CZECH TECHNICZL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

Department of Economics, Management and Humanities

DEVELOPMENT OF A HYBRID POWER PLANT FOR THE POWER SUPPLY OF A RURAL AREA

Master's thesis

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Scientific Adviser: Ing. Július Bemš, PhD

Alena Pavlova

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Student's name: **Pavlova Alena** Personal ID number: **487327**

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Name and workplace of master's thesis supervisor:

doc. Ing. Július Bemš, Ph.D., FEE CTU in Prague, K 13116

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

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doc. Ing. Július Bemš, Ph.D. Supervisor's signature	Head of department's signature	prof. Ing. Pavel Ripka, CSc. Dean's signature

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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

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List of abbreviations

ATS – automatic transfer switch;

AC – alternative current;

DC – direct current;

PV – photovoltaic;

SR – solar radiation;

SP – solar panels;

NPV – Net Present Value;

IRR – Internal Rate of Return;

PP – Payback Period;

RF – Russian Federation.

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Abstract

The main task of this thesis is to find a solution to the problem of decentralized power supply in remote areas of Russia. Most often the decentralized power supply is carried out using diesel generators. This method is quite expensive, because in remote areas it is quite difficult to deliver fuel. Therefore, in this case, the cost of fuel delivery may exceed the cost of fuel. Thus, the cost of electricity produced in this way is quite high. It is also worth noting that this method of generating energy brings harm to the environment

In this paper, I analyzed the possible scenarios for constructing a hybrid power plant for decentralized power supply of a rural settlement. I tried to develop a power supply system for the village, so that it was cheaper and more environmentally friendly than the old one.

In the introduction I justified the relevance of the problem and in subsequent chapters I proceeded directly to the solution of the question.

This diploma contains the following structure: initially, the diploma contains information about the object under study, its technical characteristics, as well as climatic conditions. Further, the data on the amount of insolation in accordance with information on electrical loads are calculated, the selection and calculation of the required number of equipment (solar panels, batteries, diesel generators) is made. Then, after the technical part, a financial model was prepared. The final part of this work is the consideration of possible scenarios of the project implementation and sensitivity analysis.

The results of this thesis and its conclusion are presented at the end of this work.

Introduction

Power supply system in Russia is well developed and meets the standards of electricity quality. The average cost of electricity is 3.2 rubles / kWh (in 2017) [1]. In the ranking of European countries with the cheapest cost of electricity Russia is on the 3rd place [2]. According to the availability of electricity (by the number of kWh available for the average monthly earnings of residents) at 11th [1]. However, there are a number of features that darken the energy situation in Russia.

One of these feature associated with the fact that Russia occupies a huge territory - 17 125 191 km^2 [3], but the population is not evenly distributed. Accordingly, there are many settlements with a small population that are quite remote and distant from large cities.

For such places, it is economically inexpedient to build overhead power lines and connect them to the General power system, because it requires huge capital investments. More acceptable, and the most common today is the option of using diesel power plants. However, in this case, the cost of electricity will be quite high (can reach 104 rubles/kW). This is due to the high cost of diesel fuel and its delivery to the place of use.

In this thesis, we consider the case when the connection to the centralized power supply systems is not economically justified, and the delivery of fuel makes the cost of electricity too high. In this situation, it could be profitable to use a hybrid power supply system, in which energy received not only from traditional sources, but also from alternative ones. For the region considered in this paper, the Sun was chosen as such a source of energy. In addition to the economic positive effect, such a power plant will make energy more environmentally friendly.

Thus, the aim of this work is to develop a decentralized hybrid power plant for the village of Nazino, the creation of a financial model for the evaluation of the project, the comparison of possible scenarios and sensitivity analysis.

Application field: power supply of remote regions with low population density, autonomous power supply systems.

1 Choosing an alternative energy source

In this paper, I will consider the power supply of Nazino village. According to the information of resource [4] in 2017 year in village Nazino lived 383 people. There are school and ambulatory. Diesel power station works.

Due to the remoteness of the territory, it is not advisable to build overhead lines and connect the village to the general power grid. The use of a diesel generator also does not solve the problem of energy supply, since a lot of money is spent on the purchase of fuel, as well as on its delivery (which may be several times higher than the cost of fuel), which makes the cost of electricity very high by the standards of the country. Therefore, it is advisable to build a hybrid power plant. The first task of modeling a hybrid power plant will be the selection of an alternative energy source.

Currently, the most common and effective types of alternative energy for decentralized power supply are solar, wind and wave energy of the seas and oceans. There is no sea and ocean in village Nazino, so it would be optimal to install solar or wind power plant. In order to choose one of them we should estimate solar and wind potential. I will do it in next chapter.

1.1 Potential of using wind as alternative energy source

As noted earlier, for the territory of Nazino village it will be efficient to use solar or wind energy. We know, that wind speed varies with height. To find wind speed at the height of blade we will use formula from manual [5]:

$$V_h = V_w (h / h_w)^a, \tag{1}$$

where V_h - wind speed at the height h;

V_w - wind speed at the height of the weathercock;

h_w - height of the weathercock;

a -coefficient, depend of average wind speed at the height of the weathercock.

For an example I will do calculation for January 2017. Other values are obtained in the same way. From the site [6] I got information about the daily average wind value for whole 2017 [Appendix 1], for January, the value is equal:

$$V_w = 2{,}8 \quad m/s \tag{2}$$

According to the previously mentioned manual [5], the coefficient for the found wind speed value is:

$$a = 0{,}2 \tag{3}$$

According to the Formula (1), knowing that wind strength data was obtained by equipment installed at a height of 10 meters and assuming that the wind turbines will be installed at an altitude of 25 meters, I found the value of the wind speed:

$$V_h = 2{,}8 \cdot (25/10)^{0,2} = 3{,}33 \ m/s \tag{4}$$

For the remaining months, the result of the calculation is presented in table 1.

Table 1 – Average wind speed calculation results

Month	V_w, m/s	a	V_h, m/s
January	2,77	0,2	3,33
February	3,43	0,18	4,04
March	4,16	0,18	4,91
April	4,10	0,18	4,84
May	4,39	0,18	5,17
June	3,70	0,18	4,36
July	2,77	0,2	3,33
August	3,26	0,18	3,84
September	3,13	0,18	3,70
October	3,45	0,18	4,07
November	2,97	0,2	3,56
December	2,90	0,2	3,49
Annual average			4,05

According to the data obtained, the average value of wind at a height of 25 meters is 4,05 m/s. According to the source [7], it is advisable to use wind power plants at wind speeds of more than 4,5 m/s. Since in the village of Nazino the speed does not reach such values, in this area the use of wind generators is inefficient. However, in a few months the wind speed reaches quite high values (5,17 m/s). This means that wind generators can be used effectively (more detailed calculations are needed to confirm this). But in this project, solar energy will be used due to the following disadvantages of wind turbines:

- **Shadow Flicker**

The shadows that are cast by wind turbine blades may be disruptive to people, especially if they have some agricultural land.

- **Construction**

During the construction of a wind farm, heavy machinery is used that may cause erosion and damage to the landscape. The village of Nazino is located in hard to reach place and it will be extremely problematic to deliver all the necessary equipment and facilities for construction. Of course, it is possible to organize it, but this will require an unjustifiably large amount of time, workers and therefore money.

- **Health problems**

Some doctors believe that the presence of wind generators adversely affect human health. Doctor, pediatrician from New York Nina Pierpont wrote a whole book on this topic - Wind Turbine Syndrome [8]. She claims that low-frequency noise from wind turbines causes disturbance of the vestibular system of the inner ear, what leads to the following consequences:

- sleep disturbance;
- headache;
- noise in ears;
- pressure in the ears;
- dizziness;
- nausea;
- visual blurring;
- tachycardia (heart palpitations);
- irritability;
- problems with concentration and memory;
- panic attacks associated with feelings of internal pulsation or trembling.

Despite the fact that Wind Turbine Syndrome is not officially adopted and many researchers criticize it, people very often complain of headaches, insomnia, tinnitus, which they associate with wind turbines.

Based on all the above information, we can conclude that the use of wind as an alternative form of energy for the village of Nazino is not the best option. Therefore, in the next chapter we will consider the sun as an alternative source of energy.

1.2 Potential of using sun as alternative energy source

Speaking of solar batteries, I want first of all to note the fact that they do not contain the main disadvantages of wind generators, which were described above. They do not cause inconvenience to local residents, and are easier to install. In addition, they have the following advantages:

- **Low maintenance**

Solar panels have no moving parts and require minimal maintenance beyond routine cleaning. Of course, the initial cost of installing the panels is large enough, but the cost of maintenance and repair is very reasonable.

- **Environmental friendliness**

The sun is both a renewable and clean source of energy. In addition to the fact that solar energy does not create greenhouse gases, nor does it create nuclear waste, it also helps reduce global warming. The

Sun is almost an endless source of energy and it shines in varying degrees, anywhere in the world. For example, as seen on a map taken from a source [9], in the village of Nazino, the value of solar insolation reaches 3,5 – 4 kWh/m^{2}day.

Figure 1 – The value of solar radiation in Russia [9]

Of course, like any technology, solar panels have disadvantages, the most important of which are:

- **Geographic Limitations**

While some areas will be in greatly benefit from the use of solar energy, other parts of the world not adapted for solar systems due to the lack of insolation. Solar panels still require a lot of sunlight to generate large amounts of energy. However, as noted earlier (Figure 1), there is sufficient solar potential in the village of Nazino.

- **Weather Dependent**

Despite the fact that solar energy can generate electricity even on the cloudy days, efficient collection of solar energy requires good weather conditions. Even a few cloudy days can have a big impact on the energy system. In this project, this disadvantage will be compensated by the use of additional equipment, such as diesel generators or storage batteries.

- **Cost**

The biggest problem of using solar energy is cost. Despite the fact that the sun shines for free solar panels remain quite expensive. After all, for their effective use you need storage batteries, which still remain very expensive.

However, for an accurate answer to the question whether it is profitable to use solar energy or not, calculations are needed, which will be presented in this project.

Chapter conclusion

As can be noted from the previously provided information, wind energy has more serious disadvantages than solar. The solar power station does not exactly have a negative impact on people, is an excellent example of green energy and the region I have chosen (the village of Nazino) has sufficient solar potential. Thus, relying on all the above information, I will use solar energy as an alternative energy source.

2 Electrical load village Nazino

When type of alternative energy source is chosen, it is necessary to determine energy demand for the village of Nazino. For selecting of equipment and further economic calculations I need to know the annual and daily load curves.

The following information was obtained from the official website of Tomsk region Tariff Regulation Department [10]:

$$W_{gen} = 702{,}3\ MWh\ ; \tag{5}$$

$$\Delta W = 10{,}5\ \%\ , \tag{6}$$

where W_{gen} – productive supply of electric energy in 2017;

ΔW – the percentage of technological losses of energy.

Using information above I found annual energy consumption:

$$W_{year.} = W_{gen}(1-\Delta W) = 702{,}3\cdot(1-0{,}105) = 628{,}56\ MWh \tag{7}$$

Using data from Formula 7 and a typical annual load schedule for rural areas [11] I found energy consumption for each month of 2017. I will give an example of the calculation of energy consumption for January. To go from relative to named units, it is necessary to divide the annual energy consumption by the sum of the monthly energy consumption in relative units and multiply by the value of energy consumption in relative units in the corresponding month. This is illustrated in formula 8.

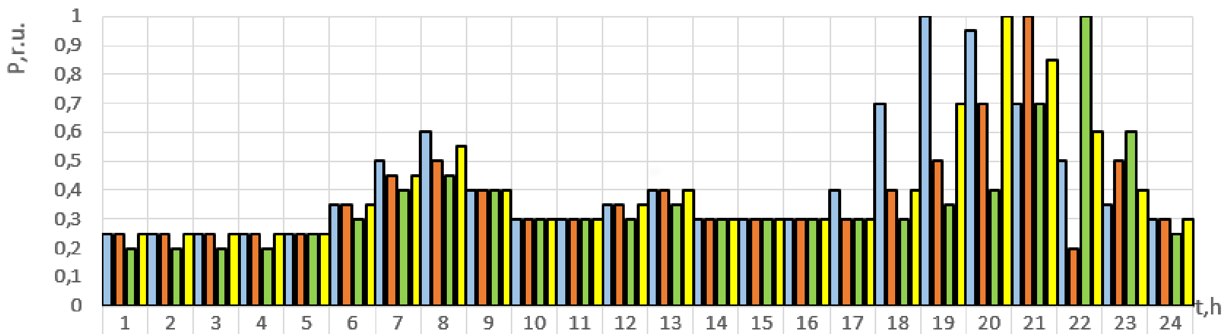
$$\mathrm{W}_{Jan} = \frac{\mathrm{W}_{year}}{\sum \mathrm{W}^*_{\mathrm{month}}}\cdot \mathrm{W}^*_{Jan} = \frac{\mathrm{W}_{year}}{\mathrm{W}^*_{Jan}+\mathrm{W}^*_{Febr}+...+\mathrm{W}^*_{Dec}}\cdot \mathrm{W}^*_{Jan} = \frac{628{,}56}{10{,}2}\cdot 1 = 61{,}6\ MWh \tag{8}$$

For remain months, calculations were carried out in the same manner. The results are shown in table 2.

Table 2 – Monthly energy consumption

Month	January	February	March	April	May	June	July	August	September	October	November	December	**Total**
W^{*}_{month}, r.u.	1	1	0,8	0,8	0,8	0,7	0,7	0,7	0,9	0,9	0,9	1	**10,2**
W_{month}, MWh	61,6	61,6	49,3	49,3	49,3	43,1	43,1	43,1	55,5	55,5	55,5	61,6	**628,6**

Now I need to find the daily value of power consumption. For this, I will use typical daily load schedules for rural houses [11].



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Winter	0,25	0,25	0,25	0,25	0,25	0,35	0,5	0,6	0,4	0,3	0,3	0,35	0,4	0,3	0,3	0,3	0,4	0,7	1	0,95	0,7	0,5	0,35	0,3
Spring	0,25	0,25	0,25	0,25	0,25	0,35	0,45	0,5	0,4	0,3	0,3	0,35	0,4	0,3	0,3	0,3	0,3	0,4	0,5	0,7	1	0,2	0,5	0,3
Summer	0,2	0,2	0,2	0,2	0,25	0,3	0,4	0,45	0,4	0,3	0,3	0,3	0,35	0,3	0,3	0,3	0,3	0,3	0,35	0,4	0,7	1	0,6	0,25
Autumn	0,25	0,25	0,25	0,25	0,25	0,35	0,45	0,55	0,4	0,3	0,3	0,35	0,4	0,3	0,3	0,3	0,3	0,4	0,7	1	0,85	0,6	0,4	0,3

Figure 2 – Typical daily load schedules for rural houses [11]

Before we start calculating hourly consumption, we need to calculate how much energy is consumed per day. For example, in January, the power consumption per day will be:

$$P_{Jan.day} = \frac{W_{Jan.month}}{N_{day}} = \frac{61,6}{31} = 1,99\ MW \qquad (9)$$

where N_{day} – number of days in a month.

The results of calculations for other months are shown in Table 3.

Table 3 – Daily power consumption

Month	January	February	March	April	May	June	July	August	September	October	November	December
N_{day}	31	28	31	30	31	30	31	31	30	31	30	31
P_{day}, MW	1,99	2,20	1,59	1,64	1,59	1,44	1,39	1,39	1,85	1,79	1,85	1,99

Calculation of daily power consumption will be performed in the same way as in formula 8. For example, for January, calculation of power consumption from 0:00 to 1:00 will look as follows:

$$P_{Jan.day(0-1)} = \frac{P_{Jan.day}}{\sum P^{*}_{day}} \cdot P^{*}_{0-1} = \frac{P_{Jan.day}}{P^{*}_{0-1} + P^{*}_{1-2} + ... + P^{*}_{23-24}} \cdot P^{*}_{0-1} = \frac{1,99}{10,25} \cdot 0,25 = 48,5\ kW \quad (10)$$

Below, in table 4, calculations for each month are given, and the maximum and average values of power consumption are found from the obtained data.

Table 4 – Daily power consumption, maximum and average power

Time	January, kW	February, kW	March, kW	April, kW	May, kW	June, kW	July, kW	August, kW	September, kW	October, kW	November, kW	December, kW
1	48,5	53,7	43,7	45,1	43,7	33,2	32,2	32,2	47,2	45,6	47,2	48,5
2	48,5	53,7	43,7	45,1	43,7	33,2	32,2	32,2	47,2	45,6	47,2	48,5
3	48,5	53,7	43,7	45,1	43,7	33,2	32,2	32,2	47,2	45,6	47,2	48,5
4	48,5	53,7	43,7	45,1	43,7	33,2	32,2	32,2	47,2	45,6	47,2	48,5
5	48,5	53,7	43,7	45,1	43,7	41,6	40,2	40,2	47,2	45,6	47,2	48,5
6	67,9	75,2	61,2	63,2	61,2	49,9	48,3	48,3	66,0	63,9	66,0	67,9
7	97,0	107,4	78,6	81,3	78,6	66,5	64,3	64,3	84,9	82,2	84,9	97,0
8	116,4	128,8	87,4	90,3	87,4	74,8	72,4	72,4	103,8	100,4	103,8	116,4
9	77,6	85,9	69,9	72,2	69,9	66,5	64,3	64,3	75,5	73,0	75,5	77,6
10	58,2	64,4	52,4	54,2	52,4	49,9	48,3	48,3	56,6	54,8	56,6	58,2
11	58,2	64,4	52,4	54,2	52,4	49,9	48,3	48,3	56,6	54,8	56,6	58,2
12	67,9	75,2	61,2	63,2	61,2	49,9	48,3	48,3	66,0	63,9	66,0	67,9
13	77,6	85,9	69,9	72,2	69,9	58,2	56,3	56,3	75,5	73,0	75,5	77,6
14	58,2	64,4	52,4	54,2	52,4	49,9	48,3	48,3	56,6	54,8	56,6	58,2
15	58,2	64,4	52,4	54,2	52,4	49,9	48,3	48,3	56,6	54,8	56,6	58,2
16	58,2	64,4	52,4	54,2	52,4	49,9	48,3	48,3	56,6	54,8	56,6	58,2
17	77,6	85,9	52,4	54,2	52,4	49,9	48,3	48,3	56,6	54,8	56,6	77,6
18	135,8	150,3	69,9	72,2	69,9	49,9	48,3	48,3	75,5	73,0	75,5	135,8
19	193,9	214,7	87,4	90,3	87,4	58,2	56,3	56,3	132,1	127,8	132,1	193,9
20	184,2	204,0	122,3	126,4	122,3	66,5	64,3	64,3	188,6	182,6	188,6	184,2
21	135,8	150,3	174,8	180,6	174,8	116,4	112,6	112,6	160,3	155,2	160,3	135,8
22	97,0	107,4	35,0	36,1	35,0	166,2	160,9	160,9	113,2	109,5	113,2	97,0
23	67,9	75,2	87,4	90,3	87,4	99,7	96,5	96,5	75,5	73,0	75,5	67,9
24	58,2	64,4	52,4	54,2	52,4	41,6	40,2	40,2	56,6	54,8	56,6	58,2
Total kW	**1988**	**2201**	**1590**	**1643**	**1590**	**1438**	**1391**	**1391**	**1849**	**1789**	**1849**	**1988**
Aver kW	**82,8**	**91,7**	**66,3**	**68,5**	**66,3**	**59,9**	**58,0**	**58,0**	**77,0**	**74,5**	**77,0**	**82,8**
Max kW	**193,9**	**214,7**	**174,8**	**180,6**	**174,8**	**166,2**	**160,9**	**160,9**	**188,6**	**182,6**	**188,6**	**193,9**

In this chapter, I received all the data necessary to select equipment. Of course, using of typical load graphs does not provide accurate results, but due to the constantly changing energy consumption, it is impossible to say exactly how much energy will be consumed. For estimation the efficiency of hybrid power plant project, the accuracy of received data will be sufficient.

3 Equipment selection

In this chapter, I will provide information about required equipment for the construction of a solar hybrid substation and will choose types of equipment.

The composition of the solar power plant in addition to solar panels usually includes the following equipment:

• Mains inverters that convert direct current generated by solar panels into alternating current;

• Maximum power take-off controllers from solar panels;

• Network - power line to which consumers are connected.

The connection diagram of the solar panels is shown in the figure below.

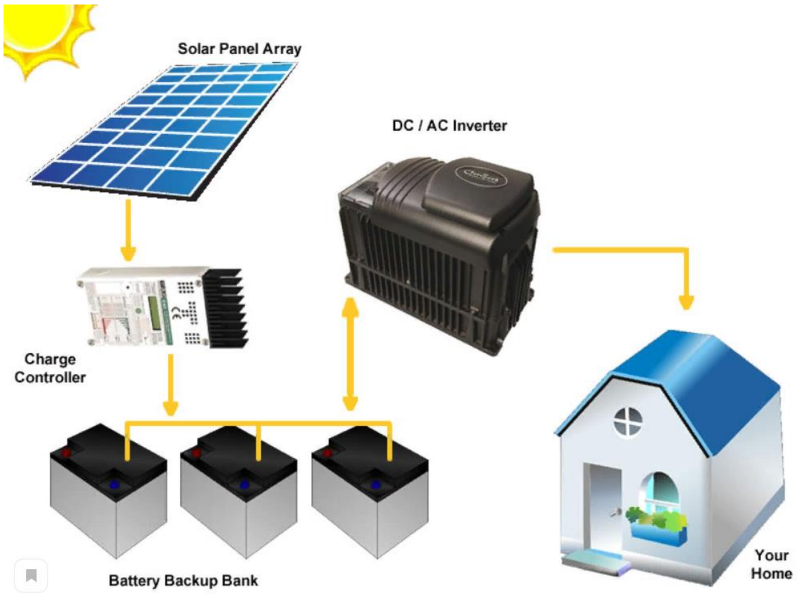


Figure 3 – Connection diagram of the PV system [12]

As can be seen from the above, we need to choose solar panels, inverters, controllers and storage batteries to supply energy to the village of Nazino. A selection of all of this equipment will be made in the following chapters.

3.1 Choosing the type of solar panels and their orientation

It was previously decided that solar energy will be used as an alternative energy source at the substation. In order to get this energy, first of all, solar panels are necessary. Therefore, it is important to choose them correctly.

Solar panels are combined photovoltaic cells (semiconductor devices that directly convert solar energy into direct electric current).

There are three most common types of solar panels:

- Amorphous;
- Polycrystalline;
- Monocrystalline.

The table 5 shows dependence of solar panel efficiency on the cell material is taken from the source [13].

Table 5 – Dependence of the efficiency of the solar panels from the material of the cell [13]

Technology of the crystal	Efficiency in the laboratory	Practical effectiveness
Monocrystalline silicium (m-Si)	25%	13-17%
Polycrystalline silicium (p-Si)	20%	11-14%
Amorphous silicium (a-Si)	13%	5-9%

As can be seen from the table above the worst performance showed amorphous panels. Therefore, the choice will be made from monocrystalline and polycrystalline.

Although monocrystalline panels have the highest efficiency in this project, it will be more profitable to choose polycrystalline panels, because according to the source [14], in addition to the lower cost, they have the following significant advantages:

1. Good performance when operating in cloudy weather conditions, this contributes to the uneven surface of the panel.

2. When a semiconductor element of polycrystalline type is heated, it does not reduce its working qualities as much as monocrystalline.

3. The decrease in the power of polycrystalline panels as the operating period increases is much slower than that of monocrystalline panels.

After analyzing the solar cell market, I chose the FSM 320P solar module [15]. It is a photovoltaic module made of polycrystalline solar cells. Warranty for 10 years of use. The module parameters are given in table 6.

Table 6 – Characteristics of the solar module FSM 320P [15]

Power P_{pan}(W)	320
Area S_{mod}(m^2)	1,94
Cost (RUB.)	12 690
Efficiency factor (%)	16,5
Size (mm)	1956 × 992 × 50
Voltage (V)	24

The flow of solar radiation (SR) will be maximized when sunlight falls on the panel at a right angle. However, to determine at what value the angle of inclination of the panel the sun's rays will fall on it at a right angle is quite difficult due to the movement of the Earth around the Sun and around the earth's axis. The angle of incidence will vary depending on the day, time of day and geographical location of the area in which we install the panel.

To obtain the highest possible efficiency of solar cells, it is necessary to use a solar tracker. However, the cost of solar trackers will significantly increase the cost of a solar substation, so the angle of the solar panels will be constant. With the help of the website [16], the following values of the angles were found at which the efficiency of the solar cells are maximized:

- Solar panels are oriented to the South (the azimuth is zero).
- Solar panels tilted at 45 degrees.

All information obtained from this website [16] is given in Appendix 2.

To verify the information received from the site [16] about tilt angle, I independently calculated the optimal angle of inclination. And I received a result confirming the data obtained from the site. Therefore, in the future, the project I will adhere to the conditions obtained from the site [16], which are listed above. The calculation of the optimum angle of inclination of the panels is given in Appendix 3.

3.2 Generator selection

Since the goal of this project is to develop a hybrid power plant, the substation should contain both an alternative energy source - solar panels, and a traditional one - diesel generators. I will select the generators taking into account the requirements given in the manual [17]:

1. The total capacity of the units should be 25% more than the daily maximum load.

2. For convenience of service, it is desirable to choose diesel generators of the same size.

3. Load of diesel generators should be in the range of 30 - 80% of nominal.

4. The number of diesel generating sets should be redundant to ensure the possibility of decommissioning units for service, maintenance and overhaul.

It is also necessary to take into account the fact that in some scenarios generator will not be the main source of energy, but a backup one (it will work only if there is a shortage of energy obtained from solar panels and stored on accumulator batteries). Therefore, it is necessary to choose a generator with an automatic transfer switch (ATS).

Based on 1 condition and knowing the maximum power consumption (in February $P = P_{\max} = 214,7\ kW$ [Table 4]) we can say that the total power of generators will be equal:

$$\sum P_{GEN} = P_{\max} \cdot 1,3 = 214,7 \cdot 1,3 = 279,1 \ kW \tag{11}$$

The total power of the generator, taking into account the installation of two similar generators should be:

$$P_{gen} = \frac{\sum P_{GEN}}{2} = \frac{279,1}{2} = 139,6 \ kW \tag{12}$$

Accept the installation of two diesel generator unit of AD140-T400, power of 140 kW [18], and one backup generator of the same type (AD140-T400). Data on the selected generator is shown in the table below.

Table 7 – Characteristics of the diesel generator AD140-T400 [18]

Power P_{gen} (kW)	140
Voltage (V)	230
Frequency (Hz)	50
Specific fuel consumption (g/kWh)	218
Efficiency (%)	93
Cost(RUB)	940 000

The manufacturer also provides the following information about the generator [18]:

Permissible overload is not more than 10% of the rated power for no more than 1 hour for every 8 hours of operation, for a total of not more than 200 hours per year. When used as a permanent source of energy, the recommended load should be in the range of 75% to 90% of the rated power. Work under load less than 25% is not allowed for more than 5 minutes.

I calculated specific fuel consumption for the selected generators, using the passport data [18] and the following formula [19]:

$$g_{gen} = \frac{g_{gen.nom}}{\eta_g} \ kg / kWh \tag{13}$$

where $g_{gen.nom}$ - fuel consumption at nominal load kg / kWh ;

η_g - the efficiency output of the generator.

Thus, the nominal specific fuel consumption for the generator AD140-T400 will be:

$$g_{gen} = \frac{0,218}{0,93} = 0,234 \ kg / kWh \tag{14}$$

Next, we need to find a mass of fuel, which is necessary to generate the required amount of energy.

We will find the absolute fuel consumption of the diesel generator by the formula from the source [19]:

$$G_{gen} = g_{gen} \cdot K_{dep} \cdot K_{\mathrm{mod}e} \cdot P_{gen}\ kg / kWh, \tag{15}$$

where K_{dep} – depreciation coefficient (for new generators is taken to be 1);

P_{gen} – generated active power of the generator, kW;

K_{mode} – mode factor, which takes into account the change in specific fuel consumption when the generator with a load less than nominal.

Now we can find the mode coefficient according to the formula [20]:

$$K_{\mathrm{mod}e} = 0,87 + 0,13 \cdot \frac{P_{nom}}{P_{gen}}, \tag{16}$$

where P_{nom} – nominal active power of the generator, kW.

When generators loaded by 80%:

$$G_{gen} = 0,234 \cdot 1 \cdot (0,87 + 0,13 \cdot \frac{140}{112}) \cdot 112 = 27,06\ kg \tag{17}$$

Since the passport data does not contain information about the fuel consumption at idle at starts and stops, we will find this value by the following formula [21]:

$$G_{id} = K_{id} \cdot g_{nom} \cdot P_{nom} \cdot n \cdot \tau_{id}\ kg \tag{18}$$

where n – number of starts of the diesel generator;

τ_{id} – normative duration of the diesel engine idling;

K_{id} – the coefficient taking into account fuel consumption of diesel generator at idle operation accepted for diesels with power up to 1000 liters per second equal 0,21 and for diesels of the bigger power equal 0,17.

Thus, the fuel consumption at idle at one start will be:

$$G_{id} = 0,17 \cdot 0,234 \cdot 140 \cdot 1 \cdot 0,15 = 0,402\ kg. \tag{19}$$

3.3 Controller selection

The controller is an integral part of the solar substation. With its help, storage batteries have a significantly increased service life. At maximum battery charge, the controller will regulate the supply of energy to it, reducing it to the required amount of compensation for the self-discharge of the device. If the battery is completely discharged, the controller will disconnect any incoming load on the device.

According to the source [22], the controllers are selected taking into account the following two conditions:

1. Incoming voltage. The maximum of this indicator should be higher by about 20% of the no-load voltage of the solar battery. For the selected solar module FSM 320P [15] this condition will look like this:

$$U_{inv} = 1,2 \cdot U_{idle.PV} = 1,2 \cdot 45,4 = 54,48\ V, \tag{20}$$

where $U_{idle.PV} = 45,4V$ – напряжение холостого хода солнечной панели FSM 320P [15].

2. Power. The maximum of this indicator should be higher than the power of the solar battery.

Knowing that the power transmitted is equal to the product of the current and the voltage. We can find the nominal current of the solar panel, dividing the nominal power by the nominal voltage:

$$I_{nom.PV} = \frac{P_{nom.PV}}{U_{nom.PV}} = \frac{320}{24} = 13,33\ A, \tag{21}$$

where $P_{nom.PV} = 320W$ – nominal power of the solar panel FSM 320P [15];

$U_{nom.PV} = 24V$ – nominal voltage of the solar panel FSM 320P [15].

After analyzing the controller market in terms of price-quality ratio, I chose controller Studer Vario Track MPPT 65A, with price of 56,5 thousand rubles [23]. Below there are its specifications and connection scheme.

Table 8 - Technical characteristics of the controller Studer Vario Track [23]

Electrical specifications	
Highest recommended solar panels power	5000 W
Maximum no-load voltage	150 V
Maximum operating voltage	145 V
Maximum battery charge current	80 A
Efficiency (in 48 V system)	98%
General Information	
Importer Warranty	1 year
Parallel operation of devices (with different arrays of solar modules)	up to 15 devices

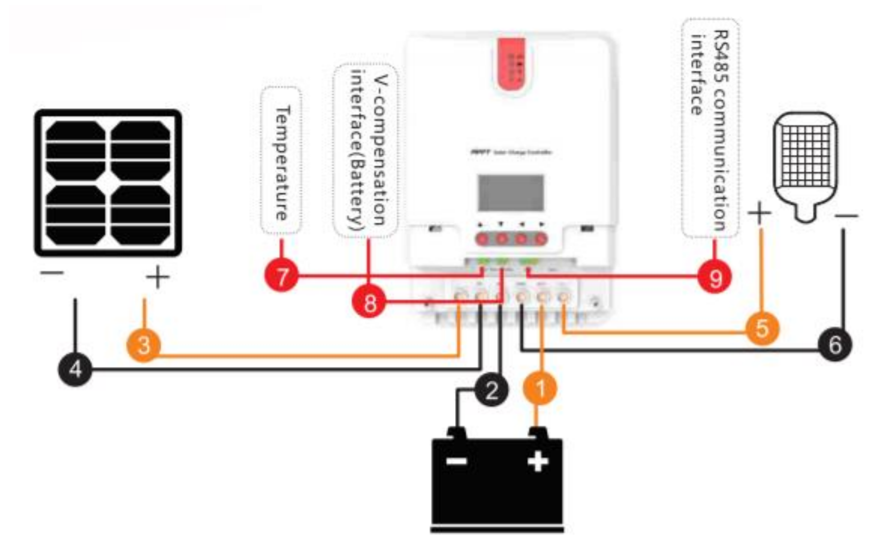


Figure 4 – Controller connection diagram [24]

Based on table 8 and the criteria described earlier, we can choose scheme of solar panels connection.

When solar panels are connected in series, their no-load voltage will be:

$$U(3)_{idle.PV} = 3 \cdot U_{idle.PV} = 3 \cdot 45,4 = 136,2\ V, \tag{22}$$

This satisfies the first selection criteria of the controller (Maximum no-load voltage is 150 W).

Since the maximum recommended power of solar panels is 5000 W. We can find how many parallel chains, assembled from 3 solar panels connected in series, we can connect to the controller. When 3 panels are connected in series, the voltage in such a chain will be:

$$U(3)_{PV} = 3 \cdot U_{nom.PV} = 3 \cdot 24 = 72\ V, \tag{23}$$

where $U_{nom.PV} = 24V$ – nominal voltage of the solar panel [Table 6].

The number of parallel chains will be:

$$N_{PV(3)} = \frac{P_{max.}}{U(3)_{PV} \cdot I_{nom.PV}} = \frac{5000}{72 \cdot 13,33} = 5,2 \approx 5\ , \tag{24}$$

where $P_{max.}$ – highest recommended solar panels power [Table 7].

Thus, we can connect 15 solar panels to one controller (5 parallel-connected chains, each of which consists of 3 series-connected solar panels). And as indicated in the passport data of the controller [Table 7], up to 15 controllers can be connected in parallel.

3.4 Inverter selection

An inverter is a device that converts direct current into alternating current with a voltage of 220 V. The source of direct current for it are both solar and storage batteries.

The inverter is chosen such power that could provide long-term peak load. Its input voltage must correspond to the internal potential difference of the solar system.

After analyzing the inverter market, I chose the model MAP HYBRID 48V, 20kW, 3 phases (60 kW), which is worth 588 thousand rubles. Technical characteristics of which are given in the table below:

Table 9 - Technical characteristics of the inverter [25]

Inverter power	60 kW
Nominal battery voltage	48 V
Number of phases	3
Built-in charger	Yes
Priority use of solar energy	Yes
Battery charge from 220 V	Yes

3.5 Storage battery selection

For solar substations, storage batteries play an important role. During daytime they accumulate excess of energy and give it back to the network during nighttime.

I will use batteries PROSOLAR OPZV – 3000 with price of 121 thousand rubles [26]. Its nominal capacity of 3000 Ah, a cell voltage of 2 V and a service life of 20 years. In order to reduce the values of charging currents, we will collect a circuit of 24 cells in series. Then, parameters of one accumulator battery, consisted of 24 cells, will be as follows:

$$U_{bat} = U_{cell} \cdot N_{cell} = 2 \cdot 24 = 48 \ V \quad (25)$$

where $U_{cell} = 2 \ V$ – nominal voltage of one accumulator;

$N_{cell} = 24$ number of series-connected batteries.

Depth of charge, with the aim of extending battery operating time, should be more than 30%.

The energy of a fully charged battery is:

$$W_{bat.0} = E \cdot U_{bat} = 3\ 000 \cdot 48 = 144 \ kW \quad (26)$$

Technical characteristics of storage batteries are given in the table below.

Table 10 - Technical characteristics of the storage battery PROSOLAR OPZV – 3000 [26]

Voltage	2 V
Capacity	3000 Ah
Maximum charge current	600 A
Weight	225 kg
Maximum discharge current	9000 A (5 sec)

4 Calculation of solar insolation

As a source of information about the solar insolation, I used website [16], where according to the information about location of the panel and its characteristics, its Monthly Energy Output is calculated. For the selected type of panels and the selected territory (the village of Nazino), the results obtained as follows:

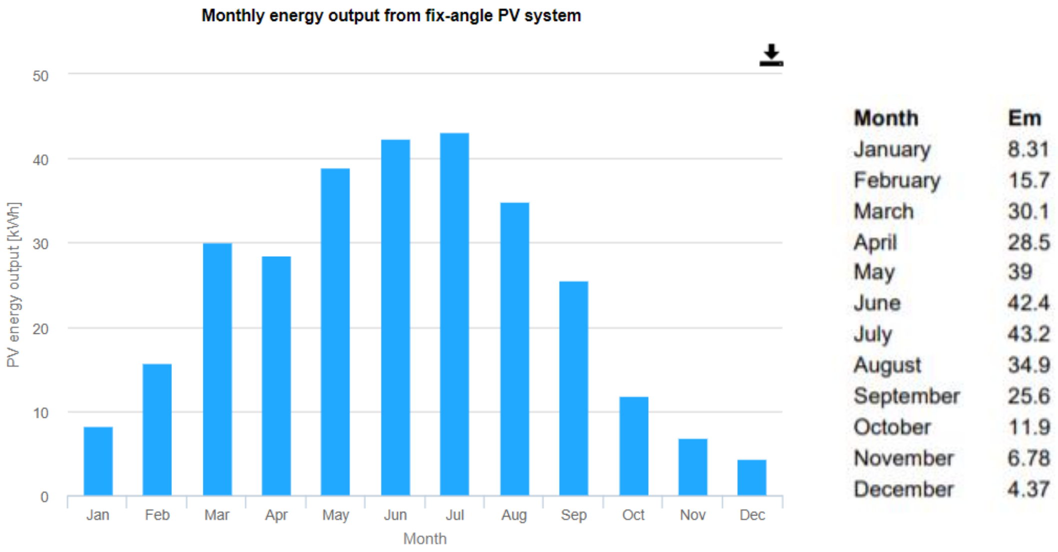


Figure 5 – Monthly PV energy production for one panel [16]

(Em - Average energy production from the given system by month, kWh)

In order to make the calculation of the project more accurate, I need information about solar insolation for each hour. However, from the obtained data I can calculate only the average energy per day. The table below shows these calculations, which I did according to the formula:

$$E_{m.day} = \frac{E_m}{N_{day}} \quad (27)$$

where N_{day} – the number of days in the month.

Table 11 – Calculation of the average energy generated by one panel per day

	January	February	March	April	May	June	July	August	September	October	November	December
E_m, kWh	8,31	15,7	30,1	28,5	39	42,4	43,2	34,9	25,6	11,9	6,78	4,37
N_{day}	31	28	31	30	31	30	31	31	30	31	30	31
$E_{m.day}$, Wh	268	561	971	950	1258	1413	1394	1126	853	384	226	141

Thus, I know the average output of energy, generated by one solar panel per day, but it is necessary to take into account that the panel produces energy only during solar activity hours, and with different insolation different amounts of energy are produced. For clarity, below is a graph of solar insolation per day in the village of Nazino in May.

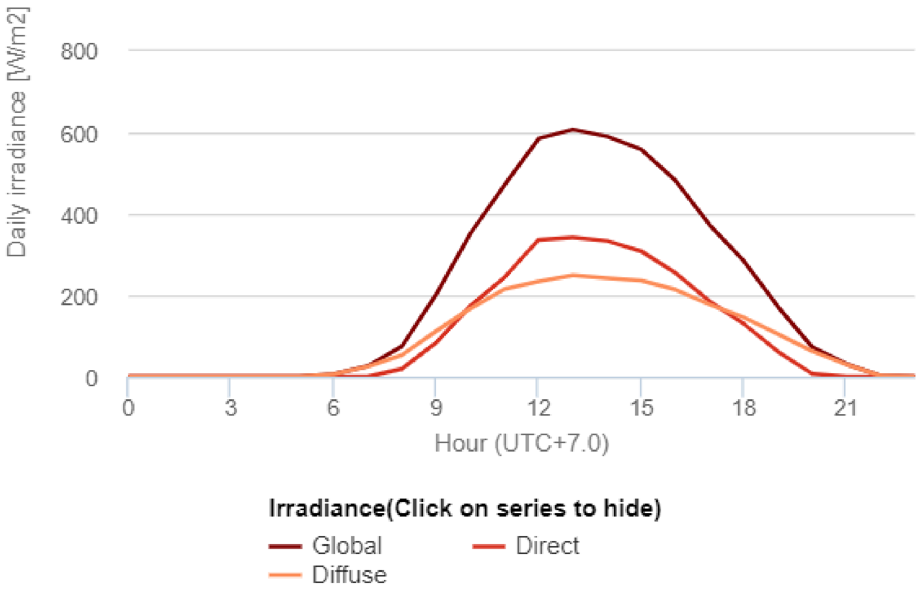


Figure 6 – Daily insolation in May [16]

As can be seen from the figure, the graph can be approximated to a parabola with a sufficient degree of accuracy. Thus, I will assume that the solar activity graph is a power function of the second degree, intersecting the x-axis at points that reflect the time of sunset and the time of sunrise. In the figure below I graphically represent the model of the behavior of solar insolation.

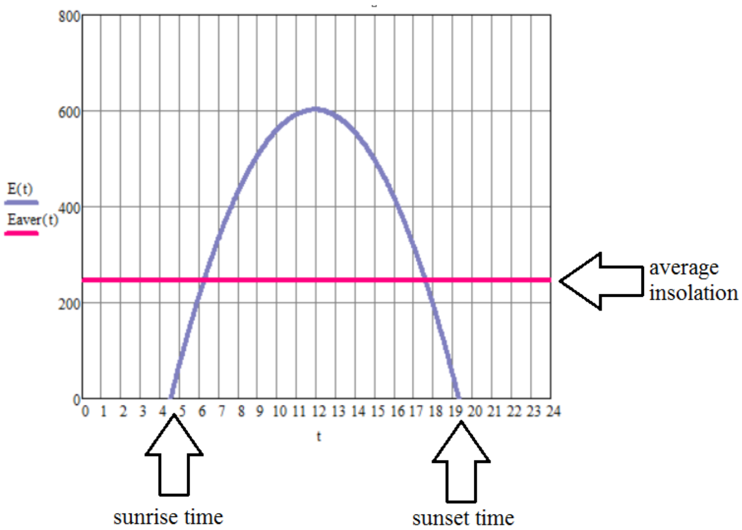


Figure 7 – The model of the behavior of solar insolation

Now I know only the mean insolation values per day, but I can find the average value of the sunrise and sunset times for each month, and determine the solar activity time from the obtained values. Using website [27], I found time of sunrise and sunset for each day of 2017, and I calculated the average value for each month. The difference between the time of sunset and the time of sunrise gave me information about the duration of a sunny day. The results are shown in the table below. For convenience of calculations, I will convert the minutes into hours according to the formula:

$$T_{(HOURS)} = \frac{T_{(MINUTES)} \cdot 100}{60} \tag{28}$$

Table 12 – Time of sunrise and sunset; the duration of solar activity

	January	February	March	April	May	June	July	August	September	October	November	December
T sunrise	8:58	8:06	6:41	5:17	4:05	3:31	3:57	4:58	6:02	7:08	8:18	9:07
T sunrise (hour)	8,97	8,01	6,69	5,29	4,09	3,52	3,95	4,97	6,04	7,13	8,30	9,12
T sunset	16:22	17:29	18:37	19:44	20:49	21:32	21:16	20:11	18:48	17:24	16:13	15:46
T sunset (hour)	16,37	17,48	18,61	19,73	20,82	21,53	21,27	20,18	18,80	17,40	16,21	15,77
Solar activity time	7:24	9:28	11:55	14:26	16:44	18:01	17:19	15:13	12:46	10:16	7:55	6:38

To determine insolation, it is necessary to find the equation of the function graph. For a parabola equation will be as follows:

$$y = a \cdot x^2 + b \cdot x + c \tag{29}$$

Thus, we need to find the coefficients of the function. Since we know the mean insolation value, we can make an equation, considering that the areas under the average insolation line and the area under the function of a parabola are equal. The area under the line of average insolation is equal to:

$$S_1 = E_{m.day} \tag{30}$$

The area under the function of a parabola is equal to:

$$S_2 = \int_{t_{SUNRISE}}^{t_{SUNSET}} \left(a \cdot x^2 + b \cdot x + c\right) dx = \left(\frac{a \cdot x^3}{3} + \frac{b \cdot x^2}{2} + c \cdot x \right) \Big|_{t_{SUNRISE}}^{t_{SUNSET}} = \frac{a(\Delta t)^3}{3} + \frac{b(\Delta t)^2}{2} + c(\Delta t) \tag{31}$$

where $\Delta t = t_{SUNSET} - t_{SUNRISE}$ solar activity time.

Since it was already noted that areas under the curves are equal, then equation (30) is equal to equation (31), thus:

$$\frac{a(\Delta t)^3}{3} + \frac{b(\Delta t)^2}{2} + c(\Delta t) = E_{m.day} \tag{32}$$

So we have one equation and three unknowns (a, b, c). To find the equation describing the graph of the function, it is necessary to create more equations. We will use for this the Viet theorem [28]. As can be seen from Figure 7, the solution of equation (29) will give us two roots, one of which will reflect the time of sunrise, and the second time of sunset.

$$\begin{aligned} & y = a \cdot x^2 + b \cdot x + c = 0 \\ & x_1 = t_{SUNSET} \\ & x_2 = t_{SUNRISE} \end{aligned} \tag{33}$$

According to the Vieta's formulas the roots of the quadratic polynomial are equal [28]:

$$r_1 + r_2 = -\frac{b}{a} \tag{34}$$

$$r_1 \cdot r_2 = \frac{c}{a} \tag{35}$$

Since we know the roots of the quadratic equation (29), using expressions (34) and (35) we can express the coefficients:

$$b = -a(r_1 + r_2) \tag{36}$$

$$c = a(r_1 \cdot r_2) \tag{37}$$

I substituted the obtained coefficients (36), (37) into the equation (32):

$$\frac{a(\Delta t)^3}{3} - \frac{a(r_1 + r_2)(\Delta t)^2}{2} + a(r_1 \cdot r_2)(\Delta t) = E_{m.day} \tag{38}$$

I solved the equation (38) for the coefficient "a" and got the following equation:

$$a = \frac{E_{m.day}}{\frac{(\Delta t)^3}{3} - \frac{(r_1 + r_2)(\Delta t)^2}{2} + (r_1 \cdot r_2)(\Delta t)} \tag{39}$$

Thus, solving the system from (39), (36), (37) equations, we can find the parameters of the graph describing solar insolation. Having carried out calculations in Excel, I found graphs describing the generated energy depending on the time of the day for each month. Then, integrating them, I got value of the energy produced by one panel in an hour. The results are shown below in tabular form, as well as graphically.

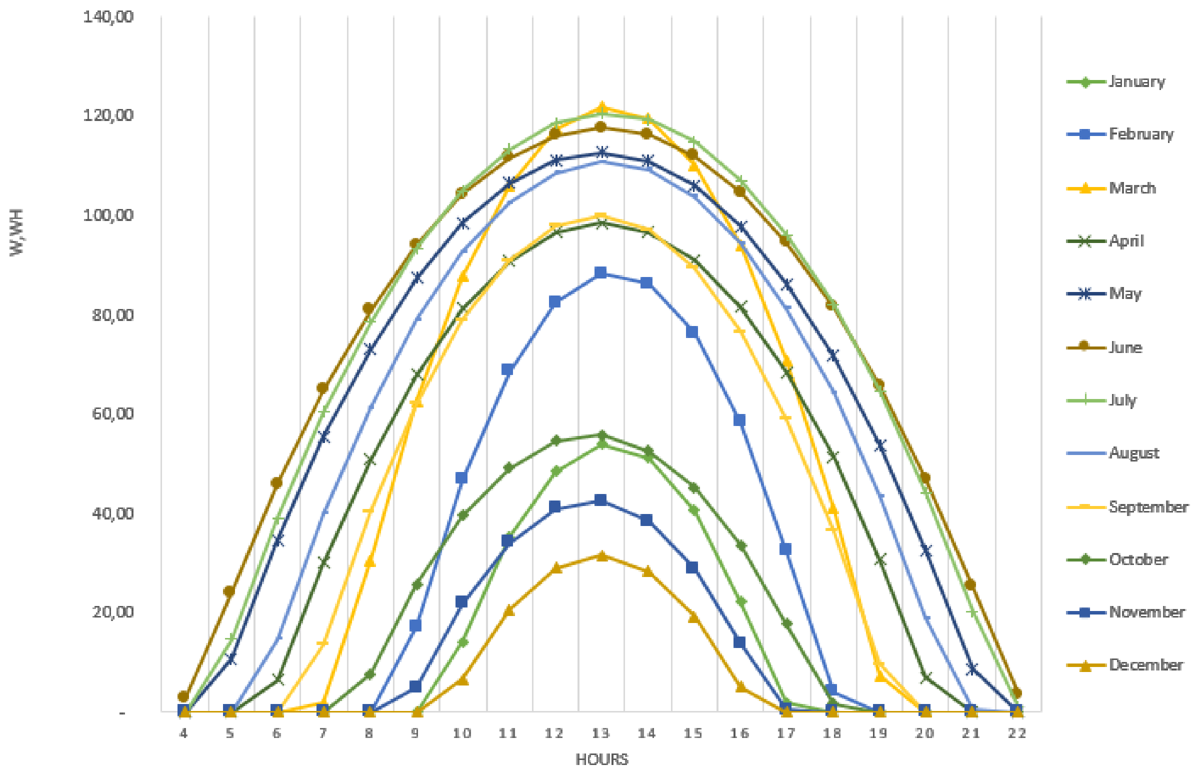


Figure 8 – Average energy production by hour

Table 13 – Average energy production by hour

Average energy production, *Wh*	January	February	March	April	May	June	July	August	September	October	November	December
E_{3-4}	0	0	0	0	0	3,0	0	0	0	0	0	0
E_{4-5}	0	0	0	0	10,8	24,1	14,7	0	0	0	0	0
E_{5-6}	0	0	0	6,6	34,7	46,0	39,2	14,8	0	0	0	0
E_{6-7}	0	0	1,9	30,1	55,5	64,9	60,5	40,0	13,8	0	0	0
E_{7-8}	0	0	30,5	50,9	73,1	80,9	78,5	61,4	40,4	7,8	0	0
E_{8-9}	0	17,2	62,6	68,0	87,4	94,1	93,4	79,0	62,2	25,7	5,0	0
E_{9-10}	14,1	46,9	87,7	81,3	98,6	104,3	105,0	92,7	79,1	39,6	21,8	6,7
E_{10-11}	35,3	68,6	106,0	90,9	106,5	111,6	113,4	102,6	91,0	49,3	34,2	20,7
E_{11-12}	48,6	82,4	117,4	96,6	111,2	116,1	118,6	108,6	98,0	54,6	41,1	29,0
E_{12-13}	53,9	88,3	121,9	98,5	112,6	117,6	120,5	110,8	100,1	55,8	42,5	31,6
E_{13-14}	51,3	86,2	119,5	96,7	110,9	116,2	119,3	109,2	97,2	52,7	38,4	28,4
E_{14-15}	40,7	76,2	110,2	91,1	105,9	111,9	114,8	103,7	89,4	45,3	28,8	19,4
E_{15-16}	22,2	58,3	94,0	81,7	97,7	104,7	107,1	94,5	76,7	33,7	13,8	5,2
E_{16-17}	1,9	32,5	71,0	68,5	86,3	94,7	96,2	81,3	59,1	17,8	0,5	0
E_{17-18}	0	4,1	41,0	51,5	71,7	81,7	82,1	64,4	36,6	1,7	0	0
E_{18-19}	0	0	7,4	30,7	53,8	65,8	64,7	43,5	9,7	0	0	0
E_{19-20}	0	0	0	7,1	32,7	47,0	44,1	18,9	0	0	0	0
E_{20-21}	0	0	0	0	8,8	25,3	20,4	0,5	0	0	0	0
E_{21-22}	0	0	0	0	0	3,6	1,0	0	0	0	0	0
$W_{m.day}^{MAX}$, Wh	**54**	**88**	**122**	**99**	**113**	**118**	**121**	**111**	**100**	**56**	**42**	**32**
$E_{m.day}^{TOTAL}$, kWh	**0,27**	**0,56**	**0,97**	**0,95**	**1,26**	**1,41**	**1,39**	**1,13**	**0,85**	**0,38**	**0,23**	**0,14**

5. Description of scenarios and preparation of the model for their calculation

5.1 Formulation of different scenarios for the project

In previous chapters, all the information needed to create a hybrid station model was obtained. In the first chapter, I chose an alternative energy source - the Sun, in the second chapter I received electrical load diagrams, in the third chapter I chose the necessary equipment, and in the fourth I received the value of the energy produced by the solar panel. Now I can proceed directly to the description of scenarios and their modeling.

Based on the fact that solar panels produce energy only in the hours of solar activity, they cannot fully cover the necessary load (there will be a lack of energy at night or in cloudy hours). Therefore, solar panels should be used either with batteries or with another energy source, such as diesel generators.

In the case of joint operation of storage batteries and solar panels, in the hours of solar activity, the batteries will not only cover the necessary load, but also charge the storage batteries, which in turn will give out energy in those hours when the energy from the panels is not enough or it will be completely absent.

Almost the same logic will be applied to the system with diesel generators. In those hours, when the energy from solar panels will not be enough or it will be completely absent, the necessary load will be covered by diesel generators.

So we have several different variations on how we can design a substation. In this paper I want to analyze several different scenarios. Below I give a brief description of all the scenarios. Then for each scenario I will write a separate chapter, they will contain all the necessary information.

1. In the summer months, solar insolation is maximal (Figure 8), and energy consumption is minimal (Table 3). If we choose the number of panels in such a way as to fully cover the load during the month solely with the help of solar panels without diesel generators (naturally, we will also use storage batteries), then the number of solar panels will be minimal in summer month. The first scenario will be exactly like that.

Because the Sun is the most active in July (Figure 8), we design the substation so that this month all the necessary energy will be generated by solar panels, which will work together with the batteries. In other months, solar insolation is lower, so the energy produced by the panels will not be enough to supply energy. At such moments we will additionally connect a diesel generator. In the morning, during peak electrical loads, we can turn on diesel generators with solar panels, cover the necessary load and charge the batteries. Then, when the peak consumption will pass, we will use the stored energy, and if necessary, turn on the generators in the evening peak loads.

2. Since batteries are very expensive compared to other equipment we will try to minimize their number. We will design a substation that will consist of solar panels, diesel generators and batteries. But unlike the first option, the generators also will be connected in July to minimize the number of batteries. We will use generators as in the first scenario, covering the necessary lack of energy during peak hours of loads and charging the batteries.

In this scenario, the number of PV panels will be the same as in the first scenario, and we will reduce the number of batteries in comparison with the first scenario, because now the lack of energy will be covered by diesel generators whole year.

3. In this case, the substation will consist only of solar panels and storage batteries. We take into account the fact that solar insolation is minimal in winter and maximal in summer. Therefore, the amount

of equipment will be chosen so that in summer the panels can store such amount of energy that would be sufficient for the winter months when the level of insolation decreases.

4. To compare the designed substation with the traditional substation I will also consider in my work the option without connecting solar panels. In this version (as in the real substation in the village of Nazino) all loads are covered exclusively by diesel generators and batteries. The use of batteries will help to use the generators most energy-efficient.

5. In this e scenario, the substation operates exclusively at the expense of diesel generators. Energy is covered by diesel generators as needed.

6. In this scenario, the substation will run on solar panels and with diesel generators, but unlike the first two scenarios, we will not use batteries. Thus, in this scenario, energy will not be stored either from the generators or from the solar panels.

For greater clarity, I created a table that shows us which equipment we will use in each scenario.

Table 14 – Description of equipment which we will use in different scenarios

	Solar panels	Batteries	Diesel generator
1 scenario	+	+	All year,except July
2 scenario	+	+	All year
3 scenario	+	+	-
4 scenario	-	+	All year
5 scenario	-	-	+
6 scenario	+	-	+

5.2 Description of the hybrid substation model in Excel

In order to make the calculations easier and also more accurate, I will build a model in Excel, in which I will calculate all the scenarios listed above. This model will provide information on the consumption and production of energy for each hour of 2017. Using this model, after calculating the scenarios, we will have information not only about generation and consumption of electricity, but also about the fuel consumption of diesel generators.

For example, I will consider the model for the first scenario. I will look at the first day of May in detail to show how the constructed model works. Under the table I will write in detail the meaning of each column.

Table 15 – An example of the work built model, the first scenario, first day of may

1	2	3	4	5	6	7	8
Time	Generated from PV panels W(PV),kWh	Energy consumption W(cons),kWh	ΔW ,kWh	Generated by generator W(1 gen), kWh	Generated by generators W(2 gen), kWh	Battery charging energy	Energy on batteries
0-1	0,0	43,7	43,7	43,7	0	0	661
1-2	0,0	43,7	43,7	43,7	0	0	661
2-3	0,0	43,7	43,7	43,7	0	0	661
3-4	0,0	43,7	43,7	43,7	0	0	661
4-5	7,4	43,7	36,3	0	0	0	625
5-6	23,7	61,2	37,5	0	0	0	587
6-7	38,0	78,6	40,6	0	0	0	547
7-8	50,0	87,4	37,4	0	0	0	509
8-9	59,9	69,9	10,0	0	0	0	499
9-10	67,5	52,4	-15,1	0	0	15,1	514
10-11	72,9	52,4	-20,5	0	0	20,5	535
11-12	76,2	61,2	-15	0	0	15	550
12-13	77,2	69,9	-7,3	0	0	7,3	557
13-14	76,0	52,4	-23,6	0	0	23,6	580
14-15	72,6	52,4	-20,2	0	0	20,2	601
15-16	66,9	52,4	-14,5	0	0	14,5	615
16-17	59,1	52,4	-6,7	0	0	6,7	622
17-18	49,1	69,9	20,8	0	0	0	601
18-19	36,8	87,4	50,6	50,6	0	0	601
19-20	22,4	122,3	99,9	99,9	0	0	601
20-21	6,0	174,8	168,8	0	168,8	0	601
21-22	0,0	35,0	35,0	0	0	0	566
22-23	0,0	87,4	87,4	87,4	0	0	566
23-24	0,0	52,4	52,4	52,4	0	0	566

1. This column shows the time interval for which data is presented.

2. This column shows the energy produced by solar panels. From table 13 we know how much energy is produced for each hour interval. For example, from 4 to 5 one panel produces:

$$W_{1PV(may\ 4-5)} = 10{,}8\ W \tag{40}$$

Suppose the first scenario uses the number of panels equal to 685. Multiplying the number of panels by the power generated by one panel, I calculated how much energy this number of panels produce:

$$W_{PV(may\ 4-5)} = W_{1PV(may\ 4-5)} \cdot N_{pan} = 10{,}8 \cdot 685 = 7{,}4\ kWh \tag{41}$$

where $W_{1PV(may\ 4-5)}$ – the amount of energy produced by one PV panel.

3. This column shows the energy consumption for a certain hour. Energy consumption information was previously obtained in table 4.

4. This column shows the difference between the energy consumed and the energy generated by solar panels. In other words, this is a lack (if the difference is positive) or an excess of energy (if the difference is negative), which we need to either produce or store:

$$\Delta W = W_{CONS} - W_{PV} \tag{42}$$

For example, the number 43.7 kW in the first line shows that the energy from the panels is not enough and we need to get such amount of energy from the generators. In line 10 (for the time from 9 to 10 hours) the number is negative -15.1 kW. This means that solar panels generate more energy than the consumer needs, and this amount of enerhy must be stored using storage batteries.

5. This column shows how much energy was generated from one generator. The column is filled in under certain conditions:

a) If the value in column 4 is positive (which indicates that additional energy is needed).

b) If the lack of energy lies within 30-80 percent of the nominal power of the generator (in Chapter 3.2, information on the optimal load on the generators was noted).

If I present both of these conditions in the form of the formula, it will look like this:

$$\Delta W = (0{,}3 - 0{,}8) P_{NOM.GEN} \tag{43}$$

In our example, the shortage of energy in the first hour satisfies condition 43. The sun has not yet risen, so the production of energy by solar panels is zero. The required power (43.7 kW) is 31 percent of the nominal generator power (140 kW), therefore in the time period from 0 to 1 am one generator will work.

6. This column shows how much energy was generated by the parallel operation of two generators. If condition 43 is not met, and the shortage of energy is too great, but it can be covered by two generators when they work within the recommended limits (30-80%), then two generators work. The formula for this condition is as follows:

$$\Delta W = (0{,}3 - 0{,}8) \cdot 2 \cdot P_{NOM.GEN} \tag{44}$$

From 20-21 hours the shortage is 168.8 kW, condition 43 is not fulfilled (one generator is not able to cover this amount of energy). Condition 44 (the shortage of energy is 60 percent of the total nominal power of two generators (280 kW)) is fulfilled, therefore two generators will operate at this hour.

7. It should be noted that the conditions discussed above (43 and 44) do not cover all possible options. We should consider cases when the power shortage is less than 30 percent of the generation of a

single generator (45) and the case when this shortage is more than 80 percent of the generation of both generators (46):

$$W_{LACK} < 0,3P_{NOM.GEN} \tag{45}$$

$$W_{LACK} > 0,8 \cdot 2 \cdot P_{NOM.GEN} = 1,6 \cdot P_{NOM.GEN} \tag{46}$$

In the case described in equation 45, the lack of energy will be taken from the storage batteries, the power taken from the storage batteries will be subtracted from 8 column. Also, if the rechargeable batteries are fully or almost fully charged, even taking into account condition 43, the energy will be taken from the batteries (this is done so that the system uses all the energy from the solar panels, because if there is not enough space for the accumulation of solar energy, we cannot use it).

The case described in equation 46 for this project can't happen, because the generators are chosen in such a way that when they work in parallel it is possible to cover the maximum energy consumed. So the case when it is necessary to produce more energy than two generators can generate will not occur in this model.

8. The last column contains information about the energy that is stored on batteries. For example, suppose that the system consists of batteries, the total power of which is:

$$P_{bat.0} = 964,8 \ kW \tag{47}$$

Since batteries cannot be discharged by less than 30 percent, the permissible power consumed from the batteries will be:

$$P_{BATT} = 0,7 \cdot P_{bat.0} = 0,7 \cdot 964,8 = 675,4 \ kW \tag{48}$$

Column 8 contains information about the allowable, rather than nominal, energy that can be consumed from the battery, so to meet the conditions for using batteries (you cannot store more than the nominal capacity and discharge more than 70 percent), the number should be in the range from 0 to 675.4 kWh.

To find the energy on the batteries, it is necessary to subtract the amount of consumed energy from energy of batteries and add the amount of generated energy. For our model the amount of energy stored on batteries is:

$$W_{BATT(4-5)} = W_{BATT(3-4)} - W^{-}_{BATT(4-5)} + W^{+}_{BATT(4-5)} = 661 - 36,3 + 0 = 624,3kWh \tag{49}$$

Also in the model were built functions that change the behavior of the parameters so that the battery is not discharged and is not overloaded more than the permissible limits. Such regulation is carried out at the expense of generators. When the charge on the batteries approaches an unacceptable minimum, the generators not only cover the necessary loads of consumers, but also work to charge the batteries.

For greater efficiency, I also took into account the fact that the generator consumes less fuel when it is more loaded. In the case of compliance with the recommendations for generator overload (the optimum mode of operation is 30-80% of the load), it turns out that when loaded by 80 percent, the generator will spend the fuel in the best way. Therefore, if it is necessary to charge the battery, first of all, energy is taken from the already working generators.

For example, if the generator works at 30 percent of its capacity, the remaining 50 percent, if necessary, will charge the batteries.

It helps us to use diesel fuel more economically, because if these 50 percent were taken from a generator that was not in working condition, first, we would use additional fuel to start it, and secondly, the specific fuel consumption would be more (in this case, the generator is loaded by 50 percent, and in the example above by 80 percent), and as a result we would spend more fuel to generate the same amount of energy.

I made similar calculations for each day of 2017. Thus, I received a model that reflects the processes occurring in a system equipped with solar panels, controllers, batteries, inverters and diesel generators. In it, the rechargeable batteries are always charged within acceptable limits, consumers receive all the necessary energy and the generators work optimally.

According to the constructed model, I can easily get the data necessary to calculate the economic efficiency of the project. In the further descriptions of scenarios, I will not provide information on how I obtained the data (the data will be calculated in the constructed model, as shown above), but I will only select the amount of necessary equipment and give the results of the calculations.

6. Scenarios calculation

6.1 Calculation of the first scenario

As noted earlier in this scenario, in July the village will be supplied exclusively by solar panels and batteries. And in all other months the shortage of energy will be covered by diesel generators.

First of all, it is necessary to determine the required number of solar panels. For this, I will divide the energy consumed in July (the value of energy consumption taken from table 2) by the energy generated by one panel (table 11):

$$N = \frac{W_{av.july}}{W_{g.july}} = \frac{43\ 089}{43,2} = 997,4 \approx 997 \qquad (50)$$

To supply energy in case of its lack, as well as its accumulation at the moments when the generated energy is more than consumed, it is necessary to use storage batteries. They will provide the energy needed by consumers at night and in cloudy weather and compensate for the peak loads that photovoltaic modules cannot cover. In addition, the batteries will act as a voltage regulator on the load, since the output voltage of the solar module according to its volt-ampere characteristic can vary widely.

Since solar panels work in conjunction with batteries, it is necessary to comprehensively consider the problem of choosing equipment. It is necessary to choose the amount of equipment in such a way that the equipment costs are minimal, but all the necessary requirements will be met, namely:

- Consumers get all the energy they need
- Battery charge ranged from 30% to 100%

As was notice earlier, we will use batteries PROSOLAR_OPZV-3000 [26]. With a nominal capacity of 3 000 Ah, a cell voltage of 2 V and a service life of 20 years. In order to reduce the values of charging currents, we will collect a circuit of 24 cells in series.

Then the parameters of single battery of accumulators will be as follows: E_{bat} = 3 000 Ah; U_{bat} = 48 V. Depth of discharge, with the aim of extending battery life, should be more than 30%.

I found the required capacity; the daily value of consumed energy was taken from the table 4.

$$E_{req} = \frac{W_{day}}{U_{bat}} = \frac{1\ 391 \cdot 10^3}{48} = 28\ 979\ \text{ Ah} \tag{51}$$

Determination of the required number of storage battery:

$$N_{bat} = \frac{E_{req}}{E_{nom.bat}} = \frac{28\ 979}{3000} = 9,65 \approx 10 \tag{52}$$

I calculated the cost of buying the selected number of batteries and solar panels:

$$C = C_{pan} \cdot N_{pan} + C_{bat} \cdot 24 \cdot N_{bat} = 12\ 690 \cdot 997 + 4\ 136\ 640 \cdot 10 = 54\ 018\ 330\ \ RUB \tag{53}$$

Based on the calculations it is accepted to install 240 batteries (10 batteries, collected 24 cells connected in series). The capacity of the selected number of batteries will be:

$$E = 3\ 000 \cdot 10 = 30\ 000\ \ Ah \tag{54}$$

I assumed that at the beginning of the month the batteries are half charged:

$$W_{bat.0} = 0,5 \cdot E \cdot U_{bat} = 0,5 \cdot 30\ 000 \cdot 48 = 720\ \ kW \tag{55}$$

The energy on the storage batteries are shown in the discharge graph-the batteries in figure 9, the same figure shows the nominal charge level on the batteries and the minimum allowable, corresponding to 30% of the nominal.

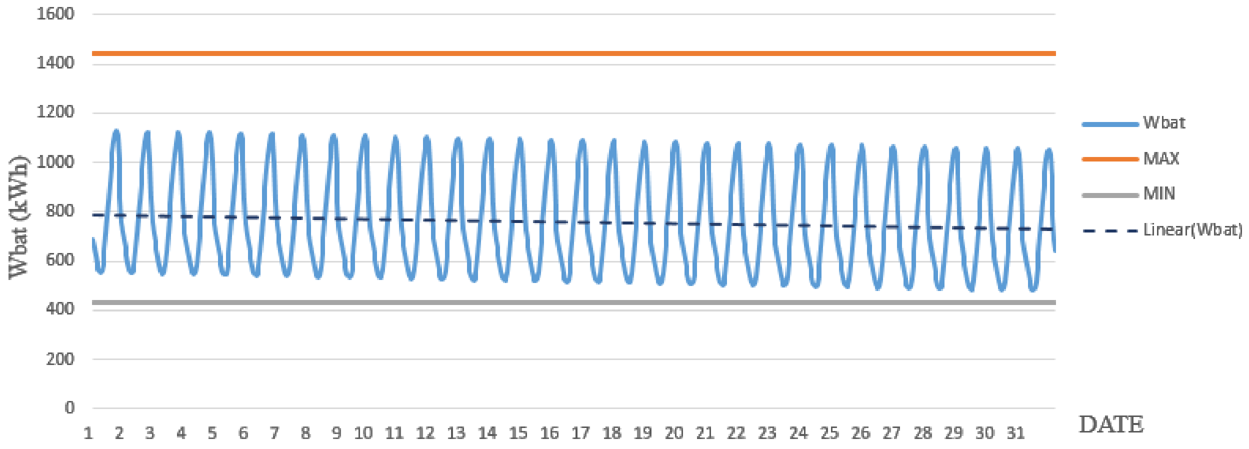


Figure 9 – The dynamics of discharge of the battery (10 batteries; 997 PV panels)

As can be seen from Figure 9, the batteries are charged within acceptable limits. This suggests that the selected amount of equipment (997 solar panels and 10 rechargeable batteries, each of which consists of 24 cells) satisfies all conditions.

However, the connection scheme of the solar panels was previously determined, one unit should consist of 15 solar panels (chapter 3.3). Therefore, the number of panels should be a multiple of 15. According to this, we will re-select the number of solar batteries, rounding it to the nearest multiple:

$$N_{pan} = 1005 \tag{56}$$

I recalculated the cost of equipment and built a battery charging schedule.

$$C = 12690 \cdot 1005 + 4136640 \cdot 10 = 54\ 119\ 850 \quad RUB \tag{57}$$

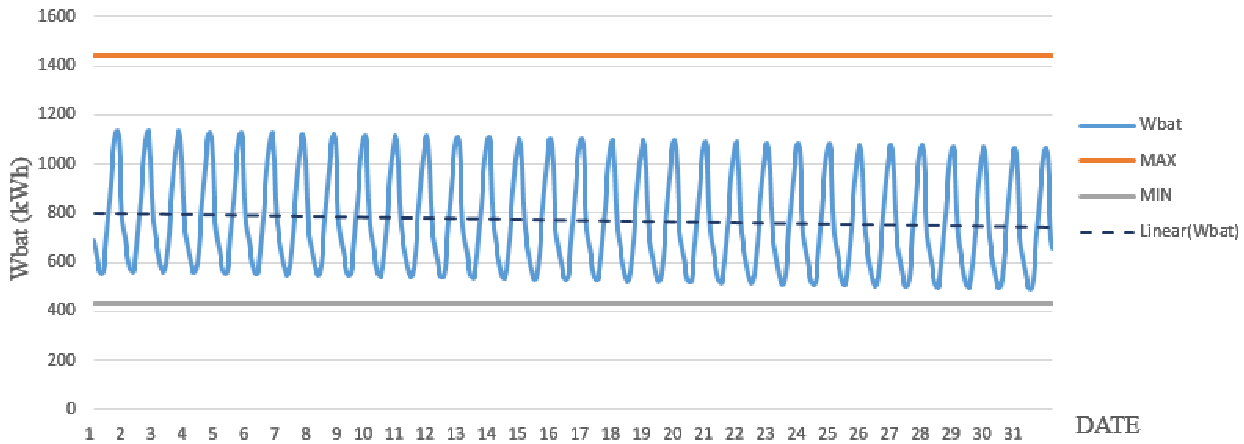


Figure 10 – The dynamics of discharge of the battery (10 batteries; 1005 PV panels)

By choosing the amount of equipment, I can calculate how much the selected number of batteries covers the consumed load in each month. To do this, I will divide the energy generated by the panels into the energy consumed per month:

$$\Delta = \frac{W_{GEN.PV}}{W_{AV.CONS.}} \cdot 100\% \tag{58}$$

To find the generated power, I multiplied the power generated by one panel (table 11) by the number of panels. For example, for January, the amount of energy produced by the panels will be equal to:

$$W_{GEN.JAN.} = E_{(JAN)} \cdot N_{PV} = 8,31 \cdot 1005 = 8,35 \ MWh \tag{59}$$

where $E_{(JAN)}$ – power generated by one panel per month (table 11)

The results of calculations for other months are given in table 16.

Table 16 – Results of calculation of energy production of PV panels (1005)

Month	Consumption, MWh	Production, MWh	Lack, MWh	Load Coverage,%
January	61,6	8,4	-53,2	13,6
February	61,6	15,8	-45,8	25,6
March	49,3	30,3	-19,0	61,4
April	49,3	28,6	-20,7	58,1
May	49,3	39,2	-10,1	79,5
June	43,1	42,6	-0,5	98,9
July	43,1	43,4	0,3	100,7
August	43,1	35,1	-8,0	81,4
September	55,5	25,7	-29,8	46,4
October	55,5	12,0	-43,5	21,5
November	55,5	6,8	-48,7	12,3
December	61,6	4,4	-57,2	7,1

Thus, for uninterrupted power supply of the consumer in July only at the expense of the energy generated by photocells, it is necessary to establish accumulators consisting of 240 cells (10 accumulator batteries collected of 24 consistently connected cells),1005 PV panels and one inverter. Considering that 15 solar panels are connected to one controller, the required number of controllers will be:

$$N_{inv} = \frac{N_{PV}}{15} = \frac{1005}{15} = 67 \ , \tag{60}$$

where N_{PV} – number of solar panels.

The results that I obtained by calculating this scenario in the constructed model are given below.

Table 17 – The result of the calculation of the first scenario

Month	Generated energy (kWh)		Fuel consumption		
	By solar panels	By generators	Gg(load),kg	Gg(idle),kg	Gg(total),kg
January	8 351	52 359	13 579	131	13 709
February	15 779	46 588	12 129	117	12 246
March	30 250	18 605	4 720	104	4 824
April	28 642	20 395	5 311	100	5 412
May	39 194	10 283	2 609	75	2 684
June	42 613	224	54	2	56
July	43 416	0	0	0	0
August	35 075	8 239	2 192	26	2 218
September	25 728	29 522	7 684	75	7 760
October	11 960	43 292	11 214	104	11 317
November	6 814	48 664	12 689	100	12 789
December	4 392	57 160	14 912	156	15 069
TOTAL	**292 213**	**335 331**	**87 093**	**991**	**88 084**

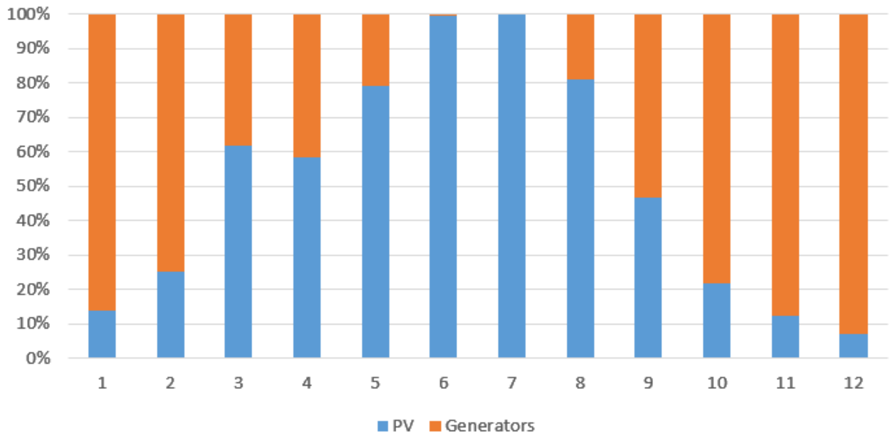


Figure 11 – Distribution of energy received from solar panels and generators for the first scenario

6.2 Calculation of the second scenario

This scenario is exactly the same as the first, with the exception of one feature. In the first scenario, there was restriction that the generators would be turned off in July, in this scenario there is no such restriction. Solar panels, batteries and generators operate year-round. Using the generator all year will help us reduce the required number of batteries. After all, now we do not need to accumulate a lot of energy to cover the lack from solar panels, because now it will be covered by a generator.

The number of solar panels will be the same as in the first scenario - 1005. As mentioned above, in this scenario, the batteries are used as a reserve and for the generator to work in the best loading conditions (work at loading from 30 to 80%). Therefore, we will install 4 batteries, consisting of 24 cells.

Table 18 – The result of the calculation of the second scenario

	Generated energy (kWh)		Fuel consumption		
Month	By solar panels	By generators	Gg(load),kg	Gg(idle),kg	Gg(total),kg
January	8 351	53 038	13 858	131	13 989
February	15 779	45 874	11 932	118	12 050
March	30 250	18 993	4 799	104	4 903
April	28 642	20 476	5 345	100	5 445
May	39 194	10 072	2 506	44	2 550
June	42 613	672	163	5	168
July	43 416	224	54	2	56
August	35 075	7 392	1 789	28	1 817
September	25 728	29 933	7 837	75	7 912
October	11 960	43 425	11 249	104	11 353
November	6 814	48 664	12 689	100	12 789
December	4 392	57 257	14 932	156	15 088
TOTAL	**292 213**	**336 020**	**87 153**	**967**	**88 119**

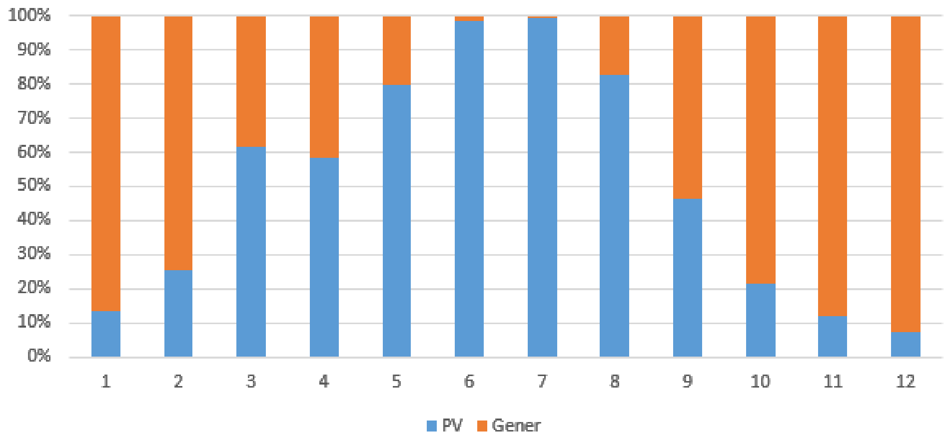


Figure 12 – Distribution of energy received from solar panels and generators for the second scenario

6.3 Calculation of the third scenario

In this scenario, the village is supplied exclusively by solar panels and batteries.

I begin the selection of equipment with a choice of solar panels. In Table 19 below, I will calculate required numbers of panels in order to cover monthly demand. Based on different consumption and generation, for each month I received different data.

Table 19 – Calculation of the number of solar panels

Month	Consumption, MWh	Production (1 PV), kWh	The number of solar panels	Production (1740 PV), MWh	Lack (1740 PV), MWh
January	61,6	8,3	7 435	18,1	-43,5
February	61,6	15,7	3 935	34,2	-27,4
March	49,3	30,0	**1 643**	65,5	16,2
April	49,3	28,4	**1 735**	62,0	12,7
May	49,3	38,9	**1 268**	84,8	35,5
June	43,1	42,3	**1 020**	92,2	49,1
July	43,1	43,1	**1 001**	94,0	50,9
August	43,1	34,8	**1 239**	75,9	32,8
September	55,5	25,5	**2 174**	55,7	0,2
October	55,5	11,9	4 678	25,9	-29,6
November	55,5	6,8	8 210	14,7	-40,8
December	61,6	4,4	14 139	9,5	-52,1
TOTAL	**628,50**				**3,9**

Analyzing the data obtained from the table, it can be concluded that it is extremely irrational to provide energy from solar panels year-round. After all, firstly, the installation of panels in the amount of 14,139 pieces will require huge capital investments, secondly, the installation of such a number of panels will require huge areas that are not available in the village, thirdly the installation of such a number of batteries will lead to a large excess generation in the summer. Therefore, this solution is not profitable.

A more rational solution would be to supply the village with solar energy in the spring, summer months and in September. To do this, we will need to install solar panels in the amount of 2175 pieces. In this case, the system will have moments in which the energy produced will be insufficient, as well as moments when generation will be excessive. Using storage batteries will help us solve this problem.

The number of batteries should be sufficient to stock up all the amount of over-generated energy over the summer and use it in the winter months. From the last column of table 16, I found the over-generated energy. I divided obtained number by battery's voltage and got the required capacity:

$$E_{req} = \frac{W_{surplus}}{U_{bat}} = \frac{197{,}345 \cdot 10^6}{48} = 4\ 111\ 361 \text{ Ah} \tag{61}$$

where $W_{surplus}$ – over-generated energy

According to the data, I found the number of storage batteries:

$$N_{bat} = \frac{E_{req}}{E_{nom.bat} \cdot 0{,}7} = \frac{4\ 111\ 361}{3000 \cdot 0{,}7} = 1957{,}79 \approx 1958 \tag{62}$$

where 0,7 – coefficient taking into account the fact that the battery is not recommended to discharge more than 30 percent, so the power that can be used with the battery is 70 percent of its nominal capacity.

Table 20 – The result of the calculation of the third scenario

	Generated energy (kWh)		Fuel consumption		
Month	By solar panels	By generators	Gg(load),kg	Gg(idle),kg	Gg(total),kg
January	18 073	0	0	0	0
February	34 148	0	0	0	0
March	65 467	0	0	0	0
April	61 987	0	0	0	0
May	84 823	0	0	0	0
June	92 221	0	0	0	0
July	93 959	0	0	0	0
August	75 908	0	0	0	0
September	55 680	0	0	0	0
October	25 883	0	0	0	0
November	14 747	0	0	0	0
December	9 504	0	0	0	0
TOTAL	**632 401**	**0**	**0**	**0**	**0**

6.4 Calculation of the fourth scenario

In this version (as in the real substation in the village of Nazino) all loads are covered exclusively by diesel generators and batteries. The use of batteries will help us to use the generators most energy-efficient way. Therefore, in this scenario, will be installed 4 batteries, consisting of 24 cells.

Table 21 – The result of the calculation of the fourth scenario

	Generated energy (kWh)		Fuel consumption		
Month	By solar panels	By generators	Gg(load),kg	Gg(idle),kg	Gg(total),kg
January	0	61 481	15 712	131	15 843
February	0	61 620	15 433	117	15 550
March	0	49 349	12 709	78	12 787
April	0	49 298	12 613	75	12 689
May	0	49 289	12 697	78	12 775
June	0	43 218	11 288	0	11 288
July	0	43 017	11 277	130	11 407
August	0	43 145	11 312	130	11 441
September	0	55 435	14 249	75	14 324
October	0	55 466	14 221	78	14 299
November	0	55 481	14 258	75	14 334
December	0	61 633	15 743	131	15 874
TOTAL	**0**	**628 431**	**161 513**	**1 097**	**162 610**

6.5 Calculation of the fifth scenario

In this scenario, neither alternative sources of energy nor batteries are used. In this scenario, the substation operates exclusively at the expense of diesel generators.

As noted earlier, the most optimal mode of operation of generators is achieved when they are loaded by 80%, but in this scenario this condition cannot be fulfilled, because generators produce as much energy as the consumers need.

Table 22 – The result of the calculation of the fifth scenario

	Generated energy (kWh)		Fuel consumption		
Month	By solar panels	By generators	Gg(load),kg	Gg(idle),kg	Gg(total),kg
January	0	62 367	16 554	105	16 659
February	0	61 631	16 033	94	16 127
March	0	49 299	13 492	52	13 544
April	0	49 296	13 381	50	13 431
May	0	49 995	13 634	52	13 686
June	0	43 367	12 160	0	12 160
July	0	43 370	12 272	52	12 324
August	0	43 146	12 238	52	12 289
September	0	55 473	14 897	50	14 947
October	0	55 462	14 882	52	14 933
November	0	55 473	14 897	50	14 947
December	0	61 637	16 405	105	16 510
TOTAL	**0**	**630 516**	**170 844**	**713**	**171 557**

6.6 Calculation of the sixth scenario

This scenario is calculated similarly to the fifth, but in this one, the generators work together with solar panels. Additional use of solar energy helps us to saves diesel fuel.

Since in this scenario, storage batteries are not used, it is rational to choose solar panels in such a way that all their power is immediately used by consumers (no excess energy is generated).

In July, the sun is the most active, and consumption is minimal (relative to other months), so it makes sense to choose panels for that month, then in other months the excess energy will be minimal.

Below, I calculated how many panels are needed to cover the load in July at each hour. To do this, I divided the power consumption of the power produced by one panel (all these data were obtained earlier).

Table 23 – Calculation of the number of solar panels

Time	Consumption (kWh)	Energy generated by one panel (Wh)	Number of panels
4 – 5	40,2	14,72	2731,0
5 – 6	48,3	39,21	1231,8
6 – 7	64,3	60,49	1063,0
7 – 8	72,4	78,54	921,8
8 – 9	64,3	93,38	688,6
9 – 10	48,3	105	460,0
10 – 11	48,3	113,39	426,0
11 – 12	48,3	118,57	407,4
12 – 13	56,3	120,54	467,1
13 – 14	48,3	119,28	404,9
14 – 15	48,3	114,8	420,7
15 – 16	48,3	107,11	450,9
16 – 17	48,3	96,2	502,1
17 – 18	48,3	82,06	588,6
18 – 19	56,3	64,71	870,0
19 – 20	64,3	44,14	1456,7
20 – 21	112,6	20,36	5530,5

Since in this scenario we choose the number of panels so that the excessive generation is minimal, it is necessary to choose the minimum number of panels. As can be seen from the table, this is 407 panels (this number was obtained for a time from 11 to 12 hours). Since the controller was selected for 15 batteries, in this scenario we will use 405 panels.

Table 24 – The result of the calculation of the sixth scenario

	Generated energy (kWh)		Fuel consumption		
Month	By solar panels	By generators	Gg(load),kg	Gg(idle),kg	Gg(total),kg
January	3 365	59 012	15 870	105	15 975
February	6 359	55 272	14 736	94	14 830
March	12 190	37 109	11 006	52	11 058
April	11 542	37 754	11 027	50	11 077
May	15 795	34 237	10 288	52	10 340
June	17 172	26 195	8 584	2	8 586
July	17 496	25 874	8 494	2	8 495
August	14 135	29 011	9 355	52	9 407
September	10 368	45 105	12 782	50	12 832
October	4 820	50 642	13 899	52	13 951
November	2 746	52 727	14 337	50	14 387
December	1 770	59 868	16 044	105	16 149
TOTAL	**117 757**	**512 806**	**146 423**	**664**	**147 087**

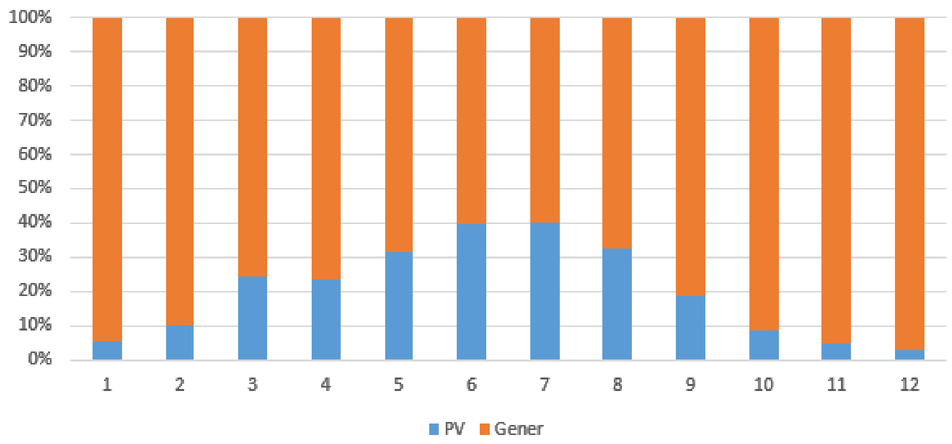


Figure 13 – Distribution of energy received from solar panels and generators for the sixth scenario

6.7 Scenario calculation results

In previous chapters, I calculated various options for building a hybrid substation. I calculated the amount of necessary equipment. Then, on the basis of this, I carried out the calculation in Excel, which was based on the energy balance. There I received information on how much energy is generated for each hour, how much is stored, how much is spent. From this data, I calculated the consumption of diesel fuel. Below I will give a summary table with the results of calculations obtained in previous chapters.

Table 25 – Scenario calculation results

Scenario	Number of solar panels	Number of controllers	Number of inverter	Number of batteries	Wpv [kWh]	Wgen [kWh]	G_g(Total) [kg]
1	1 005	67	1	10	292 213	335 331	88 084
2	1 005	67	1	4	292 213	336 020	88 119
3	2 175	145	2	1958	632 401	–	–
4	–	–	–	4	–	628 431	162 610
5	–	–	–	0	–	630 516	171 557
6	405	27	1	0	117 757	512 806	147 087

For better visibility of economic differences in the scenarios, I will calculate how much the purchase of the selected equipment costs. Information about the cost of one unit of equipment was given earlier, but for convenience I will give all prices in the one table.

Table 26 – Cost of equipment

Equipment	Price (RUB)
Solar module FSM 320P [15]	12 690
Controller Studer Vario Track MPPT [23]	56 500
Inverter MAP HYBRID[25]	588 000
Storage battery PROSOLAR OPZV – 3000 [26]	121 000

Now I can find the cost of purchase all the necessary equipment for each scenario. For this, I multiplied the amount of equipment from table 25 by the price of a piece of equipment from table 26. The result of the calculation is given in table 27. Since the selected type of generators are already installed at the substation, I will not take into account their cost in my calculations.

Table 27 – Calculation of equipment purchase costs for each scenario

Scenario	Cost of solar panels (RUB)	Cost of controllers (RUB)	Cost of inverter (RUB)	Cost of batteries (RUB)	Total cost (RUB)
1	12 753 450	3 785 500	588 000	29 040 000	46 166 950
2	12 753 450	3 785 500	588 000	11 616 000	28 742 950
3	27 600 750	8 192 500	1 176 000	5 686 032 000	5 723 001 250
4	–	–	–	11 616 000	11 616 000
5	–	–	–	–	–
6	5 139 450	1 525 500	588 000	–	7 252 950

7 Financial model

Now that I have done all the technical calculations and received all the necessary data, I can go to the economic part of my work.

In my economic part of the thesis, I will consider the following tasks:

1. The point of view of the owner of the substation. In this case, I will compare the scenarios with the fourth one, which reflects the existing situation at the substation.

2. Point of view of the investor. I will consider the case when I install solar panels and sell the generated energy to the substation. At the substation, part of the energy is produced by diesel generators, and some are bought from the me.

7.1 Theoretical part

Before describing the data used in the economic model and the model itself, I want to describe the logic of project evaluation. To evaluate scenarios, I will use the following investment decision criteria:

- Net Present Value (NPV);
- Internal Rate of Return (IRR);
- Payback Period (PP).

NPV

NPV is the most important method for determining the value of projects. The net present value (NPV) of an investment is the present value of all its future cash flows minus the present value of its cost [29]. NPV is calculated by the formula [30]:

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - INV \quad (63)$$

where CF_t – net cash inflow during the period t;

INV - total initial investment costs;

r - discount rate;

t - number of time periods.

The NPV capital budgeting rule states that you should accept projects with a positive NPV and reject those with a negative NPV [29].

However, we cannot make conclusions about the project's profitability based solely on the NPV (choosing the project with the highest NPV value). Because this indicator does not give us an idea of the amount of investment. Below, I will explain this using figure 14.

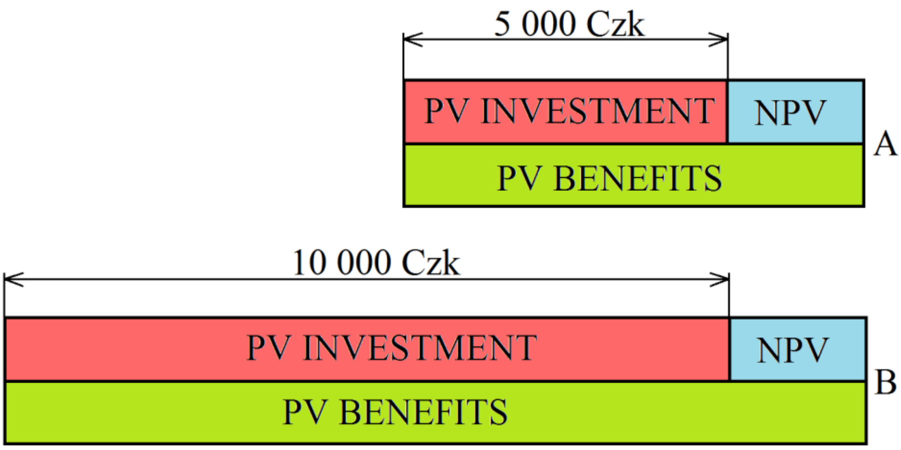


Figure 14 – Distribution of expenditures and profits of two different projects with the same NPV

As can be seen from the pictures, NPV of project A and B are the same. Consequently, if we followed the principle "The best project is the one that has the greatest value of NPV", we would consider that both projects are equally beneficial. However, Project A demanded less investment than Project B and at the same time brought the same net present value. This suggests that project A is more profitable. Because, for example, if an investor has an amount of 10 000 CZK, he can invest all the money in project B, or invest half the money in project A. In both options he will receive the same NPV, but in the second case he will still have 5 000 CZK in the account.

IRR

The lack of project evaluation using NPV can be compensated for by a parameter such as Internal Rate of Return. The internal rate of return is defined as the rate of discount that makes NPV 0. So to find the IRR for an investment project lasting T years, we must solve for IRR in the following expression [30]:

$$NPV = CF_0 + \frac{CF_1}{(1+IRR)} + \frac{CF_1}{(1+IRR)^2} + \ldots + \frac{CF_T}{(1+IRR)^T} = 0 \qquad (64)$$

where CF_t – net cash inflow during the period t;

NPV – net present value;

T - number of time periods.

The IRR rule says: «Accept investment opportunities offering rates of return in excess of their opportunity costs of capital» [30].

Payback period

Thus, evaluating the project based on the value of the NPV and IRR we get a complete look at the situation. However, it is also worth taking into account such an indicator as payback period.

A project's PP is found by counting the number of years it takes before the cumulative cash flow equals the initial investment [30].

Annuities

If the cash flow is the same every year, then it is extremely convenient to use the following formula [29] to find a present value:

$$PV = \frac{CF}{r} \cdot \left[1 - \left(\frac{1}{1+r} \right)^T \right] \quad (65)$$

If every year the cash flow increases several times by constant present (g), then the following formula [29] can be used to find a present value:

$$PV = \frac{CF_1}{r-g} \cdot \left[1 - \left(\frac{1+g}{1+r} \right)^T \right] \quad (66)$$

where g - percent of growing.

For a better understanding of the above formulas and the situations when they are applied, I will give a picture that clearly demonstrates this. I took this drawing from the book mentioned earlier [29].

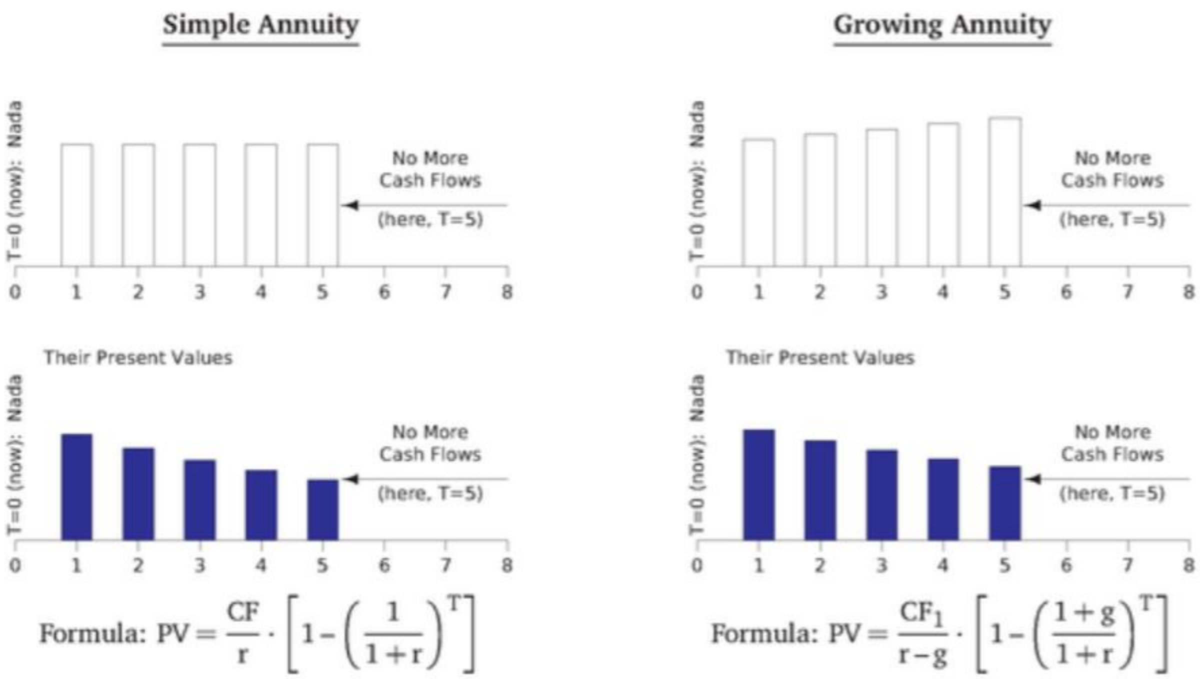


Figure 15 – Present value for different payoff streams [29]

7.2 Data for the financial model

Now when I know the methods of project evaluation, I need more information about equipments. For example, information about the service life of equipment, additional investments, the cost of diesel fuel. I will receive this information in this chapter.

7.2.1 Solar panels

The solar cell manufacturer [31] states that:

• Preservation of the declared capacity of more than 90% of the rated capacity is guaranteed for 10 years.
• Preservation of the declared power of more than 80% of the minimum rated power - for 25 years.

Thus, to take into account the possible decrease in the performance of solar panels, we will increase the number of panels by 10% for 11 years of use. In my model, this will be reflected in the form of additional investments at the end of 10 year of operation. For 1 and 2 scenarios, the number of additional panels will be:

$$N_{PV(1,2)}^{add} = N_{PV} \cdot 0,1 = 1005 \cdot 0,1 = 100,5 \approx 100 \quad (67)$$

For 3 scenario:

$$N_{PV(3)}^{add} = N_{PV} \cdot 1,1 = 2175 \cdot 1,1 = 217,5 \approx 217 \quad (68)$$

For 6 scenario:

$$N_{PV(6)}^{add} = N_{PV} \cdot 1,1 = 405 \cdot 1,1 = 40,5 \approx 40 \quad (69)$$

For clarity, I will collect all the data on the solar panels that will be used in the model in table 28. The cost of one solar panel was given earlier, and amounts to 12,690 rubles. For example, we calculate the first line of table 28.

The number of solar panels was found earlier. Multiplying the number of panels by the cost of one panel, we get amount of the investments.

$$Inv(0) = N_{PV} \cdot C_{PV} = 1005 \cdot 12\ 690 = 12\ 753\ 450\ \ rub \quad (70)$$

As noted earlier in the 10th year of use, additional investments are needed, which will be:

$$Inv(10) = N_{PV}^{add} \cdot C_{PV} = 100 \cdot 12\ 690 = 1\ 269\ 000\ \ rub \quad (71)$$

Table 28 - Initial data for solar panels

Scenario	Number of solar panels	Number of additional solar panels	Investments for the zero year [RUB]	Investments for the tenth year [RUB]
1	1005	100	12 753 450	1 269 000
2	1005	100	12 753 450	1 269 000
3	2175	217	27 600 750	2 753 730
4	–	–	–	–
5	–	–	–	–
6	405	40	5 139 450	507 600

7.2.2 Storage battery

Earlier, I received information that in project I will use store battery assembled from 24 cells (PROSOLAR OPZV – 3000). The cost of batteries is 2 904 000 rubles and service life is 15 years.

Since I will compare the project that has already been put into operation with new ones, and 4 batteries have already been installed at the power plant. In the model, I will consider the number of batteries equal to:

$$N_{batt}^{\mathrm{mod}} = N_{batt}^{real} - 4 \tag{72}$$

where N_{batt}^{real} – the number of batteries required for the substation (previously calculated);

4 – the number of batteries already installed in the substation.

Since the cost of batteries has changed, I also have to recalculate the total investment for the project (earlier, investments were calculated in the table 27).

Table 29 - Initial data for storage battery

Scenario	Number of storage batteries	Investments for the zero year [RUB]	Total cost (RUB)	Lifetime [years]
1	6	17 424 000	34 550 950	15
2	–	–	17 126 950	
3	1954	5 674 416 000	5 711 385 250	
4	–	–	0	
5	–	–	0	
6	–	–	7 252 950	

7.2.3 Diesel generators

Since I will compare the already commissioned project with the new ones, the price of diesel generators will not be included in the model, because the substation already has them.

However, we will need to take into account the variable costs of the diesel generator. They will consist of the price for the purchase and delivery of diesel fuel. The price of diesel fuel in 2017 amounted to [32]:

$$C_{fuel} = 44\ 535\ \ rub / ton = 44{,}5\ \ rub / kg \tag{73}$$

However, it is necessary to take into account that the village is located in a remote place and far from major cities. For example, the nearest gas station is located 70 kilometers from the village of Nazino in the village of Alexandrovskoe, these villages are separated by a river. Therefore, we need to find the price of fuel, taking into account transportation costs.

Since the payback period has already passed for 2017, we can assume that the cost of energy consists solely of the cost of diesel fuel consumption and repair costs. I will accept the assumption and assume that 90% of the cost of energy spend to the purchase of diesel fuel.

According to information from the technical data of diesel power plants of the Tomsk region [33] the approved electricity tariff is T = 21.53 RUB / kWh. Previously, the value of the total annual energy consumption (628,56 MWh) was found. Thus, for the year the production of energy is spent:

$$C_{year} = W_{year} \cdot T = 628\ 560 \cdot 21{,}53 = 13\ 532\ 897\ \ rub \tag{74}$$

As noted earlier, the fourth scenario reflects the situation in substation in 2017. Thus, we know that in 2017, at the substation in the village of Nazino, the following amount of fuel was consumed (table 25): 162 610 kg. Thus, the specific cost of diesel fuel including delivery is:

$$C_{fuel.total} = \frac{0{,}9 \cdot W_{year} \cdot T}{G_{year}} = \frac{0{,}9 \cdot 628\ 560 \cdot 21{,}53}{162\ 610} = 74{,}9\ \ rub / kg \tag{75}$$

The cost of fuel delivery will be:

$$C_{fuel.del} = C_{fuel.total} - C_{fuel} = 74{,}9 - 44{,}5 = 30{,}4\ \ rub / kg \tag{76}$$

Now we can calculate how much money we will spent on variable cost, namely the purchase and delivery of diesel fuel. For this I used the data on fuel consumption (table 25) and the cost of fuel, including delivery (formula 76). The calculation results are shown in the table below.

Table 30 – The results of the calculation of the cost of fuel for different scenarios

Scenario	G_g(Total) [kg]	Fuel costs [RUB]
1	88 084	6 597 492
2	88 119	6 600 113
3	–	–
4	162 610	12 179 489
5	171 557	12 849 619
6	147 087	11 016 816

7.3 Economic parameters

For a project, it is necessary to know the various economic parameters for the country in which the project is to be realized. In my case, this is Russia. Therefore, the task for the next chapter will be to find the level of inflation and the tax rate in Russia, as well as to calculate the discount rate.

Tax

Since this program is the state, therefore, the economic model will not contain taxes.

Based on this fact, the financial model will also not contain the depreciation, as it is used to reduce the amount of taxes paid.

Inflation

Since the project is calculated for 2017, we will find inflation as the average of the inflation values for 2017 and 2018 [34] and the projected inflation for 2019 - 2023 [35]. The calculations are presented in the table below.

Table 31- Inflation

Years	Inflation [%]	Average value [%]
2017	2,5	3,67
2018	4,3	
2019	4,2	
2020	4	
2021	3,8	
2022	3,4	
2023	3,5	

Discount rate

Since the substation being developed is a state project. I will find a discount rate according to the Russian Federation Decree No. 1470 [36] according to the formula:

$$d = d_i + \frac{P}{100} \quad (77)$$

where d_i – risk-free discounting factor

$\frac{P}{100}$ – risk adjustment.

The discount rate without taking into account the risk of the project is determined by the following formula [36]:

$$d_i = \frac{1 + \frac{r}{100}}{1 + \frac{i}{100}} - 1 \quad (78)$$

were r – refinancing rate,

i – inflation rate.

The key rate was introduced by the Bank of Russia on September 13, 2013 as the main indicator of monetary policy. And for 2017, it is 8.8%. Thus, the risk-free discount rate will be:

$$d_i = \frac{1 + \frac{8,8}{100}}{1 + \frac{3,67}{100}} - 1 = 4,9\ \% \quad (79)$$

Risk adjustment for investment in the intensification of production is 5 percent [36].

Thus, the discount rate will be:

$$d = 4,9 + 5 = 9,9\ \% \quad (80)$$

8 The owner point of view

8.1 Economic model calculation

In this case, I believe that the substation works according to scenario 4 and the owner needs to decide whether to change his tactics and re-equipt the substation or not.

When the substation is reconstructed, the owner will not change the cost of electricity, so the profit from the sale of electricity will remain unchanged. The profit from the reconstructing of the substation will be that it helps the owner save on variable cost (on fuel).

Below in the table I calculated how much money the owner will save annually on fuel under different scenarios of building a substation. From table 30 we know that without making changes to the work of the substation, it annually spends on the purchase of fuel:

$$C_{fuel(4)} = 12\ 179\ 489\ \ rub \qquad (81)$$

Subtracting this number from the cost of fuel for each scenario, we get annual savings.

Table 32 – The results of the calculation of fuel economy

Scenario	G_g(Total) [kg]	Annual fuel costs [RUB]	Annual savings [RUB]
1	88 084	6 597 492	5 581 997
2	88 119	6 600 113	5 579 376
3	–	–	12 179 489
4	162 610	12 179 489	0
5	171 557	12 849 619	-670 130
6	147 087	11 016 816	1 162 673

As can be seen from the table above, fuel is not saved in scenario 5, this project will contain only expenses (for the purchase of new equipment). Therefore, we can already make a conclusion that this project is not profitable and we will not consider it. If we calculated the economic model built on the 5 scenario, the NPV would be negative.

I calculated the 1,2,3 and 6 scenarios according to the methodology described earlier and obtained the results presented in table 33.

Table 33 – Results of the calculation of projects from the point of view of the substation owner

Scenario	Number of solar panels	Number of batteries	NPV, RUB	Payback period
1	1005	10	17 028 392	8
2	1005	4	34 427 852	3
3	2175	1958	-5 598 834 943	-
6	405	0	3 359 580	8

From the results it is clear that the second scenario is the most cost-effective, then comes the first one, then the sixth one. The third scenario is absolutely not profitable, due to the huge capital costs.

In 3 scenario, the project has a negative NPV. Despite the fact that in this scenario there was maximum fuel economy, the equipment expenses were enormous (almost 6 billion rubles). Such high costs are due to the fact that when supplying substations exclusively with solar panels and batteries, we need to store energy in large quantities in order to cover the shortcomings of energy in winter. In summer insolation is maximum, and consumption is minimal. In winter, the situation is reversed, and in order to cover the energy demand in the winter months, we need to use the energy stored in the summer, which, of course, leads to an unimaginable number of batteries. Such huge costs for batteries do not pay off with money that we saved on fuel use. So we can conclude that the use of solar panels is not advisable to use as the only source of power.

The worst option of the profit was in the sixth scenario. This is due to the fact that in it we installed a small number of solar panels, therefore, the fuel savings were also not as large as, for example, in the first two scenarios. It should be noted that even the installation of a small number of solar panels brought a profit, and the payback period of the project is not long – 8 years.

The second scenario is the best. It differs from the first one by the number of storage batteries. Saving on storage batteries made the project twice as profitable. Thus, we can conclude that the use of solar panels with diesel generators and with a small number of storage batteries is the most beneficial variant for decentralized power supply.

8.2 Sensitivity analysis

In order to assess how the input parameters, affect the project, I conducted a sensitivity analysis for inflation, discount rate and fuel costs. Calculations I have done for the most profitable scenario - 2.

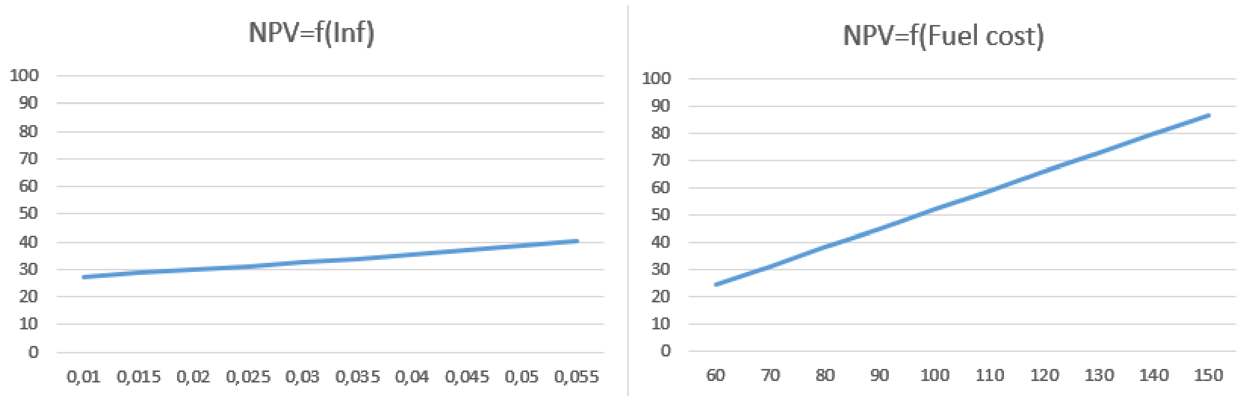


Figure 16 – NPV sensitivity analysis (inflation and fuel costs)

Both plots are increasing curves. That is, with an increase in inflation or the cost of fuel, our project will be even more profitable, and with a decrease, vice versa.

It should be noted that these two indicators: the cost of fuel and inflation are interrelated. With an increase in the rate of inflation, the cost of fuel will grow, but at the same time the price of equipment will also grow. Taking into account the fact that we buy most of the equipment before the start of project implementation, the costs will increase only for the investments that we make after the start of the substation (less than 3 percent of all investments).

Since the probability that the inflation rate or the cost of fuel decreases much less than the probability that these indicators will increase, we can say that changing of these parameters can only increase project profitability.

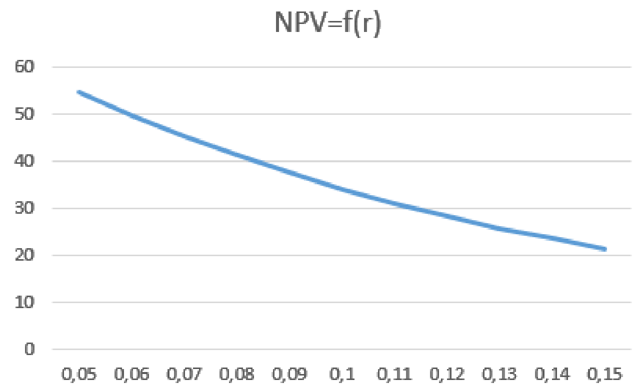


Figure 17 – NPV sensitivity analysis NPV (discount rate)

As can be seen from the figure above, with an increase in the discount rate NPV decreases. The project is quite sensitive to changes in the discount rate. According to the schedule is not possible to determine the IRR, which also speaks us about the profitability of the project, because if the IRR is greater than the discount rate, then the project is considered profitable.

9 Investor point of view

In this model, I will consider the project from the point of view of the investor. The village of Nazino is already provided with energy in the required amount. My project will consist in the fact that we will install the solar panels and will sell energy to the substation. The buyer agrees to the transaction, provided that it will be profitable for him (the price for which he will buy energy from us must be lower than that they spend on electricity generation by diesel generators).

Since this project will not be the state, as the previous one, we need to recalculate the discount rate, take into account taxes and depreciation.

9.1. Economic parameters

Tax

The tax rate is set in article 284 of the Tax Code of the RF [37]. Tax rate is equal to 20%. This value has not changed since 2009. Therefore, in this model it will be assumed that the next 15 years the tax rate will not change and will be 20%.

To reduce the taxes paid, I will use linear depreciation. Which will be calculated according to the formula [30]:

$$\text{Depreciation in year t} = 1/T \cdot \text{depreciable amount} \quad (82)$$

where T – is the useful life time.

Inflation

The level of inflation will not differ from the one adopted in the previous model and will be:

$$INF = 3,67\% \quad (83)$$

Discount rate

For finding the discount rate for a new capital investment I will use capital asset pricing model. I will find a discount rate by the formula [30]:

$$r = r_f + \beta \cdot (r_m - r_f) \quad (84)$$

where r_f – risk free rate

r_m – market return

β – beta, which measures the sensitivity to market movements.

From a site containing various useful data for economic evaluations [38] I received the following information:

Equity Risk Premium for Russia:

$$r_m - r_f = 9,43\% \quad (85)$$

Average Levered Beta for Green & Renewable Energy:

$$\beta = 0,88\% \quad (86)$$

According to the Central Bank of Russia [39], the yield of bonds with a maturity of 20 years is 8,66 %. I will take this percentage as risk free rate:

$$r_f = 8,66\% \quad (87)$$

Substituting all the found values in formula 78, I found a discount rate:

$$r = 8,66 + 0,88 \cdot (9,43) = 16,96\% \quad (88)$$

9.2 Model calculation

In order to find the cost of electricity for the investor, I need to find the cost of electricity for the owner of the substation. The owner will agree to buy energy from the investor, if it is less than the cost that he spends on the production of electricity. From the previous calculations we know the following information for the fourth scenario:

Fuel consumption per year:

$$G_{gen} = 162\ 610\ kg \tag{89}$$

Fuel price including delivery:

$$C_{fuel.total} = 74{,}9\ rub / kg \tag{90}$$

Generated energy per year:

$$W_{gen.year} = 628\ 560\ kWh \tag{91}$$

Thus, the price for electricity will be:

$$C = \frac{C_{fuel.total} \cdot G_{gen}}{W_{gen.year}} = \frac{74{,}9 \cdot 162\ 610}{628\ 560} = 20\ rub / kWh \tag{92}$$

Thus, from the point of view of the investor, the price for which it will be possible to sell energy should be less than 20 rubles.

	0	1	2	3	4	5	6	7	8	9	10
Inv.	17,1										1,8
Rev.		5,8	6,1	6,3	6,5	6,8	7,0	7,3	7,5	7,8	8,1
Dep.		1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1
Tax Shield		4,7	4,9	5,1	5,4	5,6	5,9	6,1	6,4	6,7	5,2
Tax		0,9	1,0	1,0	1,1	1,1	1,2	1,2	1,3	1,3	1,0
CF		4,9	5,1	5,3	5,4	5,6	5,8	6,0	6,2	6,5	5,3
DCF		4,1	3,6	3,2	2,8	2,4	2,1	1,8	1,6	1,4	1,0
NPV	11,1										

Figure 18 – The result of calculating (part of the calculations; numbers in tables in millions of rubles)

Using the example of the first year, I will explain the meaning of each line in the constructed model.

The first line contains information about investments. In our case, they consist of the cost of installing and purchasing solar panels and the necessary equipment to connect the solar modules to the network. Since the efficiency of the panels falls in 10 years, it is necessary to install additional panels, which is also included in the investment, but for the 10th year.

The second column contains a row about profits, which calculated according to the formula:

$$REV = C_{EE} \cdot W_{year} \tag{93}$$

where C_{PV} – cost of electrical energy;

W_{year} – amount of energy generated per year.

Take the cost of electricity equal to 20 RUB/ kWh. We know that solar panels produce 292 213 kWh per year [table 25]. Substituting all this into formula 93, we will find the revenues for the first year of using solar panels.

$$REV = 292\ 213 \cdot 20 = 5\ 844\ 260\ rub \tag{94}$$

After that I found depreciation. Using the investment information and the formula 82, I received a depreciation value equal to:

$$DEP = 17\ 126\ 950 \cdot \frac{1}{15} = 1\ 141\ 797\ rub \tag{95}$$

I used depreciation to reduce taxes paid, because the value of which I pay tax is the difference from my revenues and my expenses (depreciation), so in the first year the amount of taxes is:

$$Tax = r_{tax} \cdot (REV - DEP) = 0,2 \cdot (5\ 844\ 260 - 1\ 141\ 797) = 940\ 493\ rub \tag{96}$$

where $r_{tax} = 20\ \%$ – Tax rate.

Then I found the cash flow, deducting the amount of taxes paid from the revenues. For example, for the first year, the cache flow value is:

$$CF = REV - TAX = 5\ 844\ 260 - 940\ 493 = 4\ 903\ 767\ rub \tag{97}$$

Then, I used the formulas described earlier in Chapter 7.1 and got the NPV value:

$$NPV = 11\ 116\ 756\ rub \tag{98}$$

After creating the model, I found the minimum price for the investor. For this, I used the “search for a solution” function built into Excel and found the price at which the NPV would be zero.

The minimum cost of electricity is:

$$C = 12\ rub / kWh \tag{99}$$

Below is the dependence of the NPV project on the price of electricity. As can be seen from the figure, the higher the price, the higher the NPV, however, it should be remembered that the maximum price that can be set for electricity is 20 rubles/ kWh.

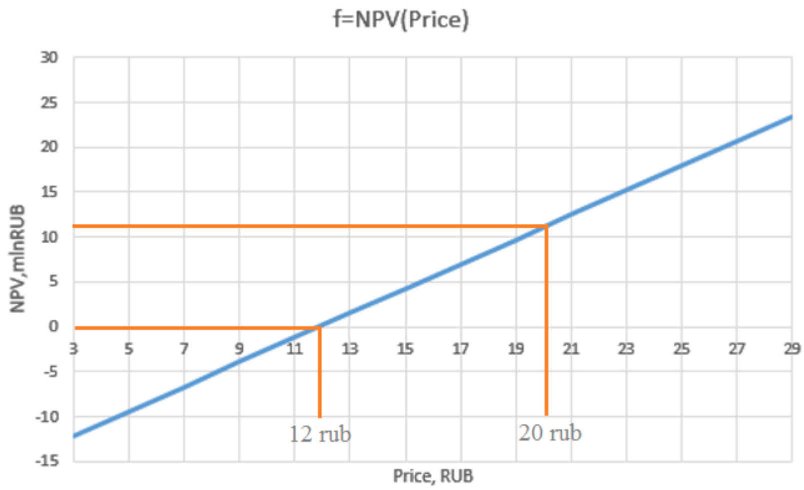


Figure 19 – NPV sensitivity analysis (Price)

Based on the schedule of dependencies on the price, we can conclude that the project will be profitable if we sell electricity for a price that exceeds 12 rubles per kilowatt hour.

Conclusion

In this paper, I tried to solve the problems of decentralized power supply of a rural settlement. Currently, most of the places in Russia that are not connected to the general energy network, receive electricity from diesel generators. This option of electricity generating not only adversely affects the environment, but also is quite expensive. Therefore, I suggested that the use of an alternative energy source, together with diesel generators, can significantly improve the situation. In this paper, I tried to confirm this assumption.

Before proceeding directly to the financial analysis, I did the following. At first, I estimated the potential of the chosen territory, after this assessment it was decided that the sun is the best alternative energy source for the village of Nazino. After determining the type of substation, I calculated the electrical loads in the selected village, I did this using typical load schedules for rural areas. Then I developed 6 different power supply options for the village, each of which contained different equipment. For example, in one option, the entire load was covered only by generators; in the other, a hybrid power plant was created, where generators work together with solar panels. Having received information on electricity consumption and knowing what equipment is needed for each scenario, I proceeded to select the amount of this equipment. Then I calculated all options. Upon completion of the calculations for each scenario, I had the following information: the amount of equipment, information about power generation (how much each source produced), as well as information about consumption of diesel fuel. After collecting all this information and choosing a project evaluation methodology, I proceeded to the economic calculation of the project. In this calculation, I considered the project from two points of view: the owner of diesel power plant (government) and the investor of solar power plant project. Below I will describe the results obtained in both cases.

From the government point of view, additional installation of solar panels at the diesel substation will lead to savings of diesel fuel, this savings will be so significant that, given all the capital costs, such a project is very profitable. The profitability of the project depends on the number of installed equipment. In my calculations, when installing 10 batteries and 1005 solar panels, the project payback period is 8 years and its NPV is 17 million rubles. When installing 4 batteries and 1005 solar panels, the project payback period is 3 years and its NPV will be 34 million rubles. If I install only 405 solar panels, the project will not be as profitable as the first two, but it will still have a positive NPV (3 million rubles) and a short payback period (8 years). It should be noted that the sensitivity analysis carried out showed that the project is stable to the market changes, for example, if inflation rate or fuel costs change, the project will either remain profitable or become even more profitable.

Based on the results obtained, it can be concluded that hybrid power plants are more profitable than traditional substations for decentralized power supply. The use of solar modules not only reduces the consumption of diesel fuel, but also reduces the operating time of diesel generators. This extends their lifetime. Accordingly, the amount of harmful substances emitted by a diesel generator is significantly reduced.

Installing even a small number of solar panels allows us to make electricity cleaner, and also save a significant amount of money. Such savings will allow selling electricity at a lower price. Also, part of the money can be used to upgrade equipment, for example, power lines or relay protection, which will make electricity in the village better and more reliable. Thus, the use of alternative energy sources for decentralized power supply will be beneficial for all parties, both for the manufacturer and for the consumer. Electricity is getting cheaper, cleaner and better.

If we consider the project from the investor point of view, it is also beneficial (due to the high cost of electricity generated by diesel generators). If we install solar panels and sell electricity to the substation for the price of 20 rubles / kWh, we will receive NPV in the amount of 11 million rubles. The solar substation practically does not require any expenses, in addition to the capital costs for the construction of the substation, and then small expenses for repairs and maintenance. The service life of the panels is quite large (25 years). Therefore, when installing a solar substation after the pay-off period of the project (in the considered variant it is 3 years), for many years we will receive almost only profit. If we consider the project from this point of view, it turns out to be less stable than in the first case. Because in this case the project is very sensitive to the price for which we sell electricity. If it falls by more than 40 percent, project will have negative NPV, which means that the project will not be profitable. However, in our case this can occur only with a significant reduction in the price of diesel fuel, which is an extremely unlikely event. Therefore, if market conditions change, the project will most likely remain profitable.

Summing up the project, it can be noted that the use of alternative energy sources is a solution to the problem of decentralized energy supply. Installing hybrid stations makes the energy produced cleaner and cheaper.

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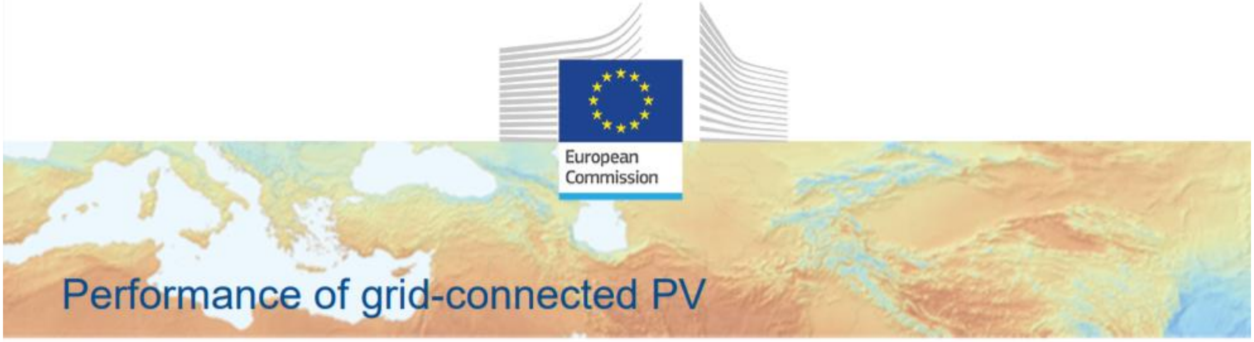
Appendices

Appendix 1 - daily wind speed by month (based on data [6])

Day	January m/s	February m/s	March m/s	April m/s	May m/s	June m/s	July m/s	August m/s	September m/s	October m/s	November m/s	December m/s
1	3	3	3	3	6	2	1	4	2	1	4	1
2	3	3	3	6	4	3	4	3	2	2	4	2
3	2	3	3	6	6	4	1	3	4	2	1	7
4	2	2	2	4	5	5	3	3	3	2	3	4
5	1	3	4	6	3	5	3	5	3	1	5	1
6	2	0	2	4	2	1	3	3	2	1	4	4
7	5	1	5	4	7	1	2	4	3	4	3	2
8	2	2	2	2	7	1	3	2	3	6	4	2
9	3	1	3	6	4	1	0	4	2	4	2	2
10	2	2	5	5	4	4	2	3	3	3	4	2
11	4	4	5	2	2	3	4	1	2	4	2	1
12	1	4	5	6	7	5	2	3	5	1	2	0
13	1	3	4	2	5	6	4	2	3	2	1	0
14	2	6	6	4	5	2	2	2	4	3	0	4
15	3	4	3	2	5	4	3	2	4	2	2	4
16	2	3	6	6	4	2	3	3	2	3	2	3
17	3	2	5	3	4	3	2	3	2	2	0	3
18	2	7	2	1	4	5	3	1	2	4	1	5
19	3	5	4	5	4	6	2	2	2	4	2	3
20	3	4	1	4	1	7	3	5	1	4	2	2
21	4	4	3	4	5	4	1	3	4	4	3	2
22	5	4	4	5	2	3	3	4	6	5	2	1
23	3	4	5	2	3	2	3	3	5	4	2	2
24	5	4	4	2	3	5	3	0	4	4	5	3
25	2	2	3	4	2	2	2	1	2	3	2	3
26	1	4	4	3	4	2	2	2	2	3	4	3
27	3	5	5	5	5	4	2	5	3	4	5	2
28	2	5	4	6	6	7	3	5	2	4	3	2
29	3		6	3	5	4	5	5	2	5	3	1
30	3		7	4	4	2	3	5	1	3	1	2
31	5		8		3		2	2		3		5
Av.month m/s	2,77	3,429	4,16	4,1	4,39	3,7	2,77	3,26	3,13	3,45	2,97	2,903
Av.year m/s												3,4198

Appendix 2 - the performance of the network-connected PV [16]



PVGIS-5 estimates of solar electricity generation:

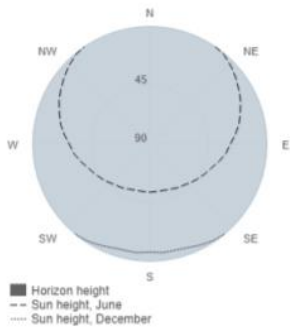
Provided inputs:

Latitude/Longitude:	60.000, 79.000
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed:	0.32 kWp
System loss:	14 %

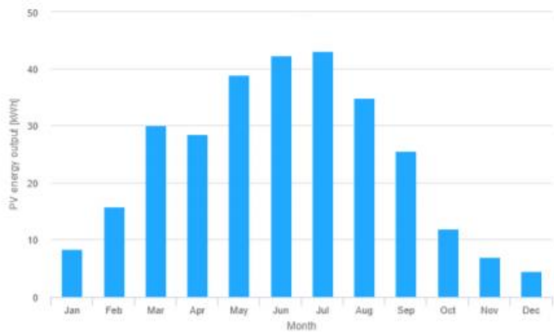
Simulation outputs

Slope angle:	45 °
Azimuth angle:	0 °
Yearly PV energy production:	291 kWh
Yearly in-plane irradiation:	1120 kWh/m²
Year to year variability:	17.20 %
Changes in output due to:	
Angle of incidence:	-2.9 %
Spectral effects:	? (0) %
Temperature and low irradiance:	-2.6 %
Total loss:	-18.7 %

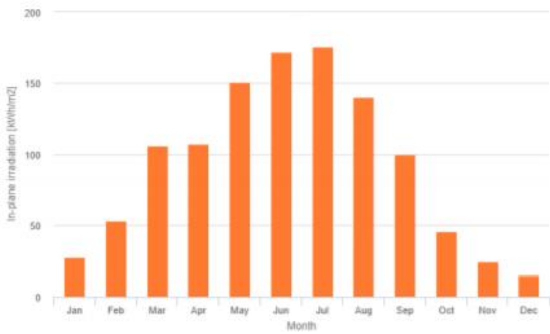
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	Em	Hm	SDm
January	8.31	27.6	3.04
February	15.7	52.9	4.07
March	30.1	106	6.17
April	28.5	107	3.13
May	39	151	4.6
June	42.4	172	4.91
July	43.2	176	4.16
August	34.9	140	4.97
September	25.6	99.7	4.7
October	11.9	45.5	2.44
November	6.78	24.3	2.26
December	4.37	15.2	1.36

Em: Average monthly electricity production from the given system [kWh].

Hm: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SDm: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Appendix 3 - Determination of the optimal angle of inclination of the panels

According to the source [5], solar radiation enters the Earth in the form of three streams of solar energy:

$$R_{\Sigma}(t) = R_{dir}(t) + R_{dif}(t) + R_{refl}(t) \qquad (100)$$

where $R_{dir}(t)$ - direct SR;

$R_{dif}(t)$ - diffusion SR;

$R_{refl}(t)$ - reflected SR.

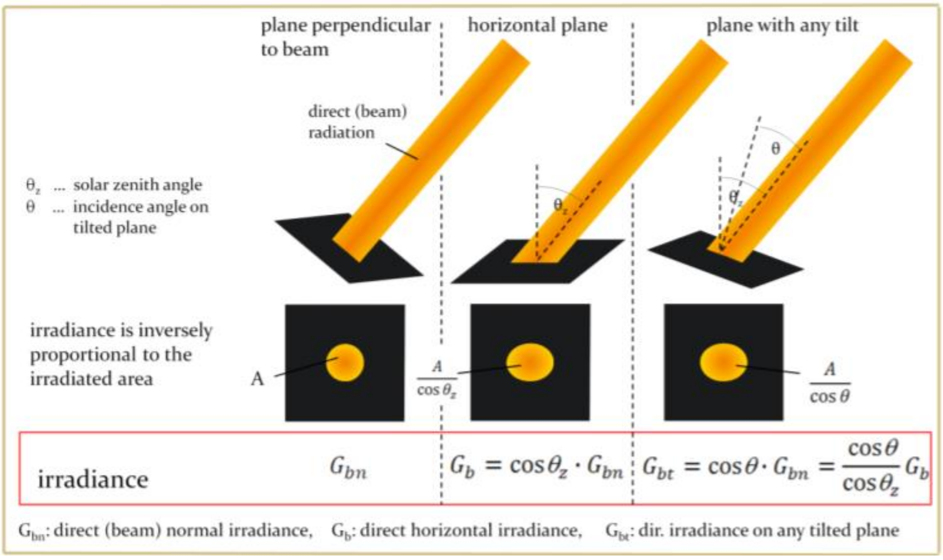


Figure 20 - Irradiance on tilted planes [40]

According to the source [40], to calculate the direct SR to the inclined panel, the angle of incidence on the inclined plane must be taken into account. The author of this book offers the following formula for calculations:

$$\begin{aligned}\mathrm{Cos}\,\theta = {} & \sin\delta\cdot\sin\varphi\cdot\cos\beta - \sin\delta\cdot\cos\varphi\cdot\sin\beta\cdot\cos\gamma + \cos\delta\cdot\cos\varphi\cdot\cos\beta\cdot\cos w + \\ & + \cos\delta\cdot\sin\varphi\cdot\sin\beta\cdot\cos\gamma\cdot\cos w + \cos\delta\cdot\sin\beta\cdot\sin\gamma\cdot\sin w\end{aligned} \qquad (101)$$

Where w - The hour angle is the angular displacement of the Sun east or west of the local meridian due to the rotation of the Earth around its axis;

φ -Latitude of the investigated object, rad;

δ -Inclination of the Sun, rad;

β -Angle of inclination of the plane to the horizon, rad;

γ - Azimuth.

For greater clarity, we present a picture with the marked angles used in the formula (60).

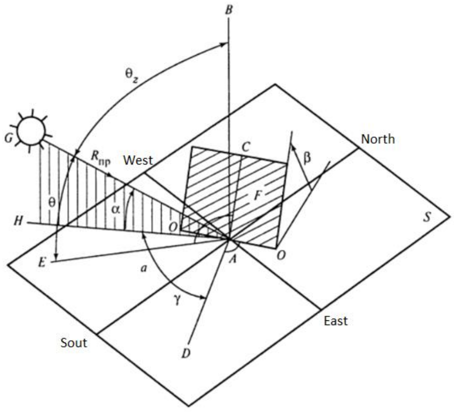


Figure 21 - Tilted plane with tilt angle β, plane azimuth angle γ and incidence angle θ [40]

To find the value of the angle of the sun we will use Cooper's formula [40].

$$\delta = 23,45° \cdot \text{Sin}(360° \frac{284 + N_{day}}{365}) \tag{102}$$

For instance, I will calculate the angle of incidence on an inclined plane for 12 hours of the day on July 15. It is 195 days. Substitute this value in Cooper's formula (61):

$$\delta_{195} = 23,45° \cdot \text{Sin}(360° \frac{284+195}{365}) = 21,66° \tag{103}$$

Next, go directly to the definition of the angle of incidence on an inclined plane. For example, at 12 o'clock in the afternoon, in the clear sky. Since the efficiency of solar panels is maximum when they are oriented to the South (because the village of Nazino is located above the equator), we will arrange them in this way. With this orientation, the azimuth is zero. The coordinates of the village of Nazino were found with the help of the RETScreen Expert program (figure 21).

Figure 22 - Coordinates of the village of Nazino [screenshot of RETScreen Expert]

Substituting all the values found in the formula (2) we obtain:

$$\begin{gathered} \text{Cos}\theta = \text{Sin}(21,66°) \cdot \text{Sin}(60,13°) \cdot \text{Cos}(45°)\text{-Sin}(21,66°) \cdot \text{Cos}(60,13°) \cdot \text{Sin}(45°) \cdot \text{Cos}(0)+ \\ +\text{Cos}(21,66°) \cdot \text{Cos}(60,13°) \cdot \text{Cos}(45°) \cdot \text{Cos}(0)+\text{Cos}(21,66°) \cdot \text{Sin}(60,13°) \cdot \text{Sin}(45°) \cdot \text{Cos}(0) \cdot \\ \cdot\text{Cos}(0)+\text{Cos}(21,66°) \cdot \text{Sin}(45°) \cdot \text{Sin}(0°) \cdot \text{Sin}(0°)=0,996 \end{gathered} \tag{104}$$

Now knowing the angle, we can calculate the amount of direct insolation on the inclined panel.

Information about total (direct and diffuse) solar radiation on a horizontal surface under actual cloud conditions, MJ/m2 was obtained from the site [40]:

$$Q_{hor} = 596 \ MJ / m^2 \tag{105}$$

Now we need to convert this value to kWh / m2:

$$Q_{hor} = \frac{596 \cdot 1000}{3600} = 165,55 \ kWh / m^2 \tag{106}$$

Thus, the value of solar insolation on the panel inclined under 45 degrees at noon on a clear July day will be:

$$Q = \mathrm{Cos}(\theta) \cdot Q_{hor} = 0,996 \cdot 165,55 = 164,89 \ kWh / m^2 \tag{107}$$

I made similar calculations for other panel angles, and as a result, I get the graphs. All this you can see on the figure 22.

$\delta_i := 23.45 \cdot \frac{\pi}{180} \cdot \sin\left(2 \cdot \pi \cdot \frac{284 + i}{365}\right)$ $\quad \delta := \delta_{195} = 0.378$ $\quad w := -\pi, \frac{-89 \cdot \pi}{90} .. \pi$ $\quad Q := 165.556 \cdot \frac{2\pi}{24}$

$$COS15(w) := \sin(\delta)\cdot\sin(\varphi)\cdot\cos\left(\frac{\pi}{12}\right) - \sin(\delta)\cdot\cos(\varphi)\cdot\sin\left(\frac{\pi}{12}\right)\cdot\cos(\gamma) + \cos(\delta)\cdot\cos(\varphi)\cdot\cos\left(\frac{\pi}{12}\right)\cdot\cos(w) \ldots + \cos(\delta)\cdot\sin(\varphi)\cdot\sin\left(\frac{\pi}{12}\right)\cdot\cos(\gamma)\cdot\cos(w) + \cos(\delta)\cdot\sin\left(\frac{\pi}{12}\right)\cdot\sin(\gamma)\cdot\sin(w)$$

$$COS30(w) := \sin(\delta)\cdot\sin(\varphi)\cdot\cos\left(\frac{2\pi}{12}\right) - \sin(\delta)\cdot\cos(\varphi)\cdot\sin\left(\frac{2\pi}{12}\right)\cdot\cos(\gamma) + \cos(\delta)\cdot\cos(\varphi)\cdot\cos\left(\frac{2\pi}{12}\right)\cdot\cos(w) \ldots + \cos(\delta)\cdot\sin(\varphi)\cdot\sin\left(\frac{2\pi}{12}\right)\cdot\cos(\gamma)\cdot\cos(w) + \cos(\delta)\cdot\sin\left(\frac{2\pi}{12}\right)\cdot\sin(\gamma)\cdot\sin(w)$$

$$COS45(w) := \sin(\delta)\cdot\sin(\varphi)\cdot\cos\left(\frac{3\pi}{12}\right) - \sin(\delta)\cdot\cos(\varphi)\cdot\sin\left(\frac{3\pi}{12}\right)\cdot\cos(\gamma) + \cos(\delta)\cdot\cos(\varphi)\cdot\cos\left(\frac{3\pi}{12}\right)\cdot\cos(w) \ldots + \cos(\delta)\cdot\sin(\varphi)\cdot\sin\left(\frac{3\pi}{12}\right)\cdot\cos(\gamma)\cdot\cos(w) + \cos(\delta)\cdot\sin\left(\frac{3\pi}{12}\right)\cdot\sin(\gamma)\cdot\sin(w)$$

$$COS60(w) := \sin(\delta)\cdot\sin(\varphi)\cdot\cos\left(\frac{4\pi}{12}\right) - \sin(\delta)\cdot\cos(\varphi)\cdot\sin\left(\frac{4\pi}{12}\right)\cdot\cos(\gamma) + \cos(\delta)\cdot\cos(\varphi)\cdot\cos\left(\frac{4\pi}{12}\right)\cdot\cos(w) \ldots + \cos(\delta)\cdot\sin(\varphi)\cdot\sin\left(\frac{4\pi}{12}\right)\cdot\cos(\gamma)\cdot\cos(w) + \cos(\delta)\cdot\sin\left(\frac{4\pi}{12}\right)\cdot\sin(\gamma)\cdot\sin(w)$$

$$COS75(w) := \sin(\delta)\cdot\sin(\varphi)\cdot\cos\left(\frac{5\pi}{12}\right) - \sin(\delta)\cdot\cos(\varphi)\cdot\sin\left(\frac{5\pi}{12}\right)\cdot\cos(\gamma) + \cos(\delta)\cdot\cos(\varphi)\cdot\cos\left(\frac{5\pi}{12}\right)\cdot\cos(w) \ldots + \cos(\delta)\cdot\sin(\varphi)\cdot\sin\left(\frac{5\pi}{12}\right)\cdot\cos(\gamma)\cdot\cos(w) + \cos(\delta)\cdot\sin\left(\frac{5\pi}{12}\right)\cdot\sin(\gamma)\cdot\sin(w)$$

$$COS90(w) := \sin(\delta)\cdot\sin(\varphi)\cdot\cos\left(\frac{6\pi}{12}\right) - \sin(\delta)\cdot\cos(\varphi)\cdot\sin\left(\frac{6\pi}{12}\right)\cdot\cos(\gamma) + \cos(\delta)\cdot\cos(\varphi)\cdot\cos\left(\frac{6\pi}{12}\right)\cdot\cos(w) \ldots + \cos(\delta)\cdot\sin(\varphi)\cdot\sin\left(\frac{6\pi}{12}\right)\cdot\cos(\gamma)\cdot\cos(w) + \cos(\delta)\cdot\sin\left(\frac{6\pi}{12}\right)\cdot\sin(\gamma)\cdot\sin(w)$$

$$Q15(w) := \begin{cases} (COS15(w)) & \text{if } COS15(w) \ge 0 \\ 0 & \text{if } Q\cdot COS15(w) < 0 \end{cases}$$

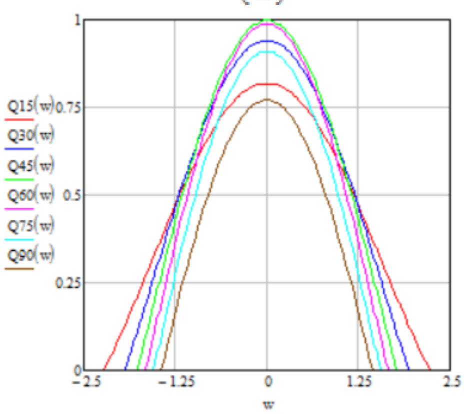
$$Q30(w) := \begin{cases} (COS30(w)) & \text{if } Q\cdot COS30(w) \ge 0 \\ 0 & \text{if } COS30(w) < 0 \end{cases}$$

$$Q45(w) := \begin{cases} (COS45(w)) & \text{if } Q\cdot COS45(w) \ge 0 \\ 0 & \text{if } COS45(w) < 0 \end{cases}$$

$$Q60(w) := \begin{cases} (COS60(w)) & \text{if } Q\cdot COS60(w) \ge 0 \\ 0 & \text{if } Q\cdot COS60(w) < 0 \end{cases}$$

$$Q75(w) := \begin{cases} (COS75(w)) & \text{if } Q\cdot COS75(w) \ge 0 \\ 0 & \text{if } COS75(w) < 0 \end{cases}$$

$$Q90(w) := \begin{cases} (COS90(w)) & \text{if } Q\cdot COS90(w) \ge 0 \\ 0 & \text{if } COS90(w) < 0 \end{cases}$$



$$Q15in := \frac{Q\cdot\int_{-2.5}^{2.5} Q15(w)\,dw}{2.207} = 163.657 \qquad Q60in := \frac{Q\cdot\int_{-2.5}^{2.5} Q60(w)\,dw}{2.207} = 154.934$$

$$Q30in := \frac{Q\cdot\int_{-2.5}^{2.5} Q30(w)\,dw}{2.207} = 168.554 \qquad Q75in := \frac{Q\cdot\int_{-2.5}^{2.5} Q75(w)\,dw}{2.207} = 134.672$$

$$Q45in := \frac{Q\cdot\int_{-2.5}^{2.5} Q45(w)\,dw}{2.207} = 166.283 \qquad Q90in := \frac{Q\cdot\int_{-2.5}^{2.5} Q90(w)\,dw}{2.207} = 142.281$$

Figure 23 - Changing the value of the cosine of the angle of incidence of sunlight depending on the angle of inclination of the panel

The highest rate of insolation is achieved by tilting the panel 15 degrees to the horizon. I found the total value of solar radiation per day, at an angle of inclination of the panel of 15 degrees. To do this, I integrated the area under the curve for the cosine graph 0 and 15 degrees. Translated the value of insolation from kWh / m2 to kWrad / m2. And then the area under the cosine curve of 15 degrees multiplied by the insolation and divided by the area under the curve of the cosine graph 0 degrees. The resulting value is transferred back to the units of measurement kWh/m2. The calculation is shown in figure 23.

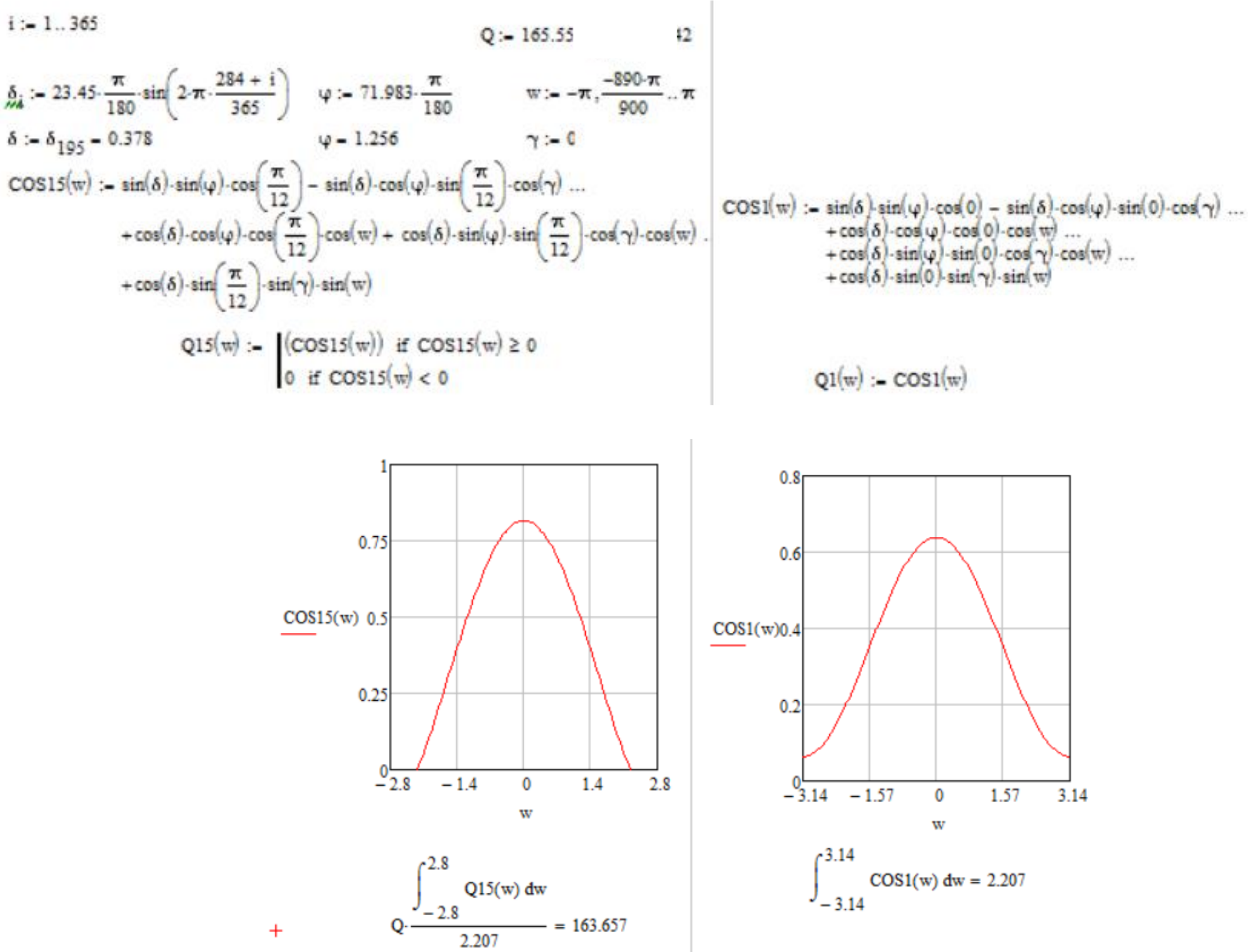


Figure 24 - Example of calculation of insolation in the program Mathcad

The result is the following value:

$$Q_{july} = 163,67 \ kWh / m^2 \tag{108}$$

In further calculations I will use information about insolation taken from the site [16]. The insolation information for a tilt angle of 15 degrees and an azimuth of 0 degrees is shown in figure 24.

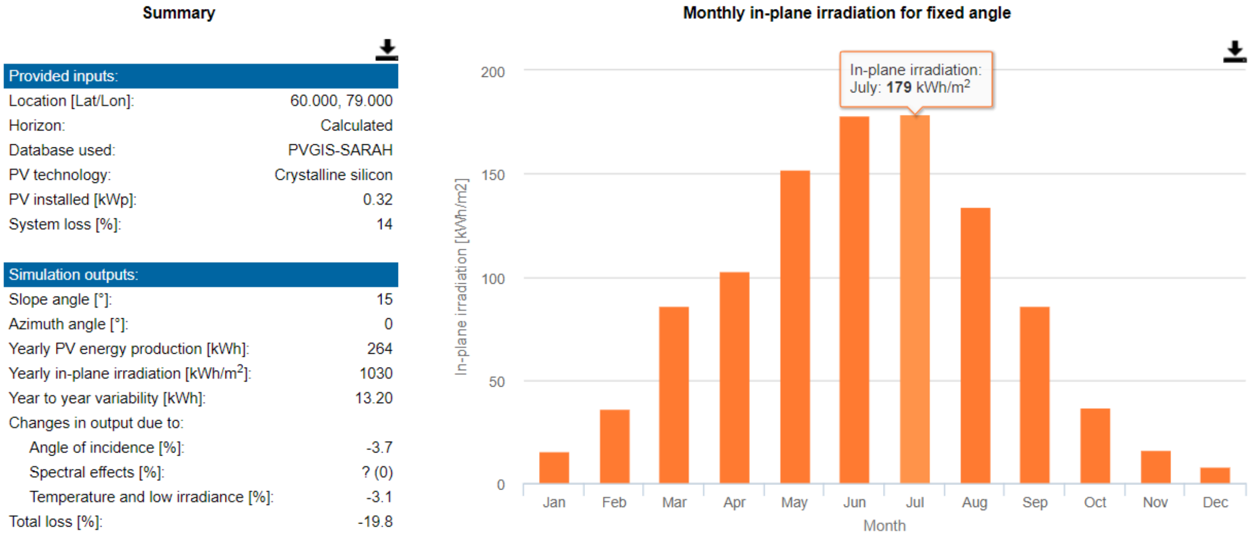


Figure 25 - Monthly insolation values for the village of Nazino [16]

As can be seen from figure 24 for July, the insolation reaches a value of 179 kWh/m2 while practical calculations showed a value of 164 kWh/m2. This difference of 15 kWh /m^2 can be explained by the fact that the value of insolation used in MathCad calculations was made under different weather conditions and other equipment than insolation from the site.

To make the obtained insolation as close as possible to the real value, we will use the data obtained from the site [16]. Since the calculations can be concluded that taking into account the angle of inclination of the panel in this source is made correctly and the data are made under real weather conditions (taking into account the clouds), this option will give the most accurate results.