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Department of Economics, Management and Humanities

Evaluation of the effectiveness of photovoltaic modules

Master's thesis

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Scientific advisor: Mgr. Sherzod Tashpulatov, M.A., Ph.D.

Mikhail Ignatenko

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Ignatenko** Jméno: **Mikhail** Osobní číslo: **483970**

Fakulta/ústav: **Fakulta elektrotechnická**

Zadávající katedra/ústav: **Katedra ekonomiky, manažerství a humanitních věd**

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2) Design and construction of an experimental model of a solar panel based on a set of photovoltaic modules
3) Conducting experiments, data collection, and data analysis
4) Economic evaluation of the project

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Vissarionov, V.I., Deryugina, G.V., Kuznetsova, V.A. Solnechnaya energetika [Solar Power Engineering]. Moscow, MEI Publ., 2008.

Jméno a pracoviště vedoucí(ho) diplomové práce:

Mgr. Sherzod Tashpulatov, M.A., Ph.D., katedra ekonomiky, manažerství a humanitních věd FEL

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

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Mgr. Sherzod Tashpulatov, M.A., Ph.D. podpis vedoucí(ho) práce	podpis vedoucí(ho) ústavu/katedry	prof. Ing. Pavel Ripka, CSc. podpis děkana(ky)

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Declaration:

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

Date Signature

Abstract

The use of renewable energy sources is rapid now due to limited traditional fossil fuels. Solar energy is an interesting and perspective area of study in power sector because of its affordability and relative cheapness. Of course, the point is to collect the energy and convert it into electricity. Solar panels are created to make it possible. For the optimal choice of solar modules, it is necessary to know its efficiency. In the technical description of solar panels, the manufacturer indicates the parameters obtained in the laboratory. Often, technical description of panels, which is obtained in laboratory, do not correspond to the data when panels are operated in real conditions. The purpose of my master's thesis is to evaluate the efficiency of photovoltaic modules in real-life conditions. To accomplish the aim, I will conduct experiments with the Aiyima solar cells. In order to evaluate effectiveness of using solar panels for power supply in Siberia, I will make technical and economic models of power supply in the decentralized village of Pervopashensk in Tomsk region. It is important to distinguish these two terms: efficiency and effectiveness. Efficiency is a quantitative technical term denoting (in case of PV panels) relation between input and output power. Effectiveness is qualitative term denoting successful achievement of tasks.

First instruction (solar panels and methods evaluating their effectiveness) is described in Chapter 2 and used in Chapter 5; second instruction (design and construction of an experimental model of a solar panel based on a set of photovoltaic modules) is presented in Chapter 3. By set of photovoltaic modules I mean solar cells; third instruction (conducting experiments, data collection, and data analysis) is presented in Chapters 4, 5; fourth instruction (economic evaluation of the project) is presented in Chapters 6, 7, 8.

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List of abbreviations

DPP – Diesel power plant

HTC – High Temperature Conditions

IRR – Internal rate of return

LIC – Low Irradiance Conditions

LTC – Low Temperature Conditions

NOCT – Nominal Operating Cell Temperature

NPV – Net Present Value

PP – Payback period

PI – Profitability Index

PV – Photovoltaic

PVUSA – Photovoltaics for Utility Systems Applications

RES – Renewable energy sources

SPP – Solar Power Plant

STC – Standard Test Condition

VAC – Volt-Ampere Characteristic

1. Introduction

Nowadays, renewable energy is one of the most promising and fast-growing energy industries. The problem of the lack of fossil resources at the moment is not acute, but its depletion is inevitable. Moreover progressive humanity is engaged in the search for alternatives where renewable energy is predominant. Of course, this type of energy sources is not perfect and it has a number of disadvantages, such as noise of wind turbines and flooding of land near reservoirs of hydropower plants, but since this branch of energy is only developing, it is possible to minimize all drawbacks. However, in regions where there are no large rivers and the wind speed is not high enough, but insolation level is high or medium, the most feasible type is solar energy.

Today over a billion of people around the world has problems with access to electricity. For example in Africa, climate and level of solar radiation create great environment for implementing solar power plants.

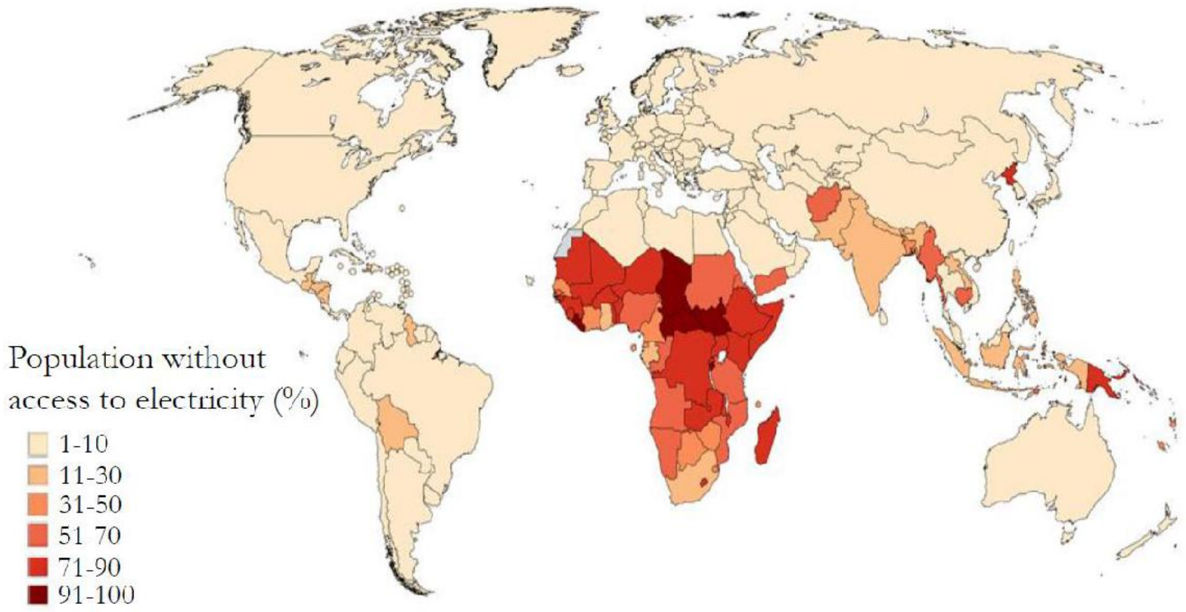


Figure 1 – Global distribution of population without access to electricity [1]

The Sun is a huge, inexhaustible and safe source of energy, equally owned and accessible to everyone. Renewable energy sources and solar energy in particular in the long term should be considered as the only choice for humankind. Main problem of solar energy is limited efficiency of photovoltaic panels. Nowadays, depending on type of the panel, its average efficiency ranges from 17 to 22% [2].

The chosen topic is relevant because solar panels are increasingly used not only in industry but also in private use and in decentralized villages, and the consumer does not see accurate data about the product in conditions of real work, but only results, obtained in a laboratory. In the course of work, I will try to estimate how much the parameters declared by the manufacturer differ from the real ones.

For evaluating effectiveness of solar modules, experimental model of solar panel based on polycrystalline solar cells was built. The design provides the ability to change the angle of the panel to the solar radiation and to change load. Nowadays exist various methods of PV panels efficiency evaluating, which will be described and applied during the work. Economic aspects of the topic also will be described.

There are two main types of photovoltaic modules: monocrystalline and polycrystalline panels on silicon base. The manufacture of solar cells based on monocrystalline silicon allows to obtain the highest rates of photoelectric conversion efficiency among commercial application modules due to the highest possible purity of the material. According to [2] the efficiency of monocrystalline solar cells can reach to 19–22%.

Due to a better material, monocrystalline solar cells have efficient performance for working at low illumination levels (in cloudy conditions), which is very important for power generation in the autumn-winter period. If the goal is to obtain the maximum generation per unit area, only monocrystalline modules should be used.

The main advantage of polycrystalline solar cells is that they are cheaper by an average of 15% [3], since the cost of the material is lower, but the efficiency of such modules is also lower. It is optimal to use this type of panels if there is no goal to obtain maximum power generation per unit of installed capacity and if there is no significant difference in illumination levels for a long period. For my research, I will use polycrystalline solar cells because I was provided by them by Tomsk Polytechnic University.

2. Solar panels and methods evaluating their effectiveness

Solar energy was developed relatively recently, but the technology itself owes its origin to researchers from the 1800s, who discovered that light could move electrons in solid materials. This discovery ultimately led to the development of various types of solar cells that are used today [4].

The advantage of solar panels due to the absence of moving parts (disregarding supporting structures), their high reliability and stability. Other advantages are relatively small weight, unpretentiousness, simple installation and minimum maintenance requirements during operation. Another major advantage is that energy is transformed immediately in electricity.

Today, various types of solar panels are gaining more and more popularity, mainly because of two reasons. Firstly, because the population of the Earth started to think about environmental problems of energy sources, and secondly, because solar panels are becoming more and more energy efficient.

In the following subchapters, I will describe methods of testing the efficiency of solar cells, its working principles and types.

2.1. Standard efficiency tests

In the international power engineering industry, the main tests for determining the efficiency of photovoltaic modules are Normal Operating Cell Temperature (NOCT), PV-USA Test Conditions (PTC), Standard Test Conditions (STC), Low Irradiance Conditions (LIC), High Temperature Conditions (HTC) and Low Temperature Conditions (LTC).

Module manufacturers test the product under certain equal conditions in order to be able to compare modules of different brands. One of the main lists of conditions are Standard Test Conditions (STC).

As a rule, STC tests of modules are carried out with the help of a short flash in laboratory or factory conditions, close to ideal. As described in [2] the illumination should be 1000 W/m2 and the temperature of the solar module is to be 25° C. Wind speed must be zero. These parameters correspond to the sunny day of spring or autumn, when the panel is oriented to the south at an angle of 37° to the horizon and at a height of the sun above the horizon of 41.81°.

For more accurate testing, additional parameters are introduced, such as NOCT. NOCT (Nominal Operating Cell Temperature) is measured when the solar panel is illuminated with a light intensity of 800 W/m2 and an air temperature of 20° C. In this case, the electric circuit is open, the tilt angle of the module is 45° with orientation to the South. The lower the NOCT, the better the module will work in real conditions.

PTC test parameters, or PVUSA (Photovoltaics for Utility Systems Applications) Test Conditions, show the results of tests of solar panels in conditions more close to real than STC. PTC also implies an illumination of 1000 W/m2. Panels should be at a height of 10 m above ground level, air temperature should be 20° C and wind speed should be 1 m/s. PTS are a mathematically calculated value obtained by using measurement results under various conditions. In addition, NOCT is used to calculate PTS.

The NOCT temperature is used to calculate the expected module temperature at PTC, and then the module power at PTC is calculated using the temperature power factor (usually specified in the specifications for each module) [2].

2.2. Working principle of solar panels

The solar cell is a solid-state device, which converts sunlight, as a stream of photons, into electrical energy [5]. Usually solar cell is a silicon-based semiconductor. A semiconductor is such a material, in the atoms of which either there are extra electrons (n-type), or vice versa, there are not enough electrons (p-type). Accordingly, the semiconductor photocell consists of two layers with different conductivity. An n-layer is used as a cathode, and a p-layer is used as an anode.

Excess of electrons from the n-layer can leave their atoms, while the p-layer captures these electrons. It is the rays of light that “knock out” electrons from the atoms of the n-layer, after which they move into the p-layer to occupy empty spaces. In this way, the electrons run in a circle, leaving the p-layer, passing through the load (in this case, the battery) and returning to the n-layer [6].

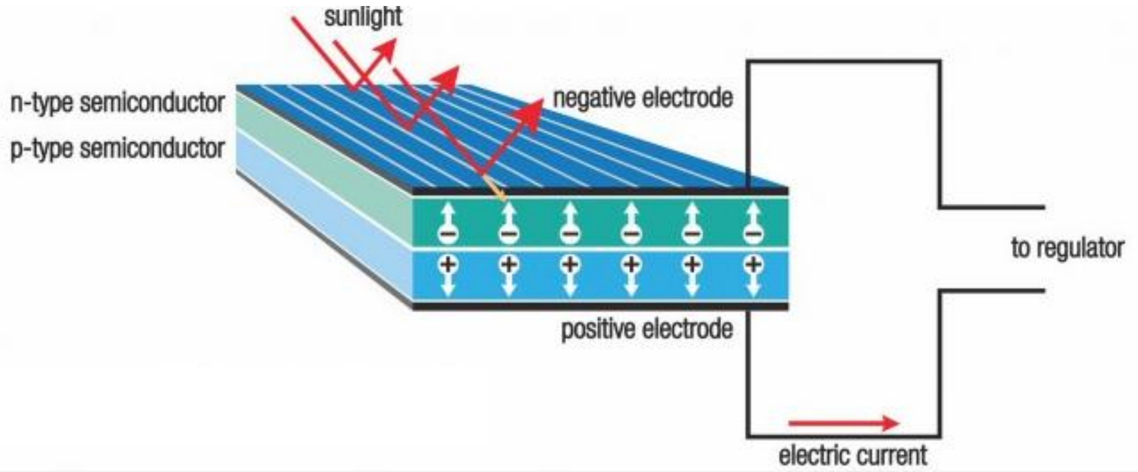


Figure 2 – Cross section of a solar cell [6]

The first photovoltaic material in history was selenium. First photovoltaic cells based on selenium were produced in the late XIX and early XX centuries. However, thanks to its extremely low efficiency (less than 1%), it was necessary to find new material.

Mass production of silicon-based solar cells became possible after the telecommunications company Bell Telephone developed its first silicon-based solar cell [6].

2.3. Types of solar panels and their efficiency

The sun is not only a reliable and lasting energy source but also a very cost-effective and efficient one, if the chosen types of solar panels and the environment are matched to one another. Nowadays many different types of solar panels exist.

The most common production technology of photovoltaic cells based on silicon crystals are:

- Monocrystalline solar cells;
- Polycrystalline solar cells;

Monocrystalline type

The production of monocrystalline photocells takes place using the Chkhoralsky method. In order to obtain a silicon monocrystal, a seed crystal is immersed in a melt of silicon with boron and gradually raised a few meters above the surface of the solution, while a crystallizing solution is drawn out behind the seed crystal. Edges are cut from the obtained single-crystal preform in order to obtain square elements and cut it into elements with a thickness of approximately 0.3 mm. After that, the elements are doped with phosphorus to add n-conductivity and create a p-n junction, and then they are polished and covered by anti-reflective coating and current paths [7]. However, a significant amount of the original silicon ends up as waste [8].

This type of cells is the purest. Because of that, it has homogeneous structure and color. Also, the silicon’s high purity makes its efficiency one of the highest in the industry of approximately 20%. Monocrystalline panels have a high power output and last the longest. That makes them the most expensive type.

The highest power outputs causes the fact that they also require the least amount of space compared to any other types. For example, monocrystalline solar panels generates four times more electricity than thin-film solar panels. Another fact is that in comparison with polycrystalline type temperature affected them less [9].

Figure 3 – Monocrystalline solar cell [7]

Polycrystalline type

The first solar panels based on polycrystalline silicon, which also is known as polysilicon (p-Si) and multi-crystalline silicon (mc-Si), were introduced to the market in 1981. This type of solar panels does not require the Chkhoralsky method. Raw silicon is melted and poured into a square mold, which is cooled and cut into perfectly square wafers [8]. In this case, unidirectional crystals ranging in size from a few millimeters to several centimeters are formed in the tank. The resulting block of polycrystals is processed in the same way as a monocrystal preform [7]. This process is a faster and cheaper than that used for monocrystalline panels.

Such technology of producing leads to a lower final price but also lower efficiency (around 15-17%), what leads to larger amount of required space for installation, and a shorter lifetime period since they are more affected by hot temperatures [9].

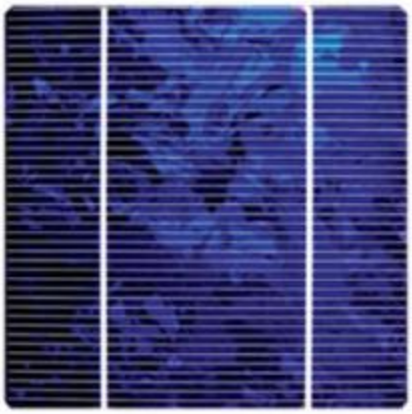


Figure 4 – Polycrystalline solar cell [7]

2.4. Factors affecting the efficiency of solar panels

Russia has a huge total energy potential of the Sun, but these resources are distributed very unevenly due to the vastness of the territory, the variety of climatic and landscape conditions. Therefore, it is advisable to carry out a consideration of the climatic potential of solar energy differentiated by regions, individual territories and points.

In assessing the potential of solar energy for this item, it is also necessary to take into account a significant number of factors. The amount of potentially useful solar radiation falling on the illuminated surface in a period of time is called insolation or irradiation. Solar irradiance is the Sun’s power, represented in units of W/m^2. Solar insolation varies greatly from one point on the earth's surface to another [10]. As solar panels receive energy of the Sun, there are several reasons of decreasing of insolation level. In this subchapter, I will describe several of them.

1) Tilt-angle of a panel. The angle at which the maximum level of insolation is reached for different points differs and depends on latitude. In addition, the position of the panel can be changed so that

it is constantly located in relation to the Sun on angle close to 90°, which allows significantly (1.5–1.8 times) to increase the converted energy [11].

2) Atmosphere. When sunlight passing through atmosphere, some part of its energy is lost because of reflection and absorption. Figure 5 demonstrates these effects.

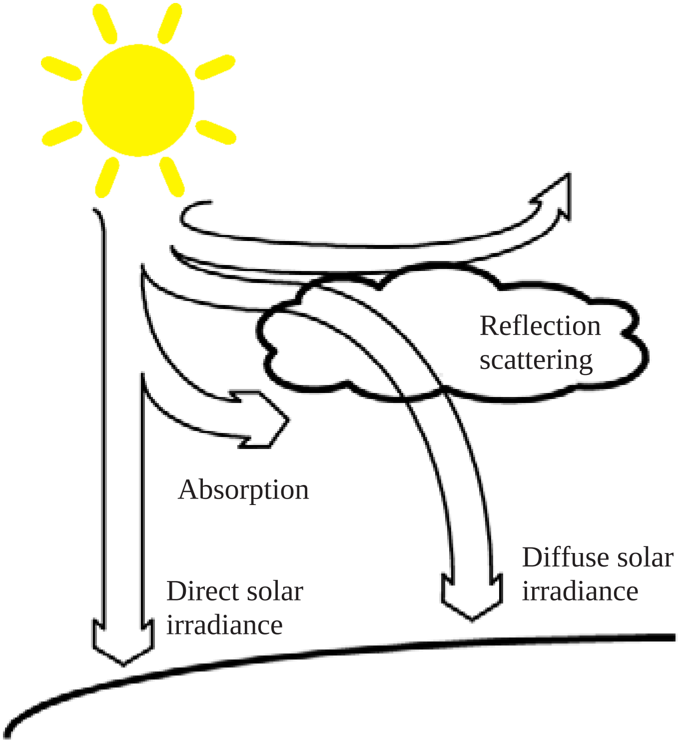


Figure 5 – Sunlight Passing Through the Atmosphere. Modified based on [12]

Other reasons of irradiance decreasing are:

- Reduction due to Rayleigh scattering caused by molecular air particles with diameters smaller than the wavelength of light. The influence of Rayleigh scattering rises with decreasing light wavelength;
- Reduction due to Mie scattering caused by dust particles and other air pollution. The diameter of these particles is larger than the wavelength of the light. Mie scattering depends significantly on location; in high mountain regions, it is relatively low, whereas in industrial regions it is usually high.

3) Weather. Weather conditions have a significant influence on the output of solar panels. Cloudless conditions are more preferred because it allows to get higher efficiency.

Values of reduction at different sun heights based on [12] are shown in Table 1:

Table 1 – Reduction of irradiance dependence

Sun Height, γ_S °	Air mass, AM	Absorption, %	Rayleigh scattering, %	Mie scattering, %	Total reduction, %
90	1.00	8.7	9.4	0–25.6	17.3–38.5
60	1.15	9.2	10.5	0.7–29.5	19.4–42.8
30	2.00	11.2	16.3	4.1–44.9	28.8–59.1
10	5.76	16.2	31.9	15.4–74.3	51.8–85.4
5	11.5	19.5	42.5	24.6–86.5	65.1–93.8

When finding the insolation value of a region, several factors need to be considered [13]:

- the influence of the season, causing a shorter duration of solar luminescence in the cold season and, accordingly, the lower accumulated illumination per day;
- the nature of the area illuminated by the Sun (relief, the presence of shading obstacles, geographic orientation of the slopes);
- local weather conditions (air mass transparency, cloudiness, precipitation, and other many weather phenomena that weaken solar radiation);
- the spatial orientation of the receiver relative to the Sun. The incident rays on the illuminated surface at a lower angle give less energy illumination.

3. Experiment description

In order to evaluate efficiency of solar panels in conditions of real work, I had conducted an experiment. The idea is to test output parameters of solar cells, when they are used in real conditions and compare results of testing with its passport parameters. For the experiment, I used Aiyima solar cells. This type of polycrystalline cells is commonly available and could be bought for personal use.

3.1. Design of experimental installation

The experimental model is a solar panel. It consists of supporting structure for eight identical Aiyima solar cells welded together and a separate block of resistors to change the load.

Supporting structure is a varnished wooden desk with four bolt feet, mechanism for changing and fixing the angle (six working positions) and four output banana type plugs for connecting solar panel with block of resistors.

Block of resistors function is creation of load. This could be explained on the example of Table 4.

Solar cells was soldered consequently. This scheme involves connecting the “plus” of the first cell with the “minus” of the second, and the output of external wires from the “minus” of the first cell and the “plus” of the last. It does not matter how many solar cells will be combined into one battery. The key point is to do not violate the principle.

Block of resistors is consist of next details:

- two banana plugs in order to connect measuring device (multimeter);
- four switchers in order to connect or to disconnect resistors from the circuit;
- six ceramic resistors.

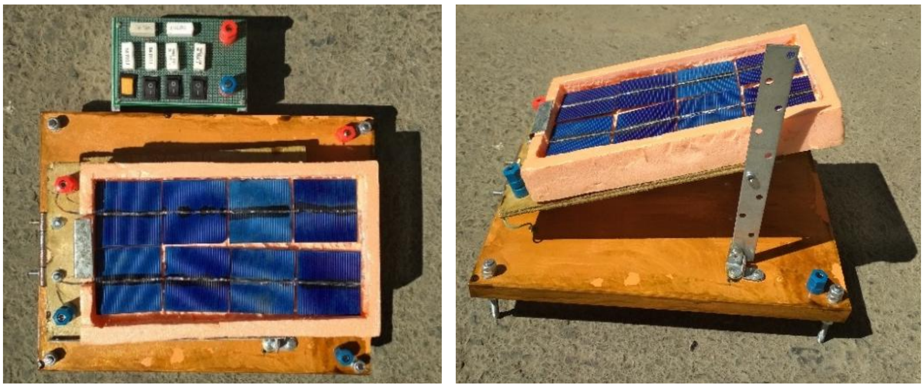


Figure 6 – Experimental model (views from different angles)

Characteristics of Aiyima solar cell:

- Material: Polycrystalline Silicon
- Size: 52x52 mm
- Power: 0.43 W

- Voltage: 0.5 V
- Current: 0.86 A
- Efficiency: 17%

3.2. Choice of resistors

A resistor is a passive element of electrical circuits that has a specific or variable value of electrical resistance, intended for linear conversion of current into voltage and voltage into current, current limiting, absorption of electrical energy, etc. In my experiments, I used ceramic resistors of different denominations as a load.

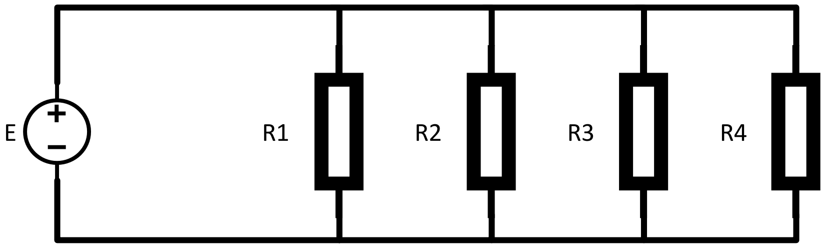


Figure 7 – Scheme of installation

On Figure 7 scheme of installation is shown. There are four resistors are connected in parallel. Because the idea is to test work of panel with different values of load. If resistors will be connected in series, then we will have no opportunity to use several resistors. Difference between real and calculated amount of resistors will be described after calculations in the end of this subchapter.

For estimation of resistors parameters, currents will be assumed as follows:

$$I_1 = 0.01 \ \ A;$$

$$I_2 = 0.2 \ \ A;$$

$$I_3 = 0.6 \ \ A;$$

$$I_4 = 0.82 \ \ A;$$

where

I_1, I_2, I_3, I_4 are currents in the circuit matching resistors R_1, R_2, R_3, R_4.

Intervals between currents are taken close to equal in order to get more uniform results.

$$U_{nom} = 0.5 \ \ V;$$

where

U_{nom} is nominal voltage of one solar cell.

$$U_{act} = 0.5 \cdot 8 = 4 \ \ V;$$

where

U_{act} is actual voltage when 8 solar cells are connected in series.

$$I_{nom} = 0.86 \ \ A;$$

where

I_{nom} is nominal current of one solar cell.

Take the minimal current as:

$$I_{\min} = 0.01 \ \ A;$$

Then,

$$I_{act} = 0.86 \cdot 8 = 6{,}88 \ \ A;$$

where

I_{act} is actual current in the circuit when 8 solar cells are connected in series.

$$P_{\max} = 0.43 \ \ W;$$

where

P_{max} is maximum power of one solar cell.

$$P_{act} = 4 \cdot 6.88 = 28 \ \ W;$$

where

P_{act} is power in the circuit when 8 solar cells are connected in series.

Taking into account the fact that under the terms of reliability it is necessary to take the power by 30% more than the actual:

$$P_{nom} = 36 \ \ W;$$

Resistance of the first resistor R_1 is:

$$R_1 = \frac{U}{I_1} = \frac{4}{0.01} = 400 \ \ Ohm;$$

Using the table of standard resistors E24, I take the closest to the minimum value: $R_1 = 390 \ \ Ohm;$

Table 2 – E24 Standard resistor values [14]

R, Ohm	R, Ohm	R, Ohm
1.0	1.1	1.2
1.3	1.5	1.6
1.8	2.0	2.2
2.4	2.7	3.0
3.3	3.6	3.9
4.3	4.7	5.1
5.6	6.2	6.8
7.5	8.2	9.1

Next, I find the value of R_2:

$$R_{eqv1} = \frac{U}{I_2} = \frac{4}{0.2} = 20 \ \ Ohm;$$

where

R_{eqv1} is equivalent resistance of the first resistor.

$$R_2 = \frac{R_{eqv1} \cdot R_1}{R_1 - R_{eqv1}} = \frac{20 \cdot 390}{390 - 20} = 21.08 \ \ Ohm;$$

where

R_2 is actual resistance of the second resistor.

Using the table of standard resistors E24, I take the closest value: $R_2 = 22 \ \ Ohm;$

Resistance of resistor R_2 is 22 Ohm. Then, find real values of R_{eqv1} and I_2:

$$R_{eqv1act} = \frac{R_1 \cdot R_2}{R_1 + R_2} = \frac{390 \cdot 22}{390 + 22} = 20.83 \ \ Ohm;$$

where

$R_{eqv1act}$ is actual equivalent resistance of first and second resistors.

$$I_{2act} = \frac{U_{act}}{R_{eqv1act}} = \frac{4}{20.83} = 0.19 \quad A;$$

Next, I calculate resistance of resistor R_3:

$$R_{eqv2} = \frac{U}{I_3} = \frac{4}{0.6} = 6.66 \quad Ohm;$$

$$R_3 = \frac{R_{eqv2} \cdot R_{eqv1act}}{R_{eqv1act} - R_{eqv2}} = \frac{6.66 \cdot 20.83}{20.83 - 6.66} = 9.79 \quad Ohm;$$

Using the table of standard resistors E24, we take the closest value: $R_3 = 10 \quad Ohm$;

Real value of resistor R_3 is 10 Ohm. Then, find real values of R_{eqv2} and I_3:

$$R_{eqv2act} = \frac{R_{eqv1act} \cdot R_3}{R_{eqv1act} + R_3} = \frac{20.83 \cdot 10}{20.83 + 10} = 6.76 \quad Ohm;$$

$$I_{3act} = \frac{4}{6.76} = 0.59 \quad A;$$

Next, I calculate value of resistor R_4:

$$R_{eqv3} = \frac{U}{I_4} = \frac{4}{0.82} = 4.88 \quad Ohm;$$

$$R_4 = \frac{R_{eqv3} \cdot R_{eqv2}}{R_{eqv2} - R_{eqv3}} = \frac{4.88 \cdot 6.66}{6.66 - 4.88} = 18.26 \quad Ohm;$$

Using the table of standard resistors E24, we take the closest value: $R_4 = 18 \quad Ohm$;

Real value of resistor R_4 is 18 Ohm. Then, find real values of $R_{eqv3act}$ and I_{4act}:

$$R_{eqv3act} = \frac{R_4 \cdot R_{eqv2}}{R_4 + R_{eqv2}} = \frac{18 \cdot 6.66}{18 + 6.66} = 4.82 \quad Ohm;$$

$$I_{4act} = \frac{U}{R_{eqv3act}} = \frac{4}{4.82} = 0.82 \quad A;$$

Hence, Table 3 represents all chosen resistors with its nominal (passport) value of resistance:

Table 3 – Chosen resistors

Resistor	Resistance, Ohm
R_1	390
R_2	22
R_3	10
R_4	18

Because of the absence in the store in which the resistors were bought of 18 Ohm resistor, instead of it three resistors of 10, 5.1 and 3 Ohm were installed. So total resistance is the same with calculated values. That is explain the difference between calculated and used number of resistors.

4. Analysis of collected experimental data

Experimental data were collected under the following conditions:

Date: 16.07.2018;

Time: 12:07;

Ambient temperature: 22°C;

Temperature of the panels before experiments: 35° C;

Temperature of the panels after experiments: 46° C;

Weather: natural level of cloudiness;

Panel's orientation: south.

I will analyze the constructed model by Volt-Ampere Characteristic (VAC), power and efficiency. In order to get all this data, I need to measure only two parameters: current and voltage. According to them, I will build VAC, get power by multiplying these two indicators, and calculate the efficiency of the constructed model.

As it is known, many different indicators influence on the production of solar energy, the main ones are insolation, load, tilt-angle, temperature of the panels. Since it is difficult to analyze the influence of different weather conditions and temperature of the panels on its efficiency, I decided to analyze influence of two parameters: load and tilt-angle. Therefore, I took measurements for 5 different loads (calculated earlier in Subchapter 3.2) and for five different tilt-angles, and then analyzed obtained data.

Before proceeding directly to the measurements, I determined the angles for which I would take readings. Since I assembled the installation myself, it has some drawbacks, for example, I cannot change the angle as I would like (0, 10, 20 ... 60 degrees). As can be seen from Figure 6, the design is assembled in such a way that the angle changes in steps, and I directly measured the value of the tilt angle itself when the model was already assembled. Therefore, I got the following tilt-angles of my solar panel:

$$\beta_1 = -2.27°;$$

$$\beta_2 = 1.9°;$$

$$\beta_3 = 8.97°;$$

$$\beta_4 = 14.77°;$$

$$\beta_5 = 18.8°;$$

$$\beta_6 = 39.32°;$$

As we see, the first angle turned out to be negative. As noted earlier, I obtained the data from the installation, which was located in such a way that insolation was maximum, in other words, it was located to the south. A negative angle means the installation has been turned north.

After measuring the values of the angles, I began to take readings. At the same time, during the experiments, I followed the following rules:

- surface of the panels should not be shaded;

- when measuring the current, the multimeter is connected in series;

- when measuring the voltage, the multimeter is connected in parallel.

Since insolation has a direct impact on the performance of the panels, shading on the panels will lead to inaccurate results.

From the course of electrical engineering, it is known that the currents in series circuits are equal, the voltage is the same in parallel circuits. Therefore, when we need to measure the current, we connect the multimeter, assuming that its internal resistance is zero, and we get the value of the current equal to the current flowing in this branch.

When we measure voltage, we consider that the resistance of the multimeter tends to infinity, and then the voltage on the multimeter will be the same as the voltage between the terminals to which it was connected. The infinite resistance of the multimeter is taken so that no current flows in the circuit of the multimeter, because otherwise the voltage between the terminals where the measurements are taken would increase.

Thus, I carried out 30 measurements, the results of which are presented in Table 4.

Table 4 – Experimental data

R=0 Ohm (no load)			R=384 Ohm (Resistor 1)			R=22.3 Ohm (Resistors 1, 2)			R=9.8 Ohm (Resistors 1, 2, 3)			R=8 Ohm (Resistors 1, 2, 3, 4)		
β, deg	I, mA	U, V	β, deg	I, mA	U, V	β, deg	I, mA	U. V	β, deg	I, mA	U. V	β, deg	I, mA	U, V
-2.27	0	4.55	-2.27	10.8	4.53	-2.27	181	4.3	-2.27	420	3.9	-2.27	500	3.13
1.98	-	4.38	1.98	11	4.35	1.98	172	4.2	1.98	401	3.85	1.98	465	3.32
8.97	-	4.51	8.97	10.8	4.5	8.97	180	4.26	8.97	425	3.8	8.97	519	3.45
14.77	-	4.52	14.77	11	4.5	14.77	175	4.2	14.77	400	3.81	14.77	491	3.4
18.80	-	4.43	18.8	11.1	4.41	18.8	170	4.21	18.8	420	3.78	18.8	515	3.53
39.32	-	4.45	39.32	11	4.39	39.32	170	4.19	39.32	412	3.8	39.32	490	3.62

where

R – Resistance in the circuit;

β – Value of tilt-angle of the panel.

I – Current in the circuit;

U – Voltage in the circuit.

In Table 4 values of resistance are received during experiment and because each next resistor was connected after previous, in total we obtained equivalent resistance. That is why values of resistance in Table 4 are not the same with calculated nominal values of resistance in Table 3. Because of the fact that panel was constructed by me in not precise conditions, values of angles are not standard and there is even negative value of angle.

Next, volt-ampere characteristic curves at different angles of the panel will be obtained and presented on Figure 8. First and last values of angles are presented on Figure 8. All intermediate values will be presented in Appendix A.

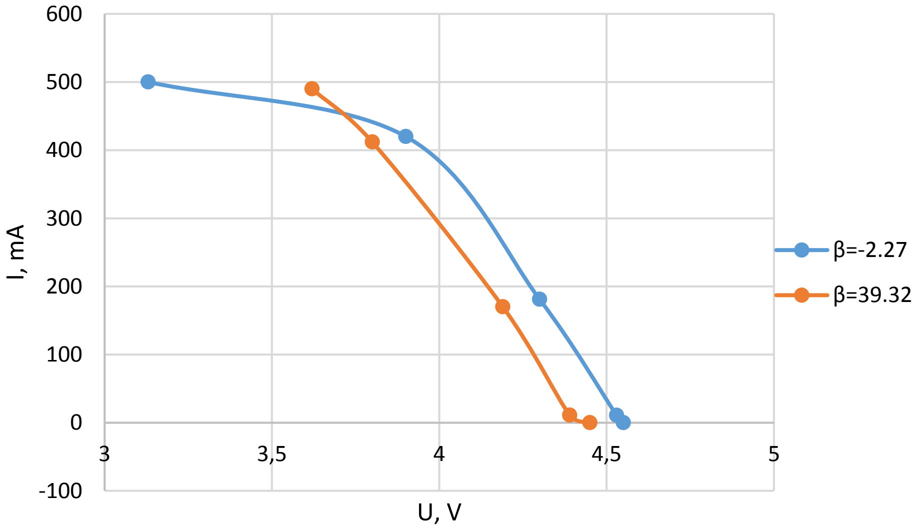


Figure 8 – Volt-ampere characteristics of experimental installation

In addition, in order to visually see how the angle of inclination affects the power, I will construct a graph of dependencies reflecting the change in power depending on the angle of inclination of the panel. Values of power I calculated from Table 4 by multiplying current by voltage. Results are shown in the following table:

Table 5 – Influence of tilt-angle on output power

	β = -2.27°	β = 1.98°	β = 8.97°	β = 14.77°	β = 18.80°	β = 39.32°
	P_1, mW	P_2, mW	P_3, mW	P_4, mW	P_5, mW	P_6, mW
R=384 Ohm (R_1)	48.92	47.85	48.60	49.50	48.95	48.29
R=22.3 Ohm (R_1, R_2)	778.3	722.4	766.8	735	715.7	712.3
R=9.8 Ohm (R_1, R_2, R_3)	1 638	1 544	1 615	1 524	1 588	1 566
R=8 Ohm (R_1, R_2, R_3, R_4)	1 565	1 544	1 791	1 669	1 818	1 774

According to previous table, graph for 8 Ohm was built.

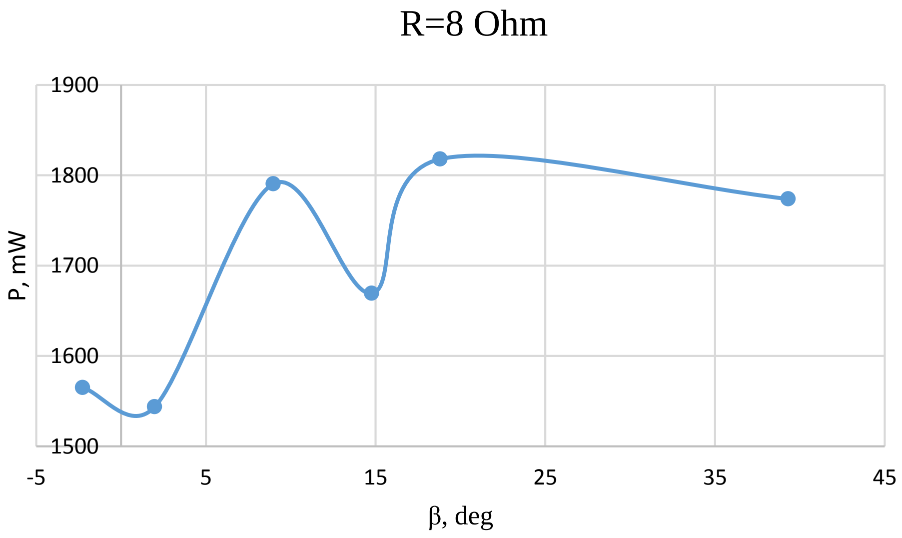


Figure 9 – Influence of tilt-angle on output power

The resulting graph is different from the expected. In theory, when the angle of inclination changes, that is, as it approaches the angle at which the sun's rays fall on it at a right angle, the production of the panel should increase. Our dependence is not linear. At a panel tilt angle of 14.77°, a sharp power drawdown is formed. I can explain this incompatibility of a real situation with a theoretical one by several reasons:

- Changing the angle of inclination of the model took time, so while I was moving from measurement at one angle of inclination to measurement at another angle, weather conditions changed and this had an impact on the results of the calculations.
- The angle of inclination was measured directly at the site where I took readings from the instruments. Therefore, I accepted the assumption that this site is horizontal. However, due to the absence of a device for measuring the level, these measurements were not carried out. This also introduces a certain error in the measurements, because I should consider this angle. For example, if the slope angle relative to the south were β0, then the actual angle of the panel would be equal to:

$$\beta_1^{real} = \beta_1 + \beta_0,$$

where

β_1 – the angle of inclination, measured on an ideally horizontal plane;

β_0 – the angle of inclination of the plane on which the measurements were made.

Thus, in order to obtain more accurate information about the output power, I would have to make much more measurements, and take into account many more different factors that influence the behavior of the model in order to minimize the errors introduced into the result. However, the purpose of my work is to analyze the efficiency of photovoltaic modules, so there is no need for such exaggerated accuracy, and my level of measurement error is valid for this study.

All described steps explain experiment itself, experimental installation and obtained results. In the following chapter, I will apply methodology of evaluating solar panel's effectiveness.

5. Evaluating the effectiveness of photovoltaic panels from the experimental data

The specifics of evaluating the effectiveness include such main factors as:

- Optimal tilt-angle of the plane
- Solar radiation

After calculation this two parameters, efficiency of panel used in experiment will be estimated.

5.1. Calculation of solar radiation and optimal tilt-angle

I was conducting experiments with six different angles of panel's tilt. The first value of -2.27° will not be taken into account during optimal angle calculation, because it cannot be optimal.

The methodology of efficiency calculations is to determine optimal incidence angle of the beam radiation on plane in this region. The incidence angle depends on the following parameters: geographical location (latitude and longitude), time of the day and of the year and plane orientation (tilt angle and azimuth angle).

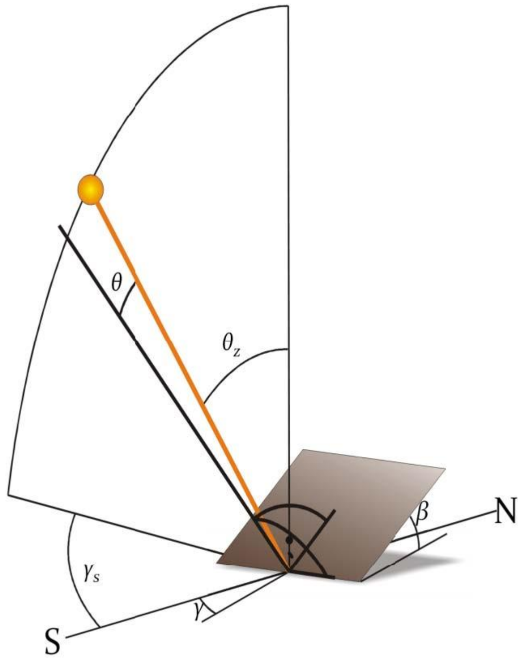
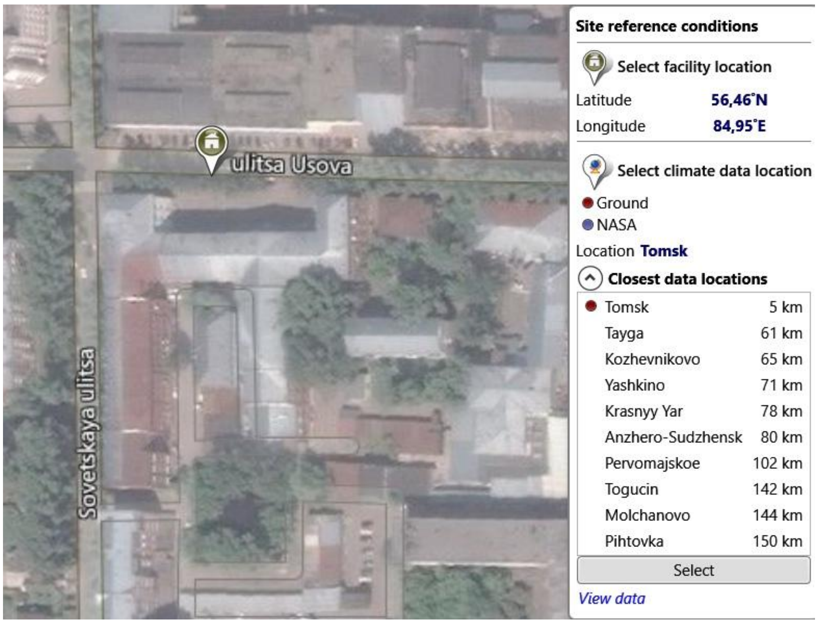


Figure 10 – Tilted plane with tilt angle β, plane azimuth angle γ and incidence angle θ, additionally solar zenith angle θz, solar azimuth angle γs [15]

The first step is to determine the latitude and longitude of the place where I conducted experiment. It was found with the help of [16].



Site reference conditions

Select facility location

Latitude 56,46˚N

Longitude 84,95˚E

Select climate data location

● Ground

● NASA

Location **Tomsk**

Closest data locations

● Tomsk	5 km
Tayga	61 km
Kozhevnikovo	65 km
Yashkino	71 km
Krasnyy Yar	78 km
Anzhero-Sudzhensk	80 km
Pervomajskoe	102 km
Togucin	142 km
Molchanovo	144 km
Pihtovka	150 km

Figure 11 – Coordinates of the experimental point in Tomsk [16]

Then it is necessary to convert latitude of experimental to radians because calculations was applied in Mathcad. Latitude in radians is found according to the formula:

$$\varphi = 56.4639^{\circ} \cdot \frac{\pi}{180^{\circ}};$$

where

56.4639° is latitude of the experimental point [16].

$$\varphi = 0.985 \ rad.$$

As experimental model was oriented on the south, then azimuth is equal to 0:

$$\gamma = 0.$$

Next step is to estimate declination value of the Sun with the help of Cooper’s formula according to [15] for the day of experiment (16.07.2018):

$$\sigma = 0.41 \cdot \sin\left(2 \cdot \pi \cdot \frac{284 + N}{365}\right),$$

where

N – number of a particular day in the year.

$$\sigma = 0.41 \cdot \sin\left(2 \cdot \pi \cdot \frac{284 + 196}{365}\right);$$

$$\sigma = 0.376.$$

Solar time (ω) according to [15] is equal to 0 at 12:00. In my case, as the experiment was conducted at 12:07, value of solar time is calculated as follows:

$$\frac{7}{60} = 0.117;$$

$$\frac{2 \cdot \pi \cdot 0.117}{24} = 0.031\ rad;$$

$$\omega = 0.031\ rad.$$

Next step is to determine the angle of received solar radiation flux on the panel at various angles of inclination of the plane to the horizon according to [17]:

$$\begin{aligned} &\cos\theta = \sin\sigma \cdot \sin\varphi \cdot \cos S - \sin\sigma \cdot \cos\varphi \cdot \cos\gamma + \\ &+ \cos\sigma \cdot \cos\varphi \cdot \cos S \cdot \cos\omega + \cos\sigma \cdot \sin\varphi \cdot \sin S \cdot \cos\gamma \cdot \cos\omega + \\ &+ \cos\sigma \cdot \sin S \cdot \sin\gamma \cdot \sin\omega, \end{aligned} \tag{1}$$

where

φ – Latitude of the investigated object, rad;

δ – Inclination of the Sun, rad;

S – Angle of inclination of the plane to the horizon, rad;

ω – Solar time, rad.

After applying formula (1) in Mathcad, the graph of the optimal angle was built. It shows dependence of insolation level and solar time ω. Insolation level here in in relative units, where 1 is maximum level of insolation in this day. Solar time is equal to time of the experiment (12:07) in radians.

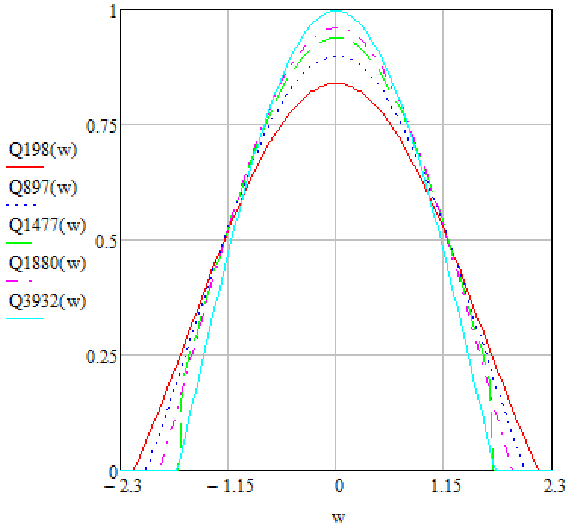


Figure 12 – Optimal angle of the panel

where according to Formula (1),

Q198(w) is Cos of the first experimental angle β (Cos(1.98)) from Table 4;

Q897(w) is Cos of the second experimental angle β (Cos(8.97)) from Table 4;

Q1477(w) is Cos of the third experimental angle β (Cos(14.77)) from Table 4;

Q1880(w) is Cos of the fourth experimental angle β (Cos(18.80)) from Table 4;

Q3932(w) is Cos of the fifth experimental angle β (Cos(39.32)) from Table 4;

As it could be seen from the Figure 12, the biggest value of solar radiation is observed at the angle of 39.32°. Calculated with the help of Formula (1) values of angles of received solar radiation on tilted plane Cos(β) are shown in the following table:

Table 6 – Values of Cos(β) at different tilt-angles

Angle β, °	Cos(β)
1.98	0.839
8.97	0.899
14.77	0.938
18.80	0.960
39.32	0.997

Next, the values of total solar radiation at the inclined tilt-angles would be calculated.

According to [18] the value of total (direct and diffuse) solar radiation on a horizontal plane under actual cloud conditions in Tomsk is equal to 612 MJ / m^2. This value should be converted into kWh/m^2:

$$Qh = 612 \cdot \frac{1000}{3600} = 170 \ kWh / m^2;$$

Then, using following formula and Table 6, the value of total solar radiation on the inclined plane would be obtained:

$$\frac{Qh \cdot \mathrm{Cos}(\beta)}{\mathrm{Cos}(0^0)};$$

where

Q_h – solar radiation on horizontal plane;

Cos(β) – calculated angles of solar radiation on different tilt-angles of the panel;

Cos(0°) – angle of solar radiation on horizontal plane.

Values of total solar radiation on inclined plane are calculated with the help of previous formula and presented in the following table:

Table 7 – Values of total solar radiation received on inclined plane

Angle β, °	Q_{inc}, kWh/m^2
1.98	174.2
8.97	186.6
14.77	194.7
18.80	199.3
39.32	206.9

As we can see, maximum of solar radiation is received on plane with tilt-angle of 39.32°. Using information from [19], I can compare calculated values with the real irradiation data.

On Figure 13, we can see average values of irradiation during the year in the selected. In July, it is 179 kWh/m^2. It is different from the calculated variant (206.9 kWh/m^2) because of the several reasons. First of all, unknown value of the losses in calculations. Information from the web site is based on precise calculation, including temperature of panels and we know, that the higher temperature of panels, the higher losses. Second reason is that time of experiment (12:07) is approximate because of the conducting of the experiment require some extra time for switching resistors, changing the wiring of a multimeter etc. Third reason is level of cloudiness.

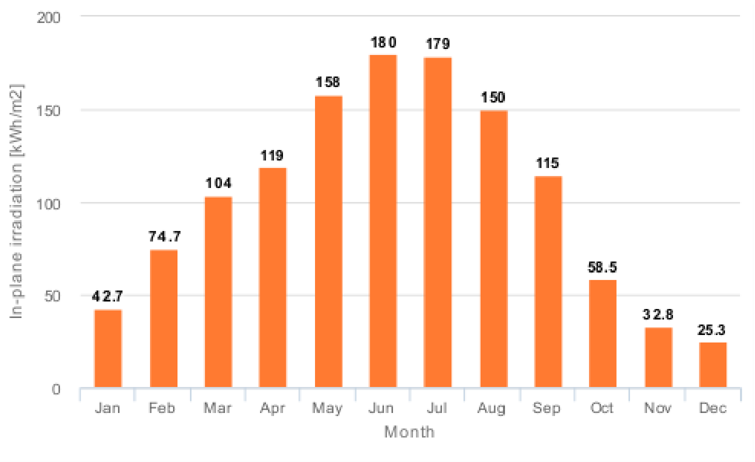


Figure 13 – Monthly in-plane irradiation in the selected area [19]

5.2. Calculation of the efficiency of experimental solar panel

In this subchapter, I will calculate efficiency of used solar panel and compare results with data provided by manufacturer.

Efficiency is relation between output power and input power. According to Table 4, we know values of resistance and current, and then we can find output power of solar panel:

$$P = I^2 \cdot R;$$

where

P – power;

I – current;

R – resistance.

Then, power output of the panel (based on Table 4):

$$0.490^2 \cdot 8 = 1.92 \; W.$$

Next step is to find input power. According to [19] global irradiance in July at 12:00 is 683 W/m^2. Then, by multiplying irradiance on area of the panel, we find input power:

$$P_{input} = \delta \cdot S;$$

where

δ – irradiance;

S – area of the panel;

Area of the panel will be calculated according to passport data. Area of one solar cell:

$$S_C = 52 \cdot 52 = 2704 \ mm^2;$$

$$S_C = 2704 / 1000000 = 0.002704 \ m^2;$$

Then, area of solar panel (8 solar cells):

$$S_p = 0.002704 \cdot 8 = 0.021632 \ m^2;$$

Now, output power will be calculated:

$$P_{input} = 683 \cdot 0.021632 = 14.775 \ W.$$

Then, total efficiency of the panel:

$$\eta = \frac{P_{output}}{P_{input}} \cdot 100;$$

$$\eta = \frac{1.92}{14.775} \cdot 100 = 13\%$$

As we can see, obtained results are differ from the data declared by the manufacturer (13% against 17%). Difference in efficiency of solar panel is significant (4%). As experiment conducted in July with high level of insolation, we can assume that in winter season, difference could be even higher. I see several reasons of difference between obtained data and declared by manufacturer:

1) Dirty surface of the panel. During the process of constructing experimental model (soldering, placing), solar cells were polluted.
2) Temperature of the cells. With increasing of temperature, the efficiency of solar cells decreases. Higher temperature increases the flow of electrons, which causes an increase in current and voltage drop. The voltage drop is higher than the increase in current. Therefore, the total power is reduced, which leads to the fact that the module operates with less efficiency [20]. In our case, temperature of the panel before and after experiment is 35° and 46° respectively.
3) Optimal tilt-angle according to [19] is 43°, however design of experimental model provides angle of 39.32°.
4) Soldering of solar cells and contacts was carried out manually, what lead to additional losses.

After analyzing obtained efficiency I can make a conclusion that in this particular case if solar panel is constructed in accordance with all norms and standards, efficiency in real conditions could be equal to the results obtained in laboratory, i.e. declared by manufacturer.

6. Modeling project for economic evaluation

At present, the economic costs of extracting electricity from renewable sources are commensurate with the cost of traditional ways of producing electricity.

In order to evaluate effectiveness of solar panels from the economic point of view, I will make a design of autonomous power supply system for the building located in the selected region.

In the following subchapters, I will chose all necessary equipment for power supply of the selected region. After model is ready, I will evaluate project from the economic point of view.

6.1. Review of the selected region: Pervopashensk village

In order to evaluate effectiveness of solar panels from a technical and economic point of view, I will make autonomous power supply systems of Pervopashensk village in Tomsk region. Pervopashensk is located in the east of Western Siberia at the confluence of the Tunguska and Bolshaya Yuksa rivers [21].

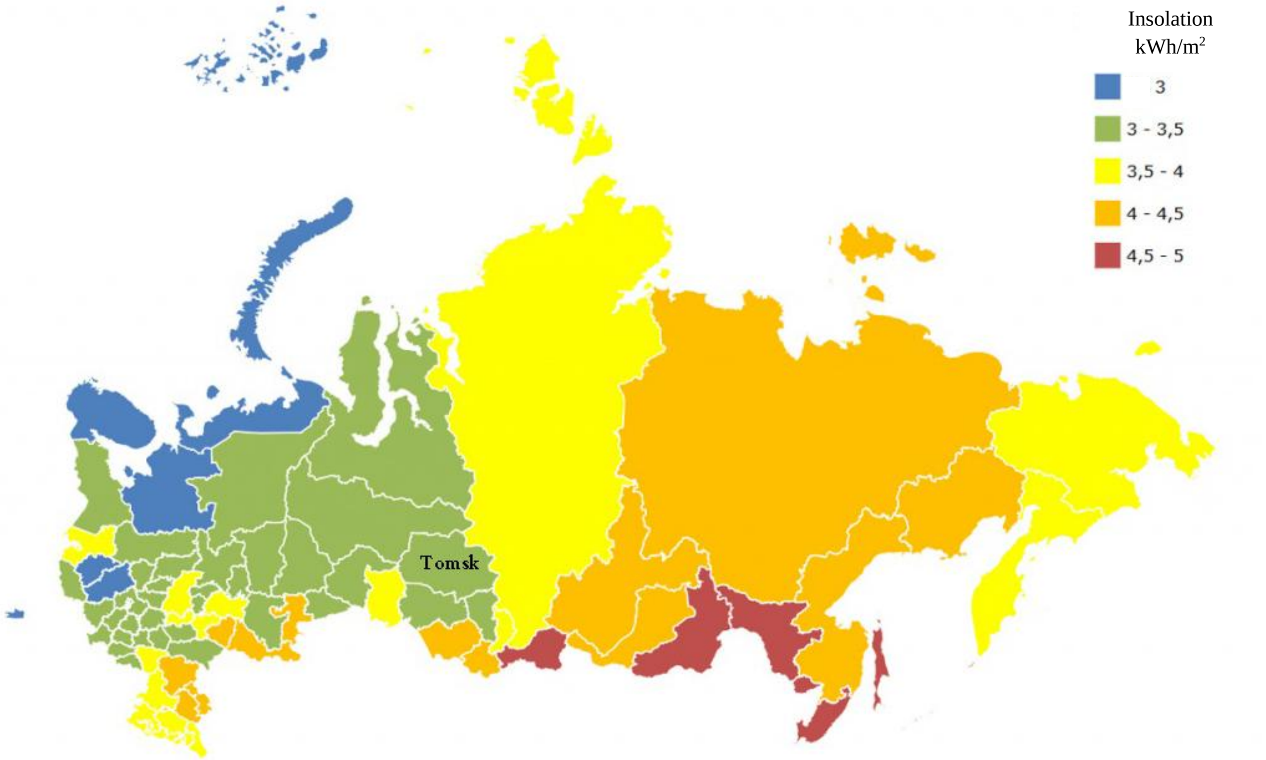


Figure 14 – Insolation level map of Russia. Based on [22]

Pervopashensk village power supply is performed by diesel power plant (DPP). There are two diesel generators with 75 kW installed capacity each [23]. Household type of load prevails.

The main energy characteristic of solar radiation is monthly solar radiation in conditions of real clouds. As village is located near the city of Tomsk, level of insolation is the same. According to Figure 13, values of insolation in Tomsk with natural level of cloudiness:

Table 8 – Monthly insolation in Tomsk [19]

Month	Monthly insolation $Q_{month},\ kWh/m^2$
January	42.7
February	74.7
March	104
April	119
May	158
June	180
July	179
August	150
September	115
October	58.5
November	32.8
December	25.3

As we can see, during summertime level of insolation is 3.5 times higher than during wintertime. Graphically insolation during the year in Tomsk region is shown in Appendix C.

After describing climatic features of the region and prospects of using solar energy, I will describe selected consumer in the following subchapter.

6.2. Consumer load graph

Installed capacity of the Pervopashensk village provided by diesel generator is 150 kW. Then, the reactive power is:

$$Q = P_{\max} \cdot tg(\phi) = 150 \cdot 0.3286 = 49.29\ kVar;$$

where

$tg(\phi)$ – Power factor equals to 0.95 [24]

Typical load graph of the village is obtained from [25].

Next, the value of consumed active power per each hour of the day will be calculated:

$$P_h = k \cdot P_{\max};$$

where

k – typical daily active power coefficient, %; [25]

P_{max} – installed capacity, kW;

$$P_h = 0.25 \cdot 150 = 37.5\ kW;$$

The values of consumed active power per hour during all seasons are given in Table 9.

Table 9 – Consumed active power per hour

Winter			**Spring**			**Summer**			**Autumn**		
hour	**k**	**P_h, kW**	**hour**	**k**	**P_h, kW**	**hour**	**k**	**P_h, kW**	**hour**	**k**	**P_h, kW**
1	0.25	37.5	1	0.25	37.5	1	0.2	30	1	0.25	37.5
2	0.25	37.5	2	0.25	37.5	2	0.2	30	2	0.25	37.5
3	0.25	37.5	3	0.25	37.5	3	0.2	30	3	0.25	37.5
4	0.25	37.5	4	0.25	37.5	4	0.2	30	4	0.25	37.5
5	0.25	37.5	5	0.25	37.5	5	0.25	37.5	5	0.25	37.5
6	0.35	52.5	6	0.35	52.5	6	0.3	45	6	0.35	52.5
7	0.5	75	7	0.45	67.5	7	0.4	60	7	0.45	67.5
8	0.6	90	8	0.5	75	8	0.45	67.5	8	0.55	82.5
9	0.4	60	9	0.4	60	9	0.4	60	9	0.4	60
10	0.3	45	10	0.3	45	10	0.3	45	10	0.3	45
11	0.3	45	11	0.3	45	11	0.3	45	11	0.3	45
12	0.35	52.5	12	0.35	52.5	12	0.3	45	12	0.3	45
13	0.4	60	13	0.4	60	13	0.35	52.5	13	0.35	52.5
14	0.3	45	14	0.3	45	14	0.3	45	14	0.4	60
15	0.3	45	15	0.3	45	15	0.3	45	15	0.3	45
16	0.3	45	16	0.3	45	16	0.3	45	16	0.3	45
17	0.4	60	17	0.3	45	17	0.3	45	17	0.3	45
18	0.7	105	18	0.3	45	18	0.3	45	18	0.4	60
19	1	150	19	0.5	75	19	0.35	52.5	19	0.7	105
20	0.95	142.5	20	0.7	105	20	0.4	60	20	1	150
21	0.7	105	21	1	150	21	0.7	105	21	0.85	127.5
22	0.5	75	22	0.2	30	22	1	150	22	0.6	90
23	0.35	52.5	23	0.5	75	23	0.6	90	23	0.4	60
24	0.3	45	24	0.3	45	24	0.25	37.5	24	0.3	45

According to the Table 9, I will build daily load graphs (Appendix B).

In order to build the annual active power graph, the amount of energy consumed monthly must be calculated [25].

Table 10 – Total daily energy consumption

Season	Winter	Spring	Summer	Autumn
W_T, kWh	1 537.5	1 350	1 297.5	1 470

Calculation of energy consumed in December:

$$W_{Tot} = W_T \cdot k_S \cdot N;$$

where

W_T – total daily energy consumption in December;

k_s – seasonal coefficient;

N – number of days in December.

$$W_{Tot} = 1537.5 \cdot 1 \cdot 31 = 47663 \ kWh.$$

Calculated data for all months is shown in Table 11.

Table 11 – Monthly energy consumption

Month	**k_s**	**N**	**W_{Tot}, kWh**
January	1	31	47 663
February	1	28	43 050
March	0.8	31	33 480
April	0.8	30	32 400
May	0.8	31	33 480
June	0.7	30	27 248
July	0.7	31	28 156
August	0.7	31	28 156
September	0.9	30	39 690
October	0.9	31	41 013
November	0.9	30	39 690
December	1	31	47 663

Energy consumption during wintertime is 1.7 times higher than during the summertime. Based on Table 11, graph for annual load was built and presented on Figure 15.

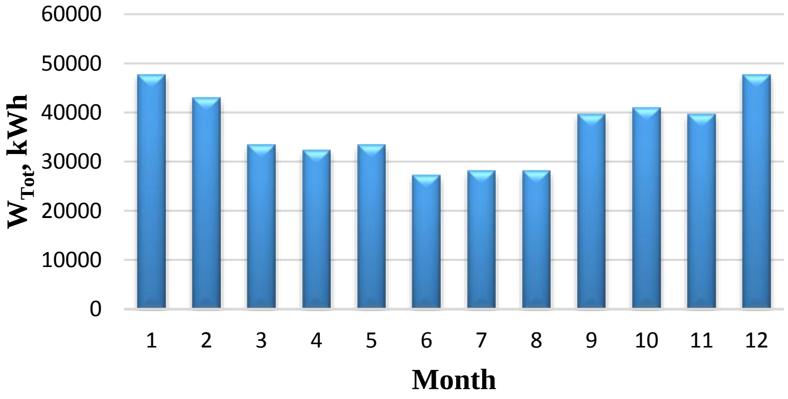


Figure 15 – Annual load graph

From the obtained data, I can make a conclusion that annual energy consumption of the Pervopashensk village is 441 687 kWh.

7. Calculation of autonomous power supply system

In order to create the most effective project of power supply, I will make three models, described different variants of using SPP. In the following subchapters, these models are described in details.

7.1. Model 1

In this model, diesel generators, solar panels and accumulator batteries will implement power supply.

Choice of solar panels

Since solar cells used in the experiment are not produced in the form of panels, I will choose another panel of the same type and efficiency as in experiment. I have chosen panel Risen RSM72-6-335P [26].

Figure 16 – Risen RSM72-6-335P Solar panel

Technical characteristics are represented in the Table 12.

Table 12 – Characteristics of solar panel

Rated power	335 W
Maximum power voltage	38.4 V
Nominal voltage	24 V
Idle voltage	46.5 V
Short-circuit current	9.3 A
Maximum power current	8.75 A
Operating temperature	-40…+85 °C
Dimension	1956 x 992 x 40 mm2
Weight	22 kg
Structure	Polycrystalline

Efficiency	17.2%
Number of cells	72 (6x12) cells
Cost	8 612 RUB

First step in calculation of required number of panels is determination of working area of solar panel. In most panels exist gap between solar cells, so in order to consider this, I subtract 3% from the total area of the module to get the working area for further calculations [17].

$$S_p = 1.956 \cdot 0.992 = 1.940\ m^2;$$

$$S_{pg} = S_p \cdot 0.97 = 1.882\ m^2.$$

Next, when data about consumption (Table 11) and technical parameters of panels are known, I will calculate necessary number of solar panels to cover demand for electricity on the example of April.

Energy produced by 1 solar panel in April:

$$W_{1pan} = S_{pg} \cdot \eta \cdot \delta;$$

where

S_{pg} – working area of solar panel, m^2;

η – efficiency of solar panel;

δ – insolation level in April, kWh/m^2.

$$W_{1pan} = 1.882 \cdot 0.172 \cdot 119 = 39\ kWh.$$

Then, number of panels to cover demand in April is:

$$N = \frac{W_{Tot}}{W_{1pan}};$$

$$N = \frac{32400}{39} = 842;$$

Required number of panels in order to cover demand for another month was calculated in the same manner and presented in Table 13.

Table 13 – Energy balance of SPP

Month	**Energy consumption W_{Tot}, kWh**	**Energy from 1 solar panel W_{1pan}, kWh**	**Required quantity of solar panels, N**	**Energy from 842 solar panels W_{pan}, kWh**	**Shortage/surplus of electricity Ws, kWh**
Jan.	47 663	14	3448	11 638	-36 025
Feb.	43 050	24	1780	20 360	-22 690
Mar.	33 480	34	994	28 346	-5 134
Apr.	32 400	39	842	32 434	34
May	33 480	51	655	43 064	9 584
June	27 248	58	470	49 061	21 813
July	28 156	58	486	48 788	20 632
Aug.	28 156	49	580	40 884	12 728
Sept.	39 690	37	1066	31 344	-8 346
Oct.	41 013	19	2166	15 945	-25 068
Nov.	39 690	11	3738	8 940	-30 750
Dec.	47 663	8	5820	6 896	-40 767
Total	**441 689**				**-168 780/+64791**

After analyzing the data, we can conclude that it is irrational to use the SPP throughout the year. The appropriate solution is to use the SPP in the period from April to August. This requires 842 panels. An annual energy shortage of 168 780 kWh will be covered by diesel generators and accumulator batteries. Surplus of energy will be stored in accumulator batteries and used during autumn period. Diesel generators will cover remaining part of the demand.

Total cost of all solar panels:

$$C_{pan} = 842 \cdot 8612 = 7\ 251\ 304\ \ RUB.$$

Choice of accumulator batteries

Main purpose of using accumulator batteries on solar power plants (SPP) is to store energy and use it in periods of lack of solar energy. In addition, batteries fix the problems connected with electricity generation variability. Most frequently used type of batteries is deep discharge lead acid batteries. These batteries have relatively high number of charge-discharge cycles, which could save significant amount of money on replacement of batteries when their resource is exhausted. In order to reduce charging currents batteries should be connected in series. In order to increase capacity of batteries they should be connected in parallel.

I choose the HGL-2-3000 [27]. Technical characteristics are shown in Table 14. It is also necessary to take into account the fact that to prolong operation life the battery should always retain at least 70% of the charge.

Table 14 – Characteristics of chosen accumulator battery

Voltage	2 V
Capacity	3000 Ah
Type	Lead Acid
Max charging current	600 A
Battery fluid	High purity sulfuric acid
Dimension	710 x 350 x 345 mm
Weight	190 kg
Cost	109 565 RUB
Life time	20 years
Number of cycles	2200 cycles at 30% depth of discharge

In this model, generation of electricity during operating months is 64 791 kWh. Besides the generation is not covered by the demand. So in order to calculate required amount of batteries we must take into account the large amount of energy required for storage.

Figure 17 – HGL-2-3000 accumulator battery [27]

To decrease charge current, we need to connect 24 batteries consequently. As a result, voltage of batteries is 48 V.

Necessary capacity of batteries according to demand is:

$$C_{nec} = \frac{W}{U_B \cdot k_d};$$

where

W – total energy surplus;

U_B – voltage of the battery;

k_d – load coefficient;

$$C_{nec} = \frac{64\,791}{2 \cdot 0.7} = 46\,280\,kAh;$$

Then, required amount of batteries is to be found:

$$N = \frac{46\,280 \cdot 10^3}{3000} = 15\,427;$$

To decrease charge current, we need to connect 24 batteries consequently. As a result, voltage of batteries is 48 V.

Total cost of all solar panels:

$$C_{battot} = 15\ 427 \cdot 109\ 565 = 1\ 690\ 368\ \ 820\ \text{RUB}.$$

This model, when during operating time from April to August we do not consume surplus energy from previous month but only store it in batteries, is ineffective because of enormous high quantity of batteries and its price, what will be proved when effective model will be made. That is why I will not make economical evaluation for this model and will make another model.

7.2. Model 2

In this model, surplus of energy produced in each month will be used for covering demand in the following month. Type of solar panels and accumulator batteries is the same with model 1. Then, total energy balance in shown in Table 15:

Table 15 – Energy balance of SPP (Model 2)

Month	**Energy consumption W_{Tot}, kWh**	**Energy from 1 solar panel W_{1pan}, kWh**	**Required quantity of solar panels, N**	**Energy from 842 solar panels W_{pan}, kWh**	**Shortage/surplus of electricity Ws, kWh**
Jan.	47 663	14	3448	11 638	-36 025
Feb.	43 050	24	1780	20 360	-22 690

Month	Energy consumption W_{Tot}, kWh	Energy from 1 solar panel W_{1pan}, kWh	Required quantity of solar panels, N	Energy from 842 solar panels W_{pan}, kWh	Shortage/surplus of electricity Ws, kWh
Mar.	33 480	34	994	28 346	-5 134
Apr.	32 400	39	842	32 434	34
May	33 480	51	655	43 064	9 550
June	27 248	58	470	49 061	12 263
July	28 156	58	486	48 788	8 369
Aug.	28 156	49	580	40 884	4 359
Sept.	39 690	37	1066	31 344	-8 346
Oct.	41 013	19	2166	15 945	-25 068
Nov.	39 690	11	3738	8 940	-30 750
Dec.	47 663	8	5820	6 896	-40 767
Total	**441 689**				**-168 780/+34541**

Here number of panels and operating time is the same with model 1 and total surplus of generated electricity is 34 541 kWh, that is two times lower than in previous case.

The second big difference between first and second models is the fact, that there is no need to store total energy surplus, what is significantly decrease number of batteries.

Calculation of required number of batteries will be based on the biggest value of energy surplus in June.

Capacity of the accumulator battery according to demand:

$$C_{nec} = \frac{W}{U_B \cdot k_d};$$

Where,

W – energy surplus in June;

U_B – voltage of the battery;

k_d – load coefficient;

$$C_{nec} = \frac{12\,263}{2 \cdot 0.7} = 8\,760\,kAh;$$

Then, required amount of accumulator batteries is to be found:

$$N = \frac{8\,760 \cdot 10^3}{3000} = 2920;$$

To decrease charge current, we need to connect 24 batteries consequently. As a result, voltage of batteries is 48 V.

Total cost of all accumulator batteries:

$$C_{battot} = 2920 \cdot 109565 = 319\ 929\ 800\ \text{ RUB.}$$

Despite of the fact that total price of accumulator batteries in this model is more than 5 times less, it is still very big number, which automatically make this project ineffective, what will be proved on the example of the following model.

7.3. Model 3

In order to obtain maximum efficiency from the economical point of view, I will design SPP for the month with maximum insolation level. Type of solar panels and accumulator batteries will be the same as in the two previous models.

Necessary amount of solar panels in June was calculated based on demand and shown in Table 16 and Table 17.

Table 16 – Energy balance of SPP with 470 panels (Model 3)

Month	**Energy consumption W_{Tot}, kWh**	**Energy from 1 solar panel W_{1pan}, kWh**	**Number of panels, N**	**Energy produced by solar panels W_{pan}, kWh**	**Shortage/surplus of electricity Ws, kWh**
Jan.	47 663	14	470	6 580	-41 083
Feb.	43 050	24	470	11 280	-31 770
Mar.	33 480	34	470	15 980	-17 500
Apr.	32 400	39	470	18 330	-14 070
May	33 480	51	470	23 970	-9 510
June	27 248	58	470	27 260	12
July	28 156	58	470	27 260	-896
Aug.	28 156	49	470	23 030	-5 126
Sept.	39 690	37	470	17 390	-22 300
Oct.	41 013	19	470	8 930	-32 083
Nov.	39 690	11	470	5 170	-34 520
Dec.	47 663	8	470	3 760	-43 903
Total	**441 689**				

In order to install solar panels in blocks, I need 10 panels extra. Therefore, there will be 6 block of panels. Each block consist of 8 parallel branches with 10 panels in each branch. Then new energy balance is:

Table 17 – Energy balance of SPP with 480 panels (Model 3)

Month	**Energy consumption W_{Tot}, kWh**	**Energy from 1 solar panel W_{1pan}, kWh**	**Number of panels, N**	**Energy produced by solar panels W_{pan}, kWh**	**Shortage/surplus of electricity Ws, kWh**
Jan.	47 663	14	480	6 720	-40 943
Feb.	43 050	24	480	11 520	-31 530
Mar.	33 480	34	480	16 320	-17 160
Apr.	32 400	39	480	18 720	-13 680
May	33 480	51	480	24 480	-9 000
June	27 248	58	480	27 840	592
July	28 156	58	480	27 840	-316
Aug.	28 156	49	480	23 520	-4 636
Sept.	39 690	37	480	17 760	-21 930
Oct.	41 013	19	480	9 120	-31 893
Nov.	39 690	11	480	5 280	-34 410
Dec.	47 663	8	480	3 840	-43 823
Total	**441 689**			**192 960**	

Total cost of all solar panels:

$$C_{pan} = 480 \cdot 8612 = 4\ 133\ 760\ \ RUB.$$

Capacity of the battery according to demand:

$$C_{nec} = \frac{W_{daily}}{U_B \cdot k_d};$$

where

W – average daily consumption in June;

U_B – voltage of the battery;

k_d – load coefficient;

$$C_{nec} = \frac{908}{2 \cdot 0.7} = 649\, kAh;$$

Then, required amount of batteries is:

$$N = \frac{649 \cdot 10^3}{3000} = 217;$$

To decrease charge current, we need to connect 24 batteries consequently. As a result, voltage of batteries is 48 V.

Total cost of all accumulator batteries:

$$C_{battot} = 217 \cdot 109565 = 23\ 775\ 605\ \text{RUB.}$$

This model seems to be effective because of adequate number of batteries and their prices. For this model, financial calculations will be made. In order to do it, I need to choose required equipment: controllers and invertors.

Choice of controllers

A charge controller or charge regulator is a voltage and/or current regulator to keep batteries from overcharging. It regulates the voltage and current coming from the solar panels going to the battery. Most 12 volt panels put out is about 16 to 20 volts, so if there is no regulation the batteries will be damaged from overcharging. Most batteries need around 14 volts to get fully charged.

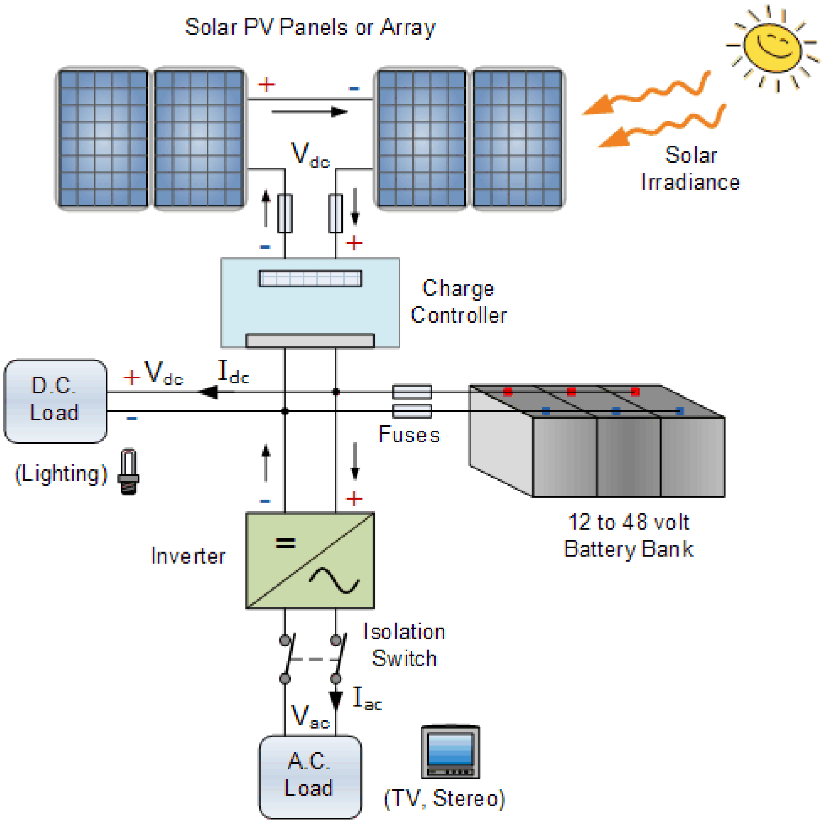


Figure 18 – Simplified PV System [28]

There are two main criteria of choosing controller [29]:

1) Input voltage. Maximum input voltage should be not higher than 20% of idle voltage of solar panels.

$$U_{contr} = U_{PVidle} \cdot 1.2;$$

where

U_{PVidle} – Idle voltage of solar panel according to Table 12.

$$U_{contr} = 46.5 \cdot 1.2 = 55.8\ V.$$

2) Nominal current of controller should be 10% higher than idle current of solar panels.

According to the law of Ohm, power is equal to the product of voltage per current. Then, we can find nominal current of solar panel:

$$I_{nom.PV} = \frac{P_{nom.PV}}{U_{nom.PV}} = \frac{335}{38.4} = 8.72\ A.$$

The controller Conext XW MPPT 80-600 fulfills necessary technical parameters. Its price is 102 461 RUB [30].

Controllers' idle voltage is 600 V. Thus, we can find number of consequently connected PV panels:

$$N = \frac{U_{idle.cont.}}{U_{PVidle}} = \frac{600}{46.5} \approx 12.$$

where

$U_{idle.cont.}$ – Idle voltage of the controller;

That means we can consequently connect 12 solar panels. Then, voltage in this branch will be:

$$U(12)_{PV} = 12 \cdot U_{nom.PV} = 12 \cdot 24 = 288\ V;$$

where

$U_{nom.PV}$ – Nominal voltage of solar panel.

Power of controller is 4800 W. Then, we can calculate number of parallel branches to which we can connect controller:

$$N_{PV(3)} = \frac{P_{\max.}}{U(12)_{PV} \cdot I_{nom.PV}} = \frac{4800}{288 \cdot 8.72} = 1.9 \approx 1.$$

Hereby, SPP will be consist of 4 blocks of 10 parallel branches with 12 solar panels in each. Required number of controllers is 40.

Figure 19 – Conext XW MPPT 80-600 Controller [30]

Total cost for controllers:

$$C_{cont} = 40 \cdot 102\ 461 = 4\ 098\ \ 440\ \text{ RUB.}$$

Choice of inverters

Inverters play a crucial role in any solar energy system and are often considered to be the brains of a project, whether it’s a 2-kW residential system or a 5-MW utility power plant. An inverter’s basic function is to “invert” the direct current (DC) output into alternating current (AC). AC is the standard used by all commercial appliances, that is why inverters are considered as the “gateway” between the photovoltaic (PV) system and the consumer.

Invertor is chosen according to voltage of controller (48 V) and total power of the system. Its type is SAJ SunTrio Plus 60K [31]. Its price is 236 147 RUB.

Figure 20 – SAJ SunTrio Plus 60K invertor [31]

Finally, when all necessary equipment has been chosen, it is possible to evaluate the project from the economical point of view. Table 18 represents total amount of money for purchasing equipment based on price per 1 piece of equipment from the sources mentioned when choosing equipment.

Table 18 – Chosen equipment and its price

Equipment	Quantity	Price, RUB
Solar panels	480	4 133 760
Accumulator batteries	217	23 775 605
Controllers	40	4 098 440
Inverter	1	236 147

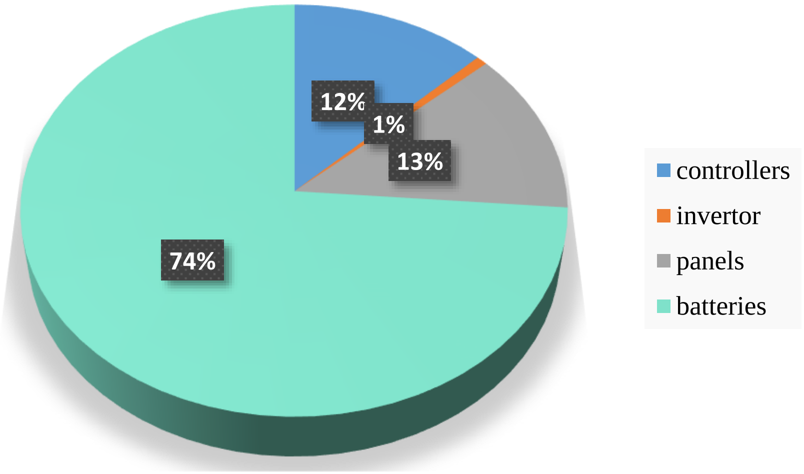


Figure 21 – Shares of equipment cost in total investments

Fuel economy

In Model 3, PV panels cover part of electricity demand, remaining part is covered by diesel generator. In this subchapter, I will investigate how much fuel was saved. I will do it in two steps. First is when diesel generators work without solar panels. Second is collaboration of diesel generators and PV panels.

Fuel consumption was calculated according to technical characteristics [32] and following formula [33]:

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

where

$g_{gen.nom}$ – specific fuel consumption of generator under nominal load, kg / kWh;

η_g – efficiency of generator, %.

$$g_{gen} = \frac{0.214}{0.906} = 0.2362 \ kg / kWh;$$

Then, mass of fuel for generating required amount of energy will be found according to [33]:

$$G = g_{gen} \cdot K_{dep} \cdot K_{\mathrm{mod}e} \cdot P_{gen};$$

where

K_{dep} – depreciation coefficient;

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

K_{mode} – mode ratio.

Mode ratio according to [34] is equal to:

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

where

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

When required amount of power is 37.5 kW (Table 9), generator is produced 37.5 kW of power. Then, required amount of fuel to produce this amount of energy is:

$$G = 0.2362 \cdot 1 \cdot (0{,}87 + 0{,}13 \cdot \frac{75}{37.5}) \cdot 37.5 = 10.0091 \ kg$$

Analogically I will calculate amount of fuel for power supply of Pervopashensk village when only diesel generators work. Results are presented in following table and more detailed results are in Appendix D.

Table 19 – Seasonal and annual fuel consumption

Season	**Fuel consumption G, kg**
Winter	34 446
Spring	31 031
Summer	30 251
Autumn	33 567
Total	**129 295**

After solar panels are installed, they cover part of electricity demand. In this case generation and fuel consumption of generators reduced. According to Table 17, I will calculate economy of fuel after installing of PV panels. Results are summarized in following table:

Table 20 – Fuel economy

Month	**Energy consumption W_{Tot}, kWh**	**Energy produced by solar panels W_{pan}, kWh**	**Fuel consumption without panels, kg**	**Fuel consumption with panels, kg**	**Fuel economy, kg**
Jan.	47 663	6 720	11 865	10 192	1 673
Feb.	43 050	11 520	10 717	7 849	2 868
Mar.	33 480	16 320	10 456	5 359	5 097
Apr.	32 400	18 720	10 119	4 272	5 846
May	33 480	24 480	10 456	2 811	7 645
June	27 248	27 840	9 864	0	9 864
July	28 156	27 840	10 193	114	10 079
Aug.	28 156	23 520	10 193	1 678	8 515
Sept.	39 690	17 760	11 066	6 114	4 952
Oct.	41 013	9 120	11 435	8 892	2 543
Nov.	39 690	5 280	11 066	9 594	1 472
Dec.	47 663	3 840	11 865	10 909	956
Total	**441 689**	**192 960**	**129 295**	**67 786**	**61 510**

Price for the fuel according to [35] is 46 RUB per liter. After converting kg in liters, I obtain 73 226 liters of fuel economy annually.

$$C_{fuel} = 73\ 226 \cdot 46 = 3\ 368\ 396\ \ RUB.$$

Hence, fuel economy excluding the cost of transportation is 3 368 396 RUB after installing SPP.

8. Financial analysis

For evaluating investment efficiency of the project, there are several basic criteria exist: Net present value (NPV), Internal Rate of return (IRR), Profitability index (PI), Payback period (PP). In the following subchapter I will describe them in details.

8.1. Investment criteria

Net present value (NPV)

Net present value (NPV) is the difference between the present value of cash inflows and outflows over a period of time. NPV is used in investment planning to analyze the profitability of a project [36].

Formula for NPV calculation [36]:

$$NPV = -INV + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$

where

INV – total initial investment;

C_t – net cash inflow during the period t;

r – discount rate;

t – period of time;

T – lifetime.

The project is considered unprofitable if NPV is less than 0.

Internal Rate of return (IRR)

The internal rate of return is defined as the rate of discount at which a project would have zero NPV [36]. Higher IRR is better.

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

where

C_0 – total initial investment costs;

C_t – net cash inflow during the period of time t;

t – period of time.

T – lifetime.

The IRR rule states that companies should accept any investment offering an IRR in excess of the opportunity cost of capital [36].

Profitability index

Profitability index is the value, which shows the cost of net present value per one dollar of the initial outlay.

$$PI = \frac{\sum_{t=1}^{T} DCF_t (1+r)^t}{INV}$$

where

DCF - discounted cash flow;

INV - investments;

r - discount rate;

t - period of time.

When profitability index more than one, the project is effective from point of view of investments.

Payback period

Payback period is a period when cumulative cash inflow is equal to the initial investments.

According to written above payback period can be found by the following formula:

$$(C_t - C_0)_1 + ... + (C_t - C_0)_T = \sum_{t=1}^{T} (C_t - C_0) \geq C_0$$

where

C_0 – cash outflow;

C_t – cash inflow.

8.2. Economic analysis of Model 3

Inflation

Inflation is a quantitative measure of the rate at which the average price level of a basket of selected goods and services in an economy increases over a period of time [37]. As a rule, inflation rate is different for different field of economy. For my model, inflation rate is equal to 5.3% [38].

Tax rate

The case under consideration is a non-taxable state project.

Depreciation

Depreciation is an accounting method of allocating the cost of a tangible asset over its useful life and is used to account for declines in value [39].

There are two main types of depreciation:

1. Straight-line depreciation
2. Accelerated depreciation

Straight-line depreciation is the simplest type and it is calculated with the following formula:

$$D = \frac{INV - RV}{T};$$

where

INV – investment;

RV – residual value;

T – lifetime.

The essence of Accelerated depreciation is in paying more in the beginning of the project with further decreasing of payment. There are two methods of accelerated depreciation:

- Double Declining Balance (DDN)
- Sum-of-years-digits (SYD)

Double Declining Balance calculated by the following formula:

$$D = \frac{2}{T} \cdot (INV - Acc.Depr)$$

where

INV – investment;

$Acc.Depr$ – accelerated depreciation;

T – lifetime.

Sum-of-years-digits calculated by the following formula:

$$D = (INV - RV) \cdot \frac{\tau}{SYD}$$

where

INV – investment;

RV – residual value;

SYD – sum of years digits;

τ – remaining useful life.

In my model, I will use straight-line depreciation method.

Discount rate

Discount rate is the rate that is used for reevaluating of future value to present value.

As the considered case is a governmental project, discount rate will be calculated according to [40].

Discount rate:

$$d = d_i + \frac{P}{100};$$

where

d_i – risk-free discount rate;

$\frac{P}{100}$ – risk adjustment = 5%.

Then, risk-free discount rate is calculated according to formula:

$$d_i = \frac{1 + \frac{r}{100}}{1 + \frac{i}{100}} - 1;$$

where

r – refinancing rate 8.8%; [38]

i – inflation rate.

$$d_i = \frac{1 + \frac{8.8}{100}}{1 + \frac{5.3}{100}} - 1 = 3.3\ \%.$$

Then, final value of discount rate:

$$d = 3.3 + 5 = 8{,}3\ \%.$$

Suchwise, all data needed for financial modeling is presented in Table 21.

Table 21 – Data for financial modeling

Total investment	32 243 952 RUB
Panels and batteries lifetime	20 years
Inverters and controllers lifetime	10 years
Discount rate	8.3%
Inflation rate	5.3%
Operation costs	5% of investment annually (1 612 198 RUB)
Current price for electricity	34.72 RUB/kWh
Tax	0%

8.3. Financial evaluation of the Model 3

NPV

My assumption about price of energy sold to consumer based on reducing its value in comparison with existed 34.72 RUB/kWh [23]. So it was arbitrary chosen as 25 RUB/kWh. This will be discussed in more detail during sensitivity analysis.

In this case NPV of the project is 9 054 070 RUB. It means that project is effective.

IRR

NPV is equal to 0 when discount rate is equal to 11.2%, than means IRR is equal 11.2%. Value of IRR higher than discount rate, so the project is effective.

Profitability index

Total cash flow divided by NPV:

$$PI = \frac{102\ 732\ 361}{39\ 143\ 221} = 2.6$$

Value of profitability index higher than 1 gives reason to believe that the project is effective.

Payback period

The project will pay off after 8.59 years. It is more than half less than project operating time, so it is one more effectiveness indicator.

8.4. Sensitivity analysis of Model 3

Sensitivity analysis is a method of evaluating the influence of input parameters of the model on its NPV [41].

I will describe influence of the following parameters:

- Discount rate
- Inflation rate
- Price of electricity
- Operation costs

Influence of discount rate

Analysis was applied in Excel. Researched range of discount rate is from 1% to 12%.

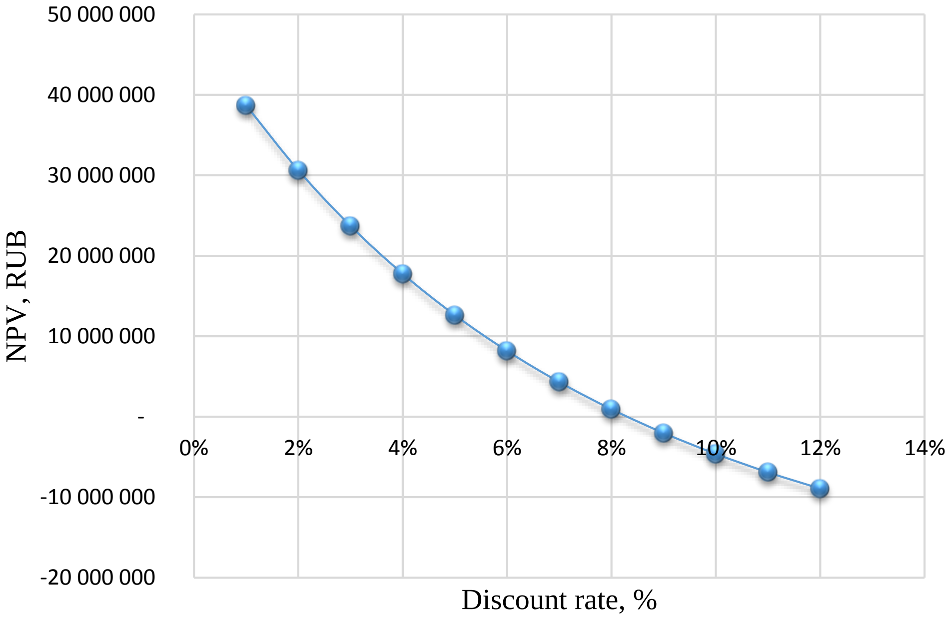


Figure 22 – Influence of discount rate on NPV

Data used is shown in Table 22:

Table 22 – Influence of discount rate on NPV

Discount rate, %	NPV, RUB
8.3	9 054 070
1	57 162 132

Discount rate, %	NPV, RUB
2	47 148 670
3	38 558 608
4	31 163 556
5	24 774 825
6	19 236 082
7	14 417 442
8	10 210 697
9	6 525 448
10	3 285 972
11	428 665
12	-2 100 038

From the obtained results, we can make a conclusion that with increasing of discount rate, NPV is decreasing. Intersection of the NPV line with discount rate axis is IRR of the project with the value of 11.2%. After reaching this value, NPV becomes negative.

Influence of inflation

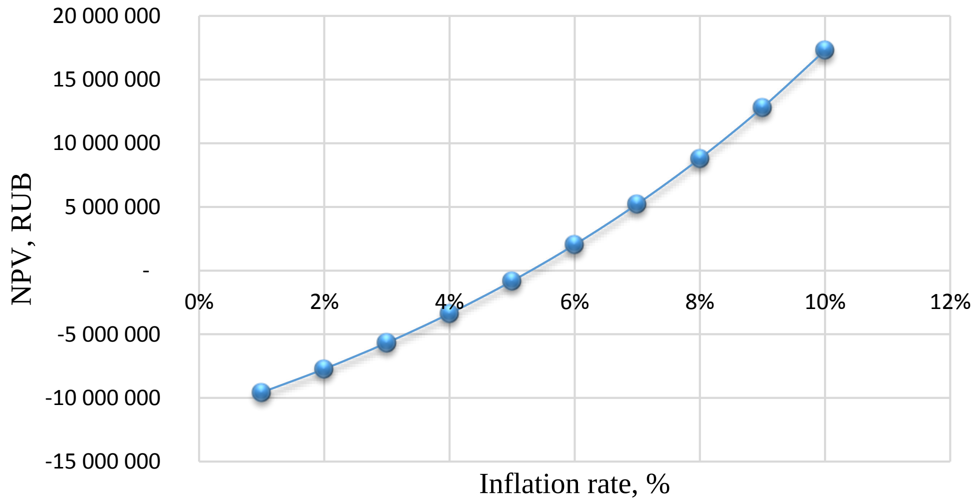


Figure 23 – Influence of inflation on NPV

Data used is shown in Table 23:

Table 23 – Influence of inflation on NPV

Inflation rate, %	NPV
5.3	9 054 070
1	-2 891 063
2	-584 937

Inflation rate	NPV
3	1 980 801
4	4 839 105
5	8 027 191
6	11 587 074
7	15 566 172
8	20 017 979
9	25 002 822
10	30 588 707

Obtain results show that with increasing of inflation rate, NPV is also increases. Value of inflation necessary to make project ineffective is less than 3%.

Influence of selling price

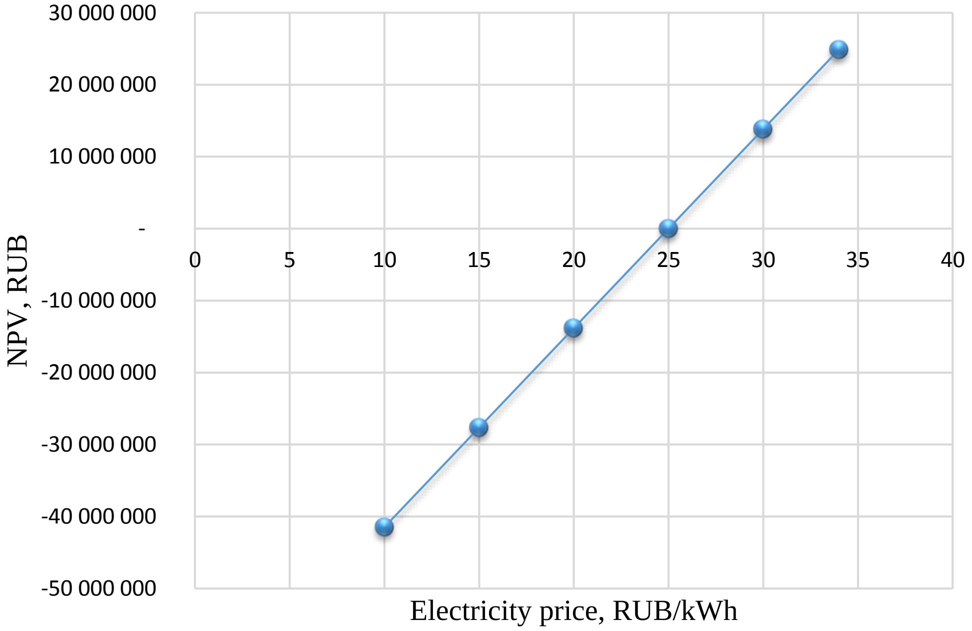


Figure 24 – Influence of electricity price on NPV

Graph was built based on Table 24:

Table 24 – Influence of electricity price on NPV

Electricity price, RUB	NPV
25	9 054 070
10	-32 416 698
15	-18 593 109

Price, RUB	NPV
20	-4 769 519
25	9 054 070
30	22 877 659
34	33 936 530

Higher price of generated electricity provides higher revenue and higher revenue means higher NPV. Minimal price which results in NPV equal to 0 is 21.73 RUB/kWh.

Influence of operational costs

Since value of 5% from investments was chosen arbitrary it is necessary to investigate project’s behavior in case of changes of operational costs.

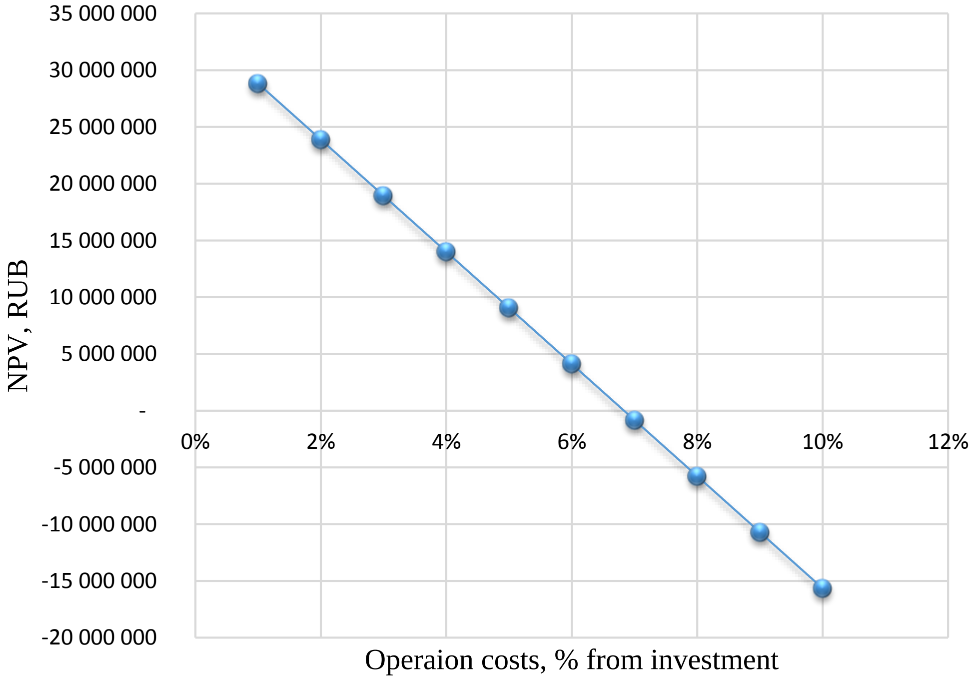


Figure 25 – Influence of operational costs on NPV

Graph was built based on Table 25:

Table 25 – Influence of operational costs on NPV

Operational costs, % from investments	NPV
5	9 054 070
1	28 823 394
2	23 881 063
3	18 938 732
4	13 996 401

Operational costs, % from investments	NPV
5	9 054 070
6	4 111 739
7	-830 593
8	-5 772 924
9	-10 715 255

Maximum value of operational costs at which project is effective is 2 202 888 RUB annually what is equal to 6.83% from investments.

Conclusion

The aim of my Master's thesis is to evaluate effectiveness of solar panels in real work conditions. The goal was achieved in three phases.

In the first phase, I calculated and built hand-made solar panel. It consist of soldered polycrystalline solar cells, supporting structure and block of resistors to change the load. Using multimeter, I conducted an experiment. Values of voltage and current under different values of load were obtained. Form of VAC graph of my model is correspond to standard form of solar panels VAC. After obtaining experimental data, I used two different data types in order to evaluate efficiency of the panel. First was methodology described in [17]. Second is data from NASA. In the end of this phase, I calculated efficiency of created panel. It differs from the manufacturer's stated 17% by 4% (obtained value of efficiency is 13%). Main reasons of decreasing of efficiency are dirt on a surface of solar cells and manual soldering of cells. If presented type of Aiyima solar cells will be assembled into the solar panel in conditions of enterprise (without dirt and soldering made by robots), efficiency of this panel will be close to efficiency declared by manufacturer of solar cells. One of my goals was achieved, I compared data provided by manufacturer of Aiyima solar cells with data obtained in real conditions. Next step is to estimate effectiveness of using solar panels in Siberia.

In the second phase, I decided to design power supply system for decentralized village of Pervopashensk in Tomsk region. Village is supplied by two diesel generators. The goal was to design SPP and check its effectiveness from technical and economic point of view. As solar cells presented in previous chapter are not available as a solar panel, for design of power supply system I used another solar panels with similar characteristics. Using typical load graphs, I calculated annual energy demand of the village. Then, after choosing necessary type and quantity of SPP equipment, I described three different ways of power supplying. Idea of the first was to install necessary quantity of solar panel in order to supply village from April until August. Energy surplus was assumed to store in accumulator batteries and to use this energy after August. Unfortunately, amount of batteries was too high (15 427). Total price of this batteries is 1 690 368 820 rubles. Economical ineffectiveness of this project will be clear after analyzing third presented model. Idea of second model was almost the same as the first, but here surplus of energy will not be stored in batteries, but it will be used to cover demand in the following month. However, surplus of energy is still higher than demand because in this period of time highest insolation and lowest energy demand in the whole year. So accumulator batteries are used for storing remaining surplus. Amount of batteries in this model is over five times less than in first model, but still it is very big number and project is ineffective from investment point of view. That is why third model was created. Idea of the third model is in using SPP only in month with highest insolation level (June). Calculated amount of panels and batteries for June is more close to reality than in the first two models. That is why this model was chosen for economic analysis.

Third phase of Master's thesis is about economic effectiveness of the project. During this phase, I calculated basic criteria of effectiveness, such as NPV, IRR, IP, PP for Model 3. All criteria showed that project is cost effective. In addition, sensitivity analysis was applied in order to evaluate influence of input parameters on the project. Hence, Model 3 showed technical and economic effectiveness.

To sum up, using energy of the Sun for power supplying of objects in condition of Siberia could be effective if there is centralized power grid. Because in this case surplus of energy could be sold into the grid. However, for decentralized objects in conditions of north, like in my case, using of SPP economically effective only in case of short period of time during the year.

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Appendices

Appendix A

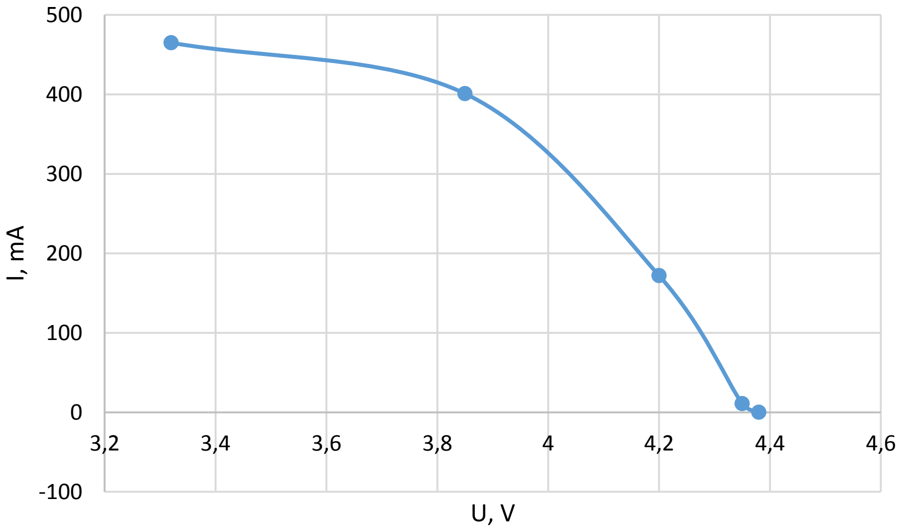

Figure 1A – VAC with tilt angle β of 1.98°

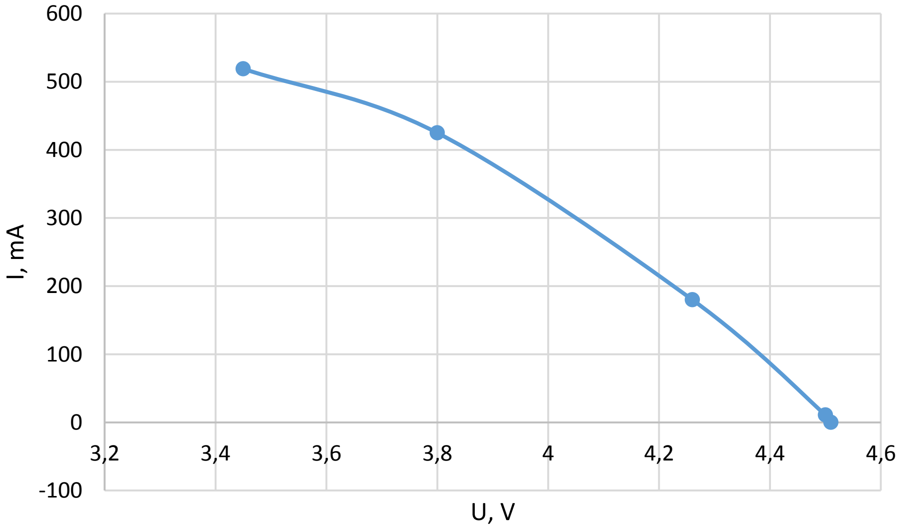

Figure 2A – VAC with tilt angle β of 8.97°

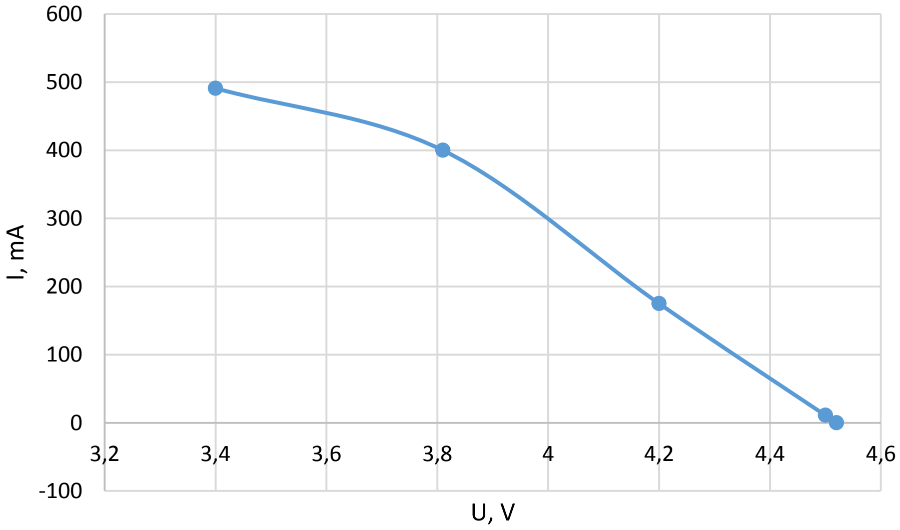

Figure 3A – VAC with tilt angle β of 14.77°

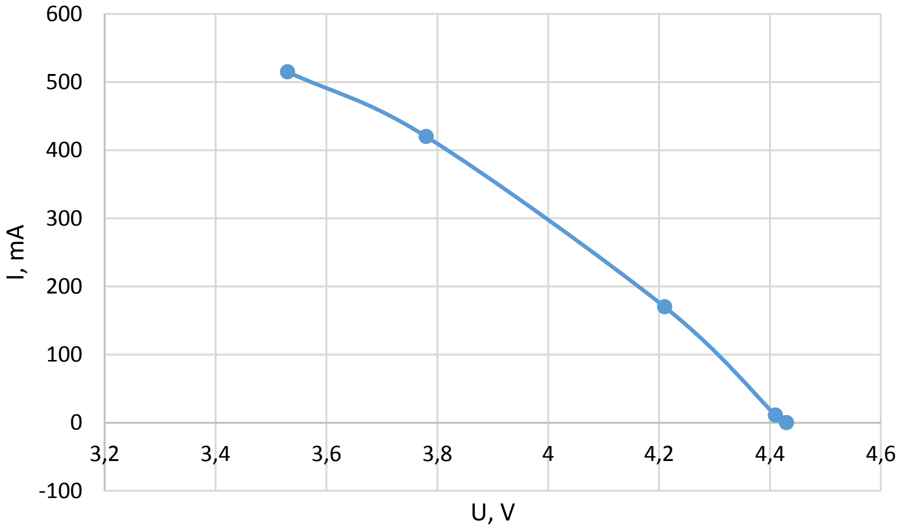

Figure 4A – VAC with tilt angle β of 18.8°

Appendix B

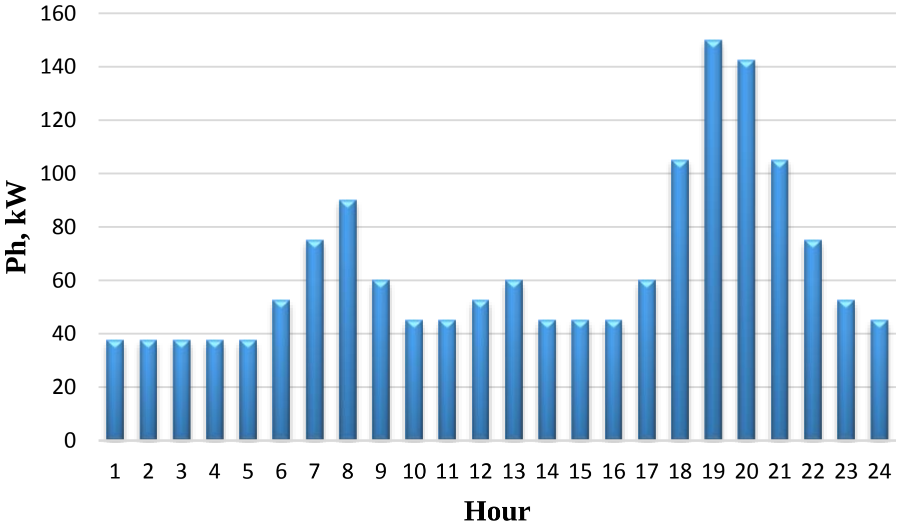

Figure 1B – Daily load graph for winter

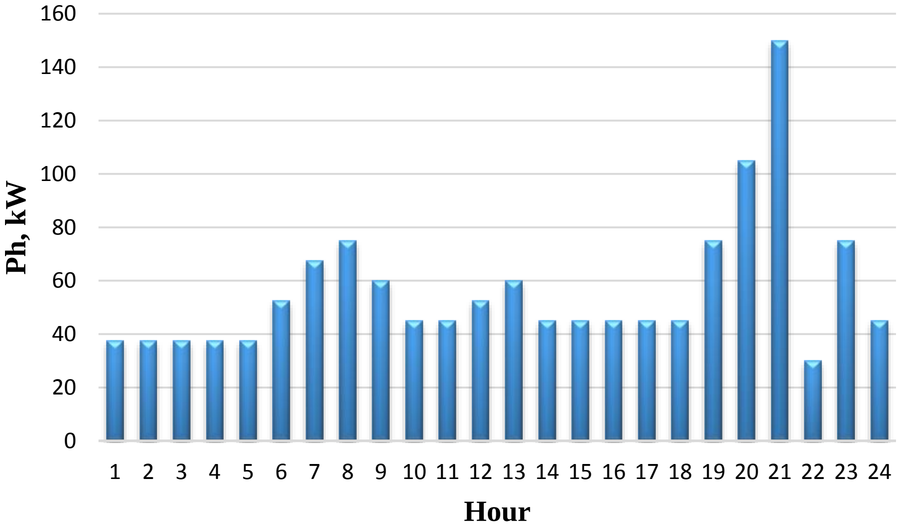

Figure 2B – Daily load graph for spring

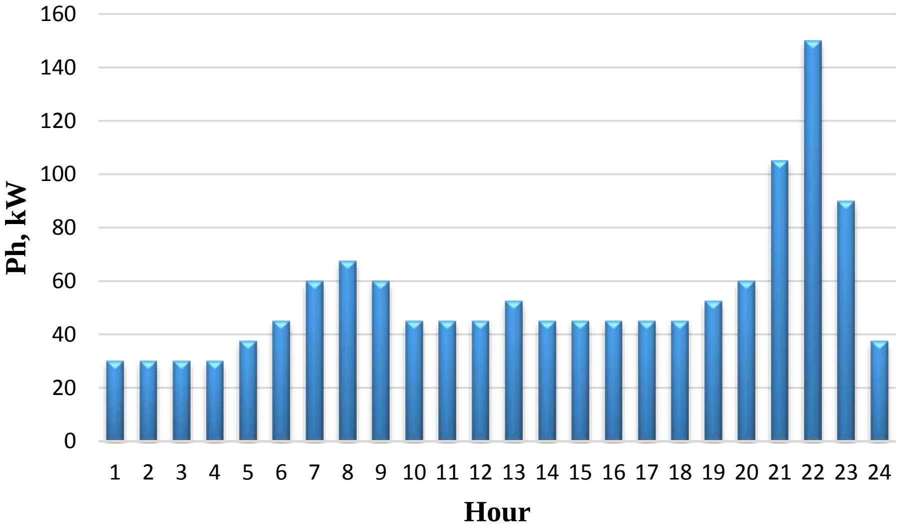

Figure 3B – Daily load graph for summer

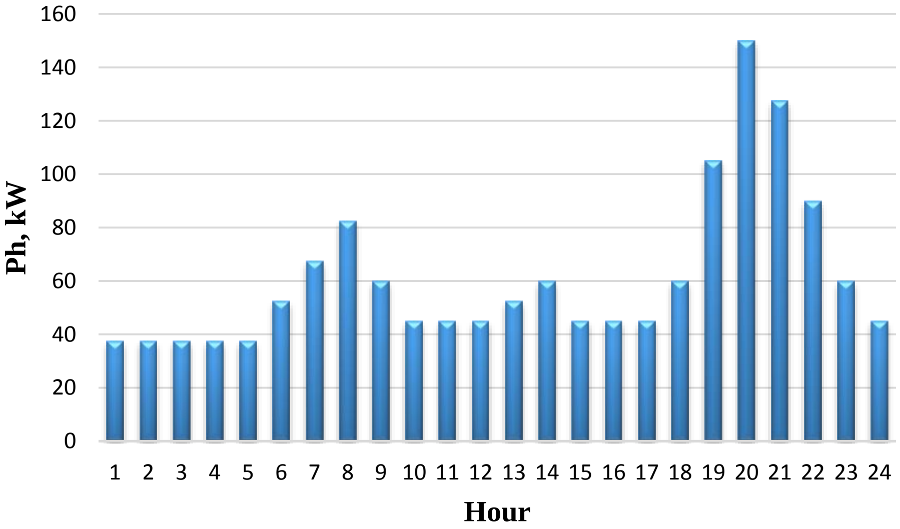

Figure 4B – Daily load graph for autumn

Appendix C

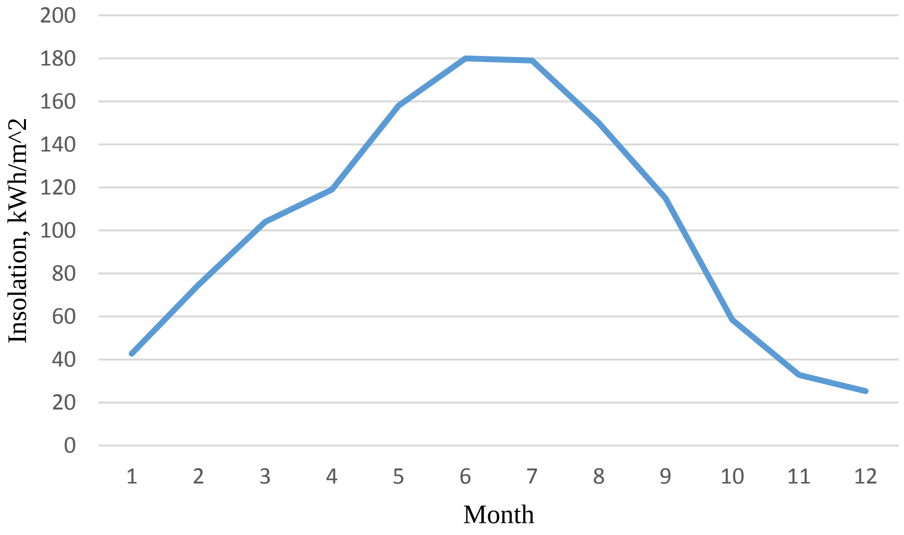

Figure 1C – Monthly insolation in Tomsk region

Appendix D

	Winter	Spring	Summer	Autumn
Hour	G, kg	G, kg	G, kg	G, kg
1	10.0	10.0	8.5	10.0
2	10.0	10.0	8.5	10.0
3	10.0	10.0	8.5	10.0
4	10.0	10.0	8.5	10.0
5	10.0	10.0	10.0	10.0
6	13.1	13.1	11.6	13.1
7	17.7	16.2	14.6	16.2
8	23.1	17.7	16.2	21.6
9	14.6	14.6	14.6	14.6
10	11.6	11.6	11.6	11.6
11	11.6	11.6	11.6	11.6
12	13.1	13.1	11.6	11.6
13	14.6	14.6	13.1	13.1
14	11.6	11.6	11.6	14.6
15	11.6	11.6	11.6	11.6
16	11.6	11.6	11.6	11.6
17	14.6	11.6	11.6	11.6
18	26.2	11.6	11.6	14.6
19	35.4	17.7	13.1	26.2
20	33.9	26.2	14.6	35.4
21	26.2	35.4	26.2	30.8
22	17.7	8.5	35.4	23.1
23	13.1	17.7	23.1	14.6
24	11.6	11.6	10.0	11.6

Table 1D – Fuel consumption of diesel generators