subsystems, which represent WT and generator. Structure of both subsystems presented on Figure B.8 and B.9. This subsystems can be described mathematically by following equations [20]:

*Motion equation*

$$J_{WT} \cdot \frac{d\omega_{WT}}{dt} = M_{WT} \ ,$$

where

$J_{WT}$ – Inertia of WT, kg·m$^2$,

$\omega_{wt}$– Angular rotation, rad/s.

$M_{WT}$– Torque of WT, N·m.

*Power produced by WT*

$$P_{WT} = C_p \cdot \frac{\rho A}{2} \cdot V_w{}^3 \ ,$$

where

$C_p$ – Power coefficient of WT.

$\rho$ – Air density, kg/m$^3$,

$A$ − Area of WT blades, m$^2$,

$V_w$ – wind speed directed to WT, m/s.

Power coefficient $C_p$ depends on several parameters and construction design of WT and it is difficult to calculate. Also it is function depending on 2 parameters $\lambda$ – fastness of WT and $\beta$ - rotation angle of blade to rotation plane [20].

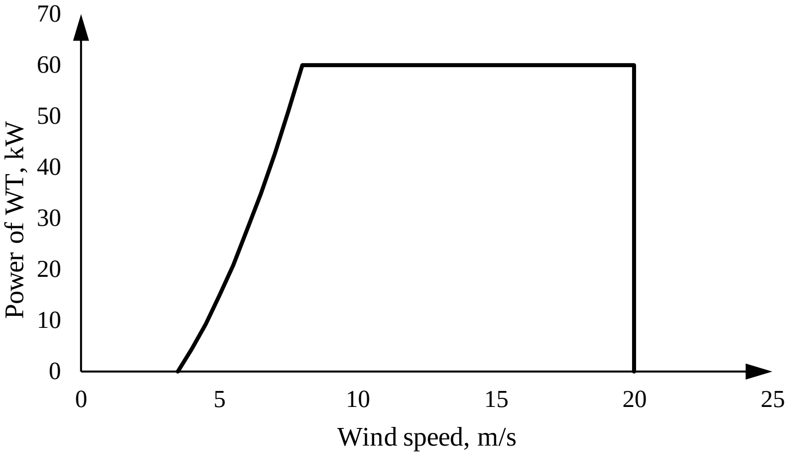


Figure 23 – Power output of WT

Simulation results show that power output characteristic have the same shape as theoretical presented on Figure 11. Thus, I can use results to calculate energy generated by WT annually.

Table 17 – Energy generated by WT annually

| Wind speed, m/s | Power, kW | Hours | Energy, kWh |
|---|---|---|---|
| 3.50 | 0.00 | 830.00 | 0.00 |
| 4.00 | 4.35 | 920.00 | 4 000.16 |
| 4.50 | 9.28 | 828.00 | 7 679.70 |
| 5.00 | 14.78 | 768.00 | 11 353.34 |
| 5.50 | 20.87 | 534.00 | 11 144.58 |
| 6.00 | 27.54 | 710.00 | 19 553.40 |
| 6.50 | 34.78 | 534.00 | 18 572.52 |
| 7.00 | 42.60 | 590.00 | 25 134.00 |
| 7.50 | 51.00 | 270.00 | 13 770.00 |
| 8.00 | 60.00 | 436.00 | 26 160.00 |
| 8.50 | 60.00 | 100.00 | 6 000.00 |
| 9.00 | 60.00 | 175.00 | 10 500.00 |
| 9.50 | 60.00 | 115.00 | 6 900.00 |
| 10.00 | 60.00 | 56.00 | 3 360.00 |
| 10.50 | 60.00 | 3.00 | 180.00 |
| 11.00 | 60.00 | 2.00 | 120.00 |
| 11.50 | 60.00 | 23.00 | 1 380.00 |
| 20.00 | 60.00 | 0.00 | 0.00 |
|  |  | **Total energy, MWh** | **165.81** |

Simulation results show that one WT generates 165.81 MWh of energy. This value is lower than theoretically calculated value of 185.106 MWh. This happens because simulation model take into account more input parameters that influence output power. For instance simulation model takes into account wind fluctuations, angle of blades and inertia of the WT.

### 9.2 Simulation of photovoltaic panel

Simulation of PV panel. Simulation of built model is performed by regulating input parameters such as sun radiation and air temperature. The simulations will be implemented at sun radiation of period from April to September and changing the ambient temperature from Figures B.1 and B.2. The main output parameters are voltage, current and generated power.

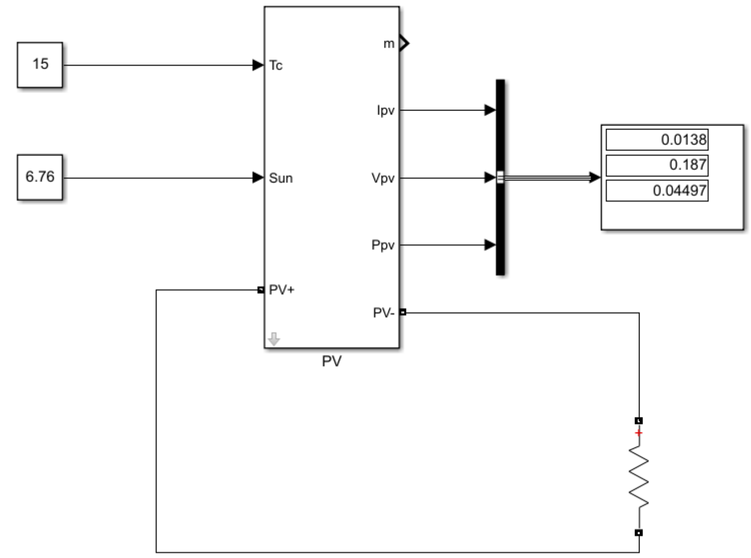


Figure 24 – Simulation model of PV panel

Next step is to obtain amount of energy generated by one PV panel.

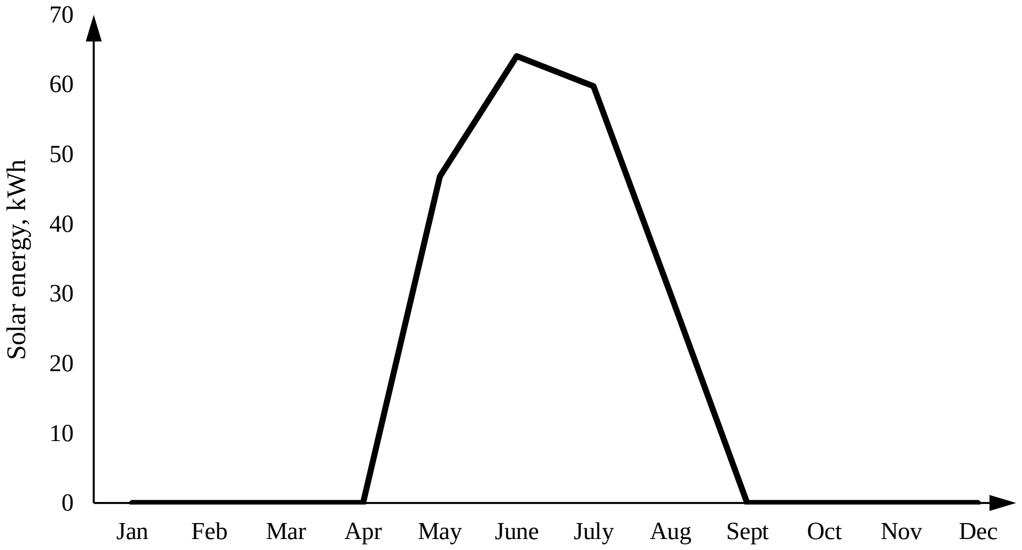


Figure 25 – Energy generated by one PV panel

Results presented on Figure 25 show that simulation model works correctly. Thus, data presented in Table 18 should be considered as correct.

Table 18 – Results of simulation

| Insolation, kW/m$^2$/day | Power, W | Daylight hours, h | $W_1$, Wh | $W_{300}$, kWh |
|---|---|---|---|---|
| 0.08 | 0 | 0 | 0 | 0 |
| 1.07 | 10.50 | 7 | 2 457.00 | 737.10 |
| 3.47 | 36.00 | 12 | 12 636.00 | 3 790.80 |
| 6.76 | 44.90 | 16 | 21 282.60 | 6 384.78 |
| 9.87 | 117.00 | 20 | 70 200.00 | 21 060.00 |
| 11.60 | 133.50 | 24 | 96 120.00 | 28 836.00 |
| 10.68 | 124.50 | 24 | 89 640.00 | 26 892.00 |
| 7.85 | 88.50 | 17 | 45 135.00 | 13 540.50 |
| 4.56 | 49.50 | 13 | 19 305.00 | 5 791.50 |
| 1.78 | 13.50 | 9 | 3 645.00 | 1 093.50 |
| 0.25 | 3.05 | 4 | 365.63 | 109.69 |
| 0 | 0 | 0 | 0 | 0 |
| | | | **Total Energy, MWh** | **108.24** |

Results of the simulation show that 300 PV panels generate 108.25 MWh of energy annually. This value is lower than theoretically calculated value of 142.75 MWh. This happens because simulation model does not take into account area of PV panel. Otherwise, theoretical calculations do not take into account load of PV panels.

Simulations show that equipment of HPSS works efficiently, and it is possible to use it. However, simulations and calculation cannot precisely predict outcome, that is why I consider both results appropriate.

## 10. Discussion of results

Analysis of energy potential shows that introduction of RES in to existing power supply system is technically and economically feasible. That is why next step is to design a structure of HPSS, selection and specification of needed equipment.

Specifications of equipment are based on different methods. Diesel power stations (DPS) are specified based on common requirements concerning their power and ability to work in severe weather conditions. The optimum number of DPS to cover energy demand is five DPS with rated power of 125 kW.

WT are chosen by different method. Before specification of WT I need to select model of WT to be used in the project. There are several alternatives with different rated power and other parameters. ADES ADES 60 with rated power of 60 kW and utilization coefficient 0.321. Allagaier StGW-34 with rated power of 100 kW and utilization coefficient 0.198. Argolabe Turbec-100 with rated power of 100 kW and utilization coefficient of 0.169. These three WT have different cut-in and furling wind speed which influences power output and generated energy. In order to determine the best option I conduct a reduced NPV analysis to see which alternative can possibly bring more profit. In addition utilization coefficient is taken into account. Wind turbine ADES ADES 60 is the best option for current project.

Finally, for specification of PV panels I should make an energy balance. Because of severe weather conditions I suggest seasonal supply from PV panels, as during the period from April to September there is a highest solar insolation and thus higher generation of energy. I compare several alternatives by energy they can generate. I consider PV panel Delta BST 330-24 because compared to other alternatives this panel generates more energy and its price compare to power is low.

When the entire equipment is selected I can design an HPSS. Initially 3 alternatives of HPSS are considered. These alternatives differ by the number of WT, other energy sources remain the same.

The 5 WT alternative implies that HPSS consist of 5 WT, 5 DPS and 300 PV panels. WT in this alternative cover approximately 58% of total energy demand per year. This leads to decrease of $CO_2$ emissions by 74%. Apart from that this alternative is more beneficial, as there are lower values of investment and NPV is -25.51 mln. RUB in 20 years.

Next alternative to consider is 6 WT alternative. In a technical way this alternative provides more generation from WT and photovoltaic panels. Energy coverage from WT exceeds 70% of total energy demand. This leads to significant decrease in fuel consumption. The 6 WT alternative implies that $CO_2$ emissions decrease by 77% comparing to DPS energy supply. However increased number of WT leads to less profitable outcome which is -33.62 mln. RUB in 20 years. Another financial criterion ROI shows that project is worth investing, as ROI of this alternative is 3.38%.

The last one is 7 WT alternative. In this case WT cover over 80% of total energy demand and respectively it leads to significant decrease in fuel consumption and $CO_2$ emissions. However, this alternative is not economically feasible. In case when tariff is equal to LEC, project will never be paid off. That is why this alternative is not included in analysis.

From conducted analyses I conclude that the best option is 6 WT alternative. Despite the fact that this alternative is less beneficial, it is less dependent on fuel and this is one of the main goals of the whole project. Sensitivity analysis of this alternative shows that for project to be profitable value of tariff should be in range from 13.47 RUB/kWh to 19.76 RUB/kWh. In case of 19.76 RUB/kWh payback period is 5 years and profitability index is 1.15.

In addition, simulation of the components of an HPSS is performed. Simulation of WT consider changing output power by changing wind speed, corresponding with analyzed data in Chapter 4. Simulation shows that WT can generate 165.81 MWh annually. This value differs from theoretically calculated value of 185.1 MWh.

Simulation of PV panels consider ambient temperature and solar insolation as input parameters. By changing this parameters I can obtain energy generated by PV panels annually. Simulation shows different result from theoretically calculated. It happens because theoretical calculation and simulation model take into account different input parameters, which described in Chapter 4 and Chapter 10 respectively. In general I consider results of simulation as satisfactory as they are approximately the same as calculated.

I made several assumptions throughout the thesis. The first assumption is related to wind speed and solar insolation. These are considered to be the same as in previous years. The second assumption is that inflation rate will stay the same as it was forecast. Another assumption is that I did not consider aging of PV-panel and decrease of their effectiveness. Also I assume that investor has enough money and he does not require bank loan.

## Conclusion

In this thesis I designed a hybrid power supply system based on diesel power station, wind turbines and photovoltaic panels in Karatayka village. I performed energy potential analysis and concluded that annual average wind speed of 6.3 m/s is higher than cut-in speed of 4m/s. However solar insolation is too low, that is why I suggested seasonal supply from April to September. According to analysis there is a lack of wind energy in period from June till September. I suggested that in this period there is a part of energy comes from photovoltaic panels and rest of energy comes from DPS.

The designed hybrid power supply system consists of 5 diesel power stations, 6 wind turbines and 300 PV panels. Photovoltaic panels serve as additional source of energy. Diesel power station AD-125 YaMZ with capacity of 125 kW and ability to operate in severe weather conditions. Wind turbines ADES ADES 60 have rated power of 60 kW and utilization coefficient's value is 0.321. This wind turbine was chosen by reduced NPV analysis, which does not include maintenance, mounting and salaries to service staff. This wind turbine generates more energy than others alternatives. Photovoltaic panel Delta BST 330-24 was chosen for designed hybrid power supply system, as this photovoltaic panel have lower price compare to its rated power and panel generates more energy than other alternatives considered. I also chose additional equipment necessary for efficient operation of hybrid power supply system, such as DC/DC converter CONV-DCDC-30KW, inverter SX 500kW ND, rectifier Schneider Electric AFE VW3A7276, charge controller ECO-MPPT Pro 200/60 and 187 accumulator batteries Trojan J185H-AC with capacity of 225 Ah each.

Economic analysis showed that introduction of RES based energy supply can be beneficial for both customer and investor. Tariffs became lower than it used to be. Sensitivity analysis showed that tariff has the greatest impact on NPV. In economic analysis I took into account lifetime of the project, which is 20 years, and lifetime of the equipment. Thus equipment with lower lifetime are repurchased.

After the introduction of RES-based energy supply, $CO_2$ emissions significantly decrease. This means that introduction of RES has not only economic and technical benefit, but ecological.

I also performed a simulation of the components of an HPSS to see whether they work efficient or not. Simulations result are satisfactory, as generated energy from wind turbine and photovoltaic panel approximately the same as they were calculated in Chapter 5.

Finally I want to emphasize that introduction of RES in current power supply system is feasible and beneficial. This project can be used as a starting point of full-scale introduction of RES in power supply system for remote locations.

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## Appendices

### Appendix A – Tables

Table A.1 – Monthly insolation [8]

| Month | Insolation, kW/m$^2$/day | $\lambda$, W/m$^2$ |
|---|---|---|
| Jan. | 0.08 | 9.65 |
| Feb. | 1.07 | 67.52 |
| Mar. | 3.47 | 135 |
| Apr. | 6.76 | 270 |
| May | 9.87 | 366.51 |
| June | 11.6 | 405.7 |
| July | 10.68 | 414.74 |
| Aug. | 7.85 | 318 |
| Sept. | 4.56 | 212 |
| Oct. | 1.78 | 96.45 |
| Nov. | 0.25 | 9.65 |
| Dec. | 0 | 0 |

Table A.2 – Cost of equipment for three alternatives

| Number of WT | Cost of equipment, RUB (mln) |
|---|---|
| 5 | 39722000 |
| 6 | 42872000 |
| 7 | 46022000 |

Table A.3 – Cost of DPS alternative

| Item | Cost, RUB |
|---|---|
| Equipment | 31200000 |
| Fuel | 23399502 |
| Wages | 2316643.2 |
| Maintenance DPS | 686280 |

Table A.4 – NPV calculation of 5 WT alternative

| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment (mln), RUB | 53.5 |  |  |  |  | 7.2 |  |  |  |  | 21.1 |  |  |  |  | 10.5 |  |  |  |  |  |
| Inflation, % |  | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 |
| Depretiation of AB (mln), RUB |  | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Depretiation of WT and PV (mln), RUB |  | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Depretiation of DPS (mln), RUB |  | 1.2 | 1.2 | 1.2 | 1.2 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Revenue (mln), RUB |  | 18.0 | 19.0 | 20.2 | 21.4 | 22.7 | 24.0 | 25.5 | 27.0 | 28.6 | 30.3 | 32.2 | 34.1 | 36.1 | 38.3 | 40.6 | 43.0 | 45.6 | 48.4 | 51.3 | 54.3 |
| Fuel price (mln), RUB |  | 10.4 | 10.9 | 11.5 | 12.0 | 12.6 | 13.2 | 13.9 | 14.6 | 15.3 | 16.0 | 16.8 | 17.6 | 18.5 | 19.4 | 20.4 | 21.4 | 22.4 | 23.5 | 24.7 | 25.9 |
| Salaries (mln), RUB |  | 2.7 | 2.8 | 2.9 | 3.0 | 3.1 | 3.2 | 3.3 | 3.5 | 3.6 | 3.7 | 3.9 | 4.0 | 4.2 | 4.3 | 4.5 | 4.7 | 4.9 | 5.0 | 5.2 | 5.4 |
| Maintenance (mln), RUB |  | 1.9 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 | 3.2 | 3.3 | 3.4 | 3.5 | 3.7 | 3.8 |
| Cost (mln), RUB |  | 15.7 | 16.4 | 17.1 | 17.8 | 18.6 | 19.5 | 20.3 | 21.2 | 22.1 | 23.1 | 24.5 | 25.6 | 26.7 | 27.9 | 29.1 | 30.4 | 31.7 | 33.1 | 34.6 | 36.2 |
| EBT (mln), RUB |  | 0.1 | 0.5 | 0.9 | 1.4 | 1.6 | 2.1 | 2.7 | 3.4 | 4.0 | 4.8 | 4.9 | 5.8 | 6.7 | 7.7 | 8.8 | 9.6 | 10.8 | 12.1 | 13.6 | 15.1 |
| EAT (mln), RUB |  | 3.0 | 3.3 | 3.6 | 4.0 | 4.5 | 4.9 | 5.4 | 5.9 | 6.4 | 7.0 | 7.8 | 8.4 | 9.2 | 10.0 | 10.8 | 11.8 | 12.8 | 13.9 | 15.0 | 16.2 |
| CF (mln), RUB |  | 5.2 | 5.5 | 5.8 | 6.2 | -0.3 | 7.3 | 7.8 | 8.3 | 8.8 | 0.7 | 10.5 | 11.2 | 11.9 | 12.7 | 3.1 | 14.9 | 15.9 | 17.0 | 18.1 | 19.3 |
| RCF (mln), RUB |  | 5.0 | 5.1 | 5.2 | 5.3 | -0.3 | 5.9 | 6.0 | 6.2 | 6.3 | 0.5 | 7.0 | 7.1 | 7.3 | 7.5 | 1.7 | 8.2 | 8.4 | 8.7 | 8.9 | 9.2 |
| DRCF (mln), RUB |  | 4.2 | 3.7 | 3.2 | 2.8 | -0.1 | 2.2 | 2.0 | 1.7 | 1.5 | 0.1 | 1.2 | 1.1 | 0.9 | 0.8 | 0.2 | 0.6 | 0.6 | 0.5 | 0.4 | 0.4 |
| NPV (mln), RUB | -25.5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Table A.5 – NPV calculation of 6 WT alternative

| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment (mln), RUB | 56.7 | | | | | 7.2 | | | | | 21.1 | | | | | 10.5 | | | | | |
| Inflation, % | | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 |
| Depretiation of AB (mln), RUB | | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Depretiation of WT and PV (mln), RUB | | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Depretiation of DPS (mln), RUB | | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Revenue (mln), RUB | | 17.0 | 18.0 | 19.1 | 20.2 | 21.4 | 22.7 | 24.1 | 25.5 | 27.0 | 28.7 | 30.4 | 32.2 | 34.1 | 36.2 | 38.3 | 40.7 | 43.1 | 45.7 | 48.4 | 51.3 |
| Fuel price (mln), RUB | | 9.2 | 10.9 | 11.5 | 12.0 | 12.6 | 13.2 | 13.9 | 14.6 | 15.3 | 16.0 | 16.8 | 17.6 | 18.5 | 19.4 | 20.4 | 21.4 | 22.4 | 23.5 | 24.7 | 25.9 |
| Salaries (mln), RUB | | 2.7 | 2.8 | 2.9 | 3.0 | 3.1 | 3.2 | 3.3 | 3.5 | 3.6 | 3.7 | 3.9 | 4.0 | 4.2 | 4.3 | 4.5 | 4.7 | 4.9 | 5.0 | 5.2 | 5.4 |
| Maintenance (mln), RUB | | 1.9 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 | 3.2 | 3.3 | 3.4 | 3.5 | 3.7 | 3.8 |
| Cost (mln), RUB | | 13.8 | 15.7 | 16.4 | 17.1 | 17.9 | 18.7 | 19.6 | 20.5 | 21.4 | 22.4 | 23.4 | 24.5 | 25.6 | 26.8 | 28.0 | 29.3 | 30.7 | 32.1 | 33.6 | 35.1 |
| EBT (mln), RUB | | 0.1 | -0.8 | -0.4 | 0.0 | 0.4 | 0.7 | 1.2 | 1.7 | 2.3 | 2.9 | 3.0 | 3.7 | 4.6 | 5.4 | 6.4 | 7.0 | 8.1 | 9.3 | 10.5 | 11.9 |
| EAT (mln), RUB | | 3.2 | 2.5 | 2.8 | 3.1 | 3.4 | 3.8 | 4.3 | 4.7 | 5.2 | 5.7 | 6.4 | 7.0 | 7.6 | 8.3 | 9.0 | 9.9 | 10.8 | 11.7 | 12.8 | 13.8 |
| CF (mln), RUB | | 5.5 | 4.8 | 5.1 | 5.4 | -1.5 | 6.4 | 6.8 | 7.3 | 7.8 | -12.9 | 9.2 | 9.8 | 10.5 | 11.2 | 1.4 | 13.2 | 14.0 | 15.0 | 16.0 | 17.1 |
| RCF (mln), RUB | | 5.3 | 4.5 | 4.6 | 4.7 | -1.2 | 5.2 | 5.3 | 5.4 | 5.5 | -8.9 | 6.1 | 6.3 | 6.5 | 6.6 | 0.8 | 7.3 | 7.5 | 7.7 | 7.9 | 8.1 |
| DRCF (mln), RUB | | 4.5 | 3.3 | 2.8 | 2.5 | -0.5 | 2.0 | 1.7 | 1.5 | 1.3 | -1.8 | 1.1 | 0.9 | 0.8 | 0.7 | 0.1 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 |
| NPV (mln), RUB | -33.6 | | | | | | | | | | | | | | | | | | | | |

Table A.6 – NPV calculation of 7 WT alternative

| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment (mln), RUB | 59.8 |  |  |  |  | 7.2 |  |  |  |  | 21.1 |  |  |  |  | 10.5 |  |  |  |  |  |
| Inflation, % |  | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 |
| Depretiation of AB (mln), RUB |  | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| Depretiation of WT and PV (mln), RUB |  | 1.2 | 1.2 | 1.2 | 1.2 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Depretiation of DPS (mln), RUB |  | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Revenue (mln), RUB |  | 13.0 | 13.8 | 14.6 | 15.5 | 16.5 | 17.4 | 18.5 | 19.6 | 20.8 | 22.0 | 23.3 | 24.7 | 26.2 | 27.8 | 29.5 | 31.2 | 33.1 | 35.1 | 37.2 | 39.4 |
| Fuel price (mln), RUB |  | 5.1 | 10.9 | 11.5 | 12.0 | 12.6 | 13.2 | 13.9 | 14.6 | 15.3 | 16.0 | 16.8 | 17.6 | 18.5 | 19.4 | 20.4 | 21.4 | 22.4 | 23.5 | 24.7 | 25.9 |
| Salaries (mln), RUB |  | 2.7 | 2.8 | 2.9 | 3.0 | 3.1 | 3.2 | 3.3 | 3.5 | 3.6 | 3.7 | 3.9 | 4.0 | 4.2 | 4.3 | 4.5 | 4.7 | 4.9 | 5.0 | 5.2 | 5.4 |
| Maintenance (mln), RUB |  | 1.9 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 | 3.2 | 3.3 | 3.4 | 3.5 | 3.7 | 3.8 |
| Cost (mln), RUB |  | 9.7 | 15.7 | 16.4 | 17.1 | 17.9 | 18.7 | 19.6 | 20.5 | 21.4 | 22.4 | 23.4 | 24.5 | 25.6 | 26.8 | 28.0 | 29.3 | 30.7 | 32.1 | 33.6 | 35.1 |
| EBT (mln), RUB |  | 0.1 | -5.1 | -5.0 | -4.8 | -4.9 | -4.8 | -4.6 | -4.4 | -4.1 | -3.9 | -4.2 | -3.9 | -3.5 | -3.1 | -2.7 | -2.5 | -2.0 | -1.4 | -0.8 | -0.1 |
| EAT (mln), RUB |  | 3.3 | -1.8 | -1.7 | -1.6 | -1.4 | -1.3 | -1.1 | -0.9 | -0.6 | -0.4 | -0.1 | 0.3 | 1.3 | 1.6 | 2.0 | 2.4 | 2.9 | 3.3 | 3.8 | 4.4 |
| CF (mln), RUB |  | 5.9 | 0.7 | 0.8 | 0.9 | -5.9 | 1.5 | 1.7 | 1.9 | 2.1 | 2.4 | 3.0 | 3.3 | 4.4 | 4.7 | -5.5 | 5.8 | 6.3 | 6.7 | 7.2 | 7.8 |
| RCF (mln), RUB |  | 5.6 | 0.6 | 0.7 | 0.8 | -4.9 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 2.0 | 2.1 | 2.7 | 2.8 | -3.1 | 3.2 | 3.3 | 3.4 | 3.6 | 3.7 |
| DRCF (mln), RUB |  | 4.8 | 0.5 | 0.4 | 0.4 | -2.2 | 0.5 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | -0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| NPV (mln), RUB | -52.0 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

## Appendix B –Figures

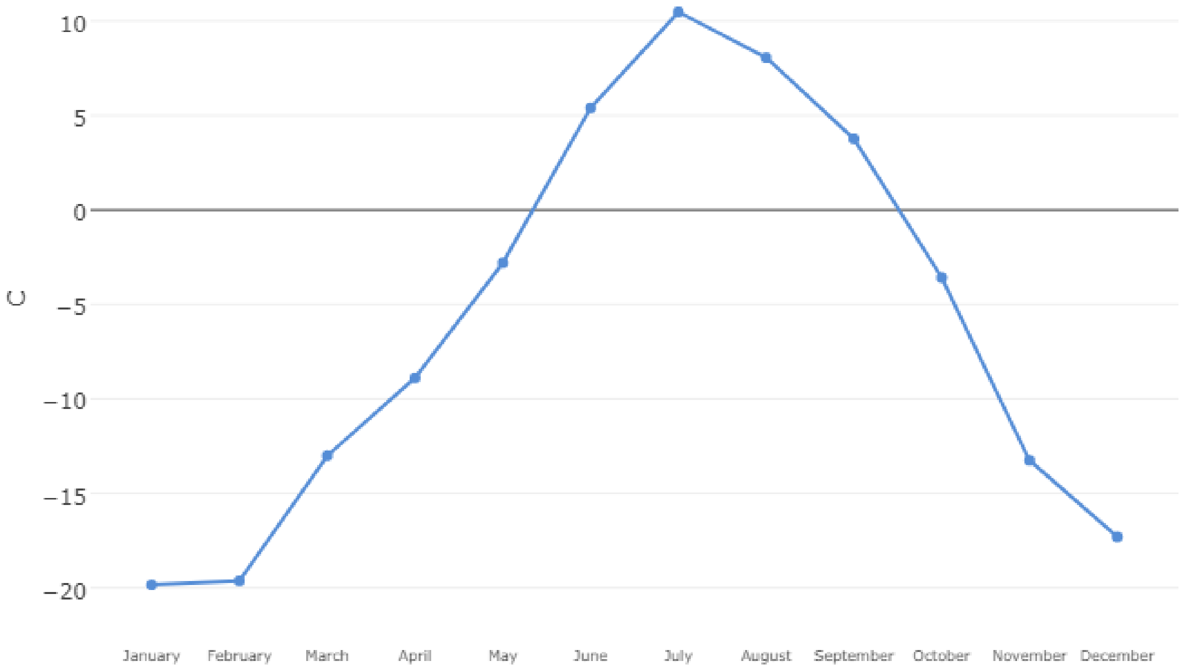

Figure B.1 – Monthly temperature [8]

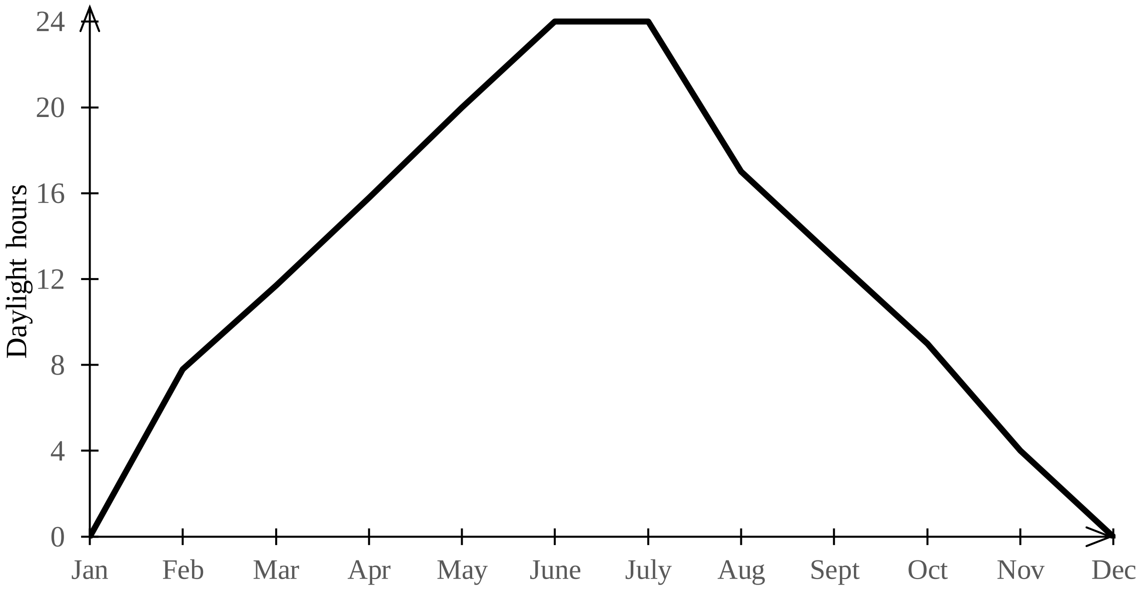

Figure B.2 – Daylight hours [8]

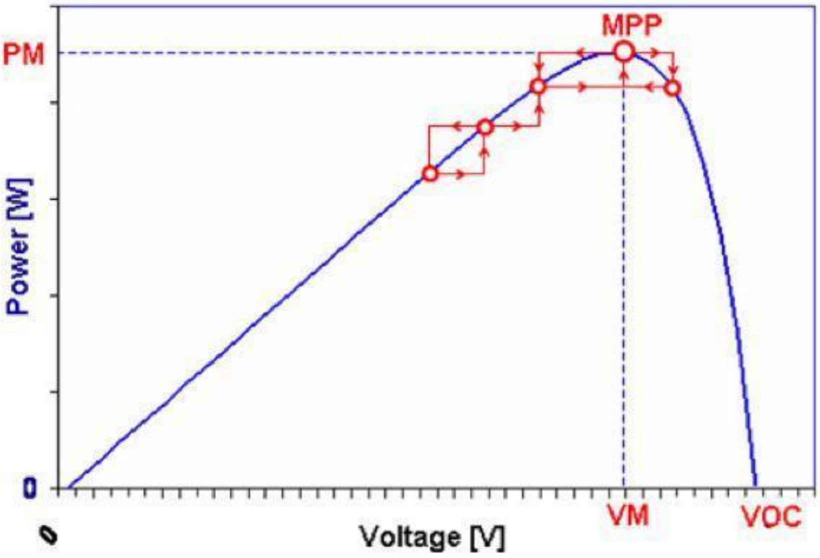

Figure B.3 – Operation principle of MPPT

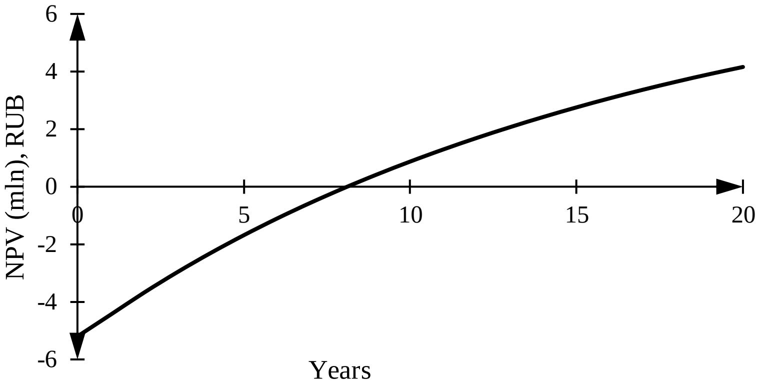

Figure B.4 – Reduced NPV of Allgaier StGW-34 WT

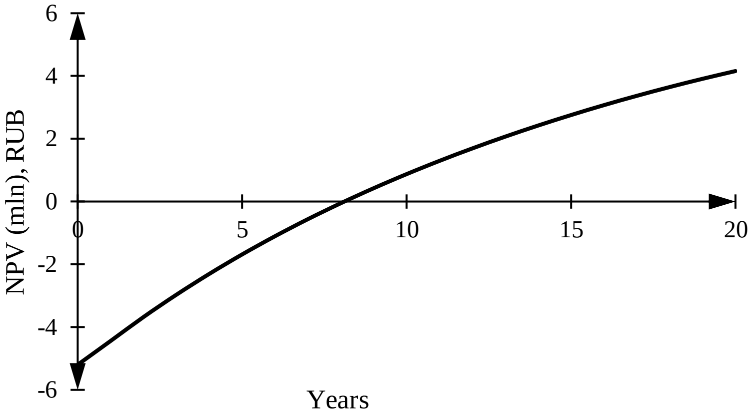

Figure B.5 – Reduced NPV of Argolabe Turbec-100

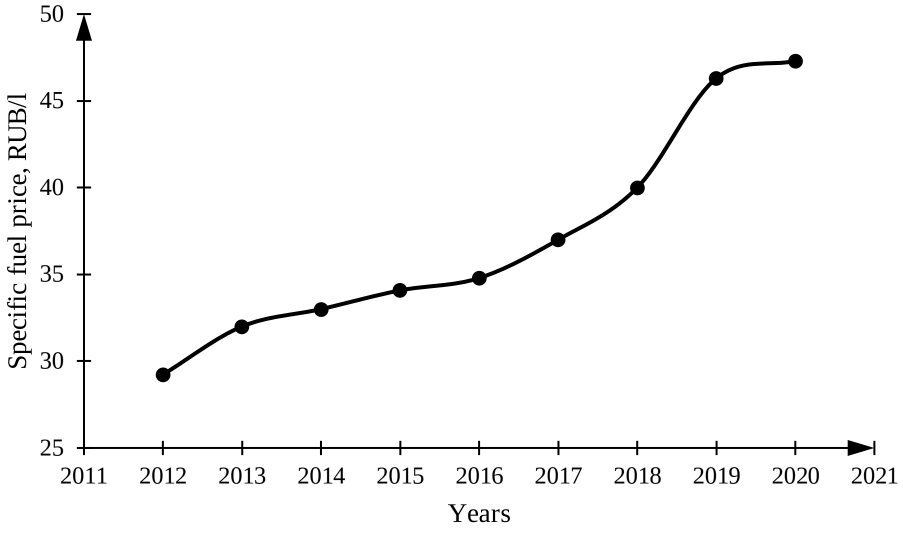

Figure B.6 – Specific fuel price per year

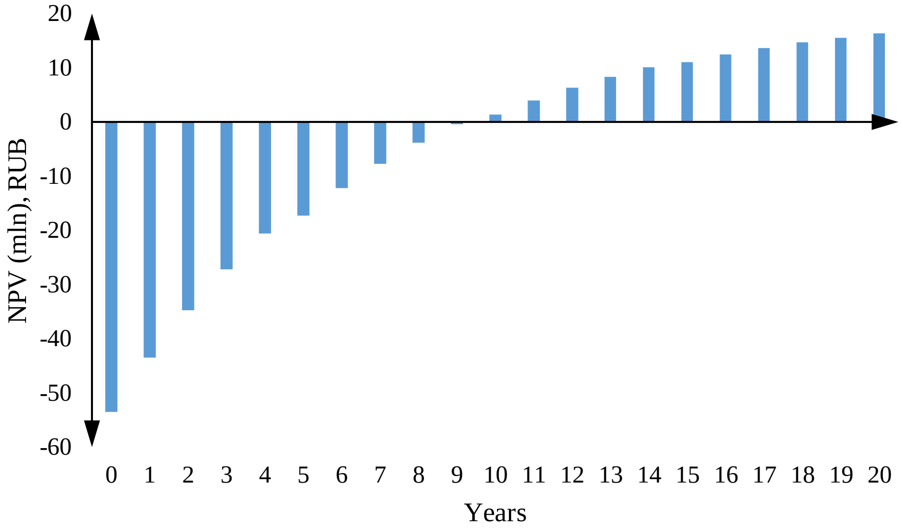

Figure B.7 – Cumulative NPV for 5 WT alternative in case of tariff equal to 15 RUB/kWh

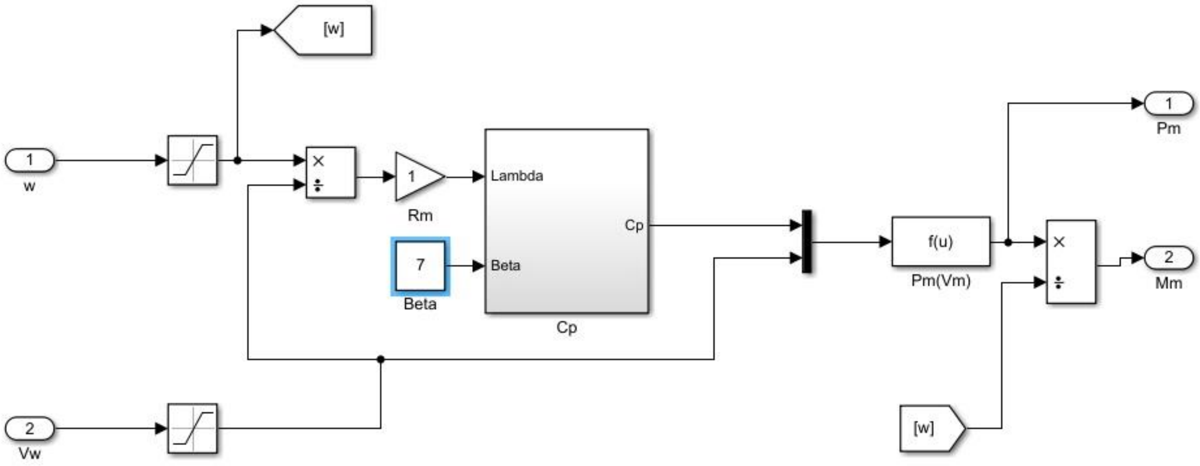

Figure B.8 – Subsystem WT

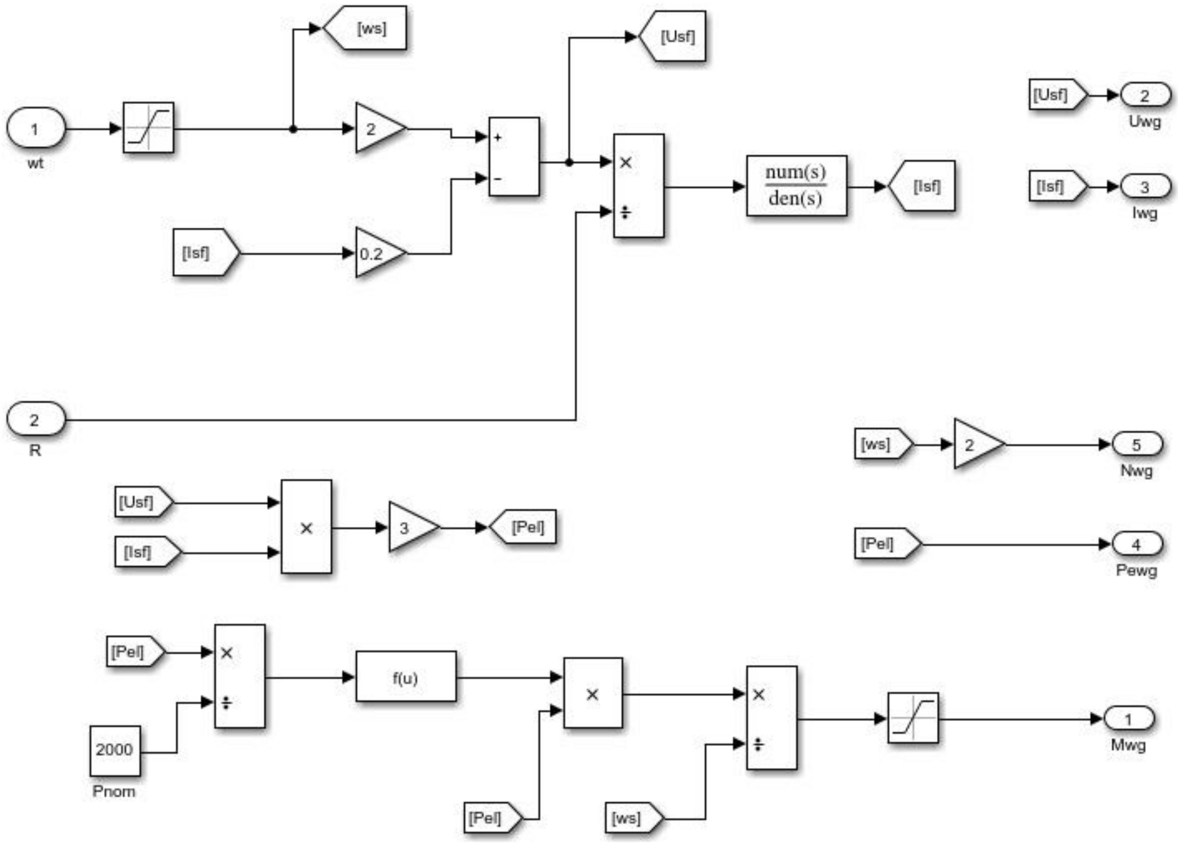

Figure B.9 – Subsystem Generator