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

Decentralized electricity supplies of village behind the polar circle

Master's thesis

Study program: Electrical engineering, power engineering and management

Field of study: Economy and management of power engineering

Scientific advisor: Ing. Julius Bemš, PhD

Bc. Alena Surovezhko

Prague 2018

ČVUT ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Fakulta/ústav: **Fakulta elektrotechnická**

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

Studijní program: **Elektrotechnika, energetika a management**

Studijní obor: **Ekonomika a řízení energetiky**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Decentralized electricity supplies of village behind the polar circle.

Název diplomové práce anglicky:

Decentralized electricity supplies of village behind the polar circle.

Pokyny pro vypracování:

Describe technical background of possible technologies.
Design the decentralized electric supply in remote area.
Prepare financial model for project evaluation.
Compare possible project scenarios and provide sensitivity analysis.

Seznam doporučené literatury:

Subhes C. - Energy Economics: Concepts, Issues, Markets and Governance, Springer, 2011, ISBN: 0857292676.
R. A. Brealey, S. C. Myers, and F. Allen, Principles of Corporate Finance, 10th ed. McGraw-Hill/Irwin, 2010.
Vissarionov V.I., Deryugina G.V., Kuznetsova V.A., Solar Power Engineering: Book for Higher Educational Institutions / Ed. by V.I.Vissarionov -M.: Publishing house MPEI, 2008. - 320p.

Jméno a pracoviště vedoucí(ho) diplomové práce:

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

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Datum převzetí zadání	Podpis studentky

Topic registration form

Student: Alena Surovezhko

Study program: Electrical engineering, power engineering and management

Topic: Decentralized electricity supplies of village behind the polar circle.

Guidelines:

- Describe technical background of possible technologies
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Literature for registration:

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3. R. A. Brealey, S. C. Myers, and F. Allen, Principles of Corporate Finance, 10th ed. McGraw-Hill/Irwin, 2010.

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”.

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Abstract

Nowadays scientists more and more talk about the shortage of hydrocarbons. And possible solution of this problem is using of alternative energy sources, since the lack of natural resources will inevitably lead to gradual increasing in energy prices. Moreover, in Russia remote areas without central power supply take about 70% of the country's territory with a population of up to 23 million people, where only diesel generators with using fuel are operated. In this case applying of alternative energy sources can be solution of the problem with lack of central power supply and with fuel savings.

The key factor in this work is the problem of object's power supply, which is remote from central power supply and which is located close to polar circle, where Midnight Sun presents. It can be solved using solar energy.

To achieve the goal of remote object power supplying, it is necessary to solve the following tasks:

- Calculate solar radiation of that are;

- Choose necessary equipment for photovoltaic power plant;

- Design of schematic diagram of the photovoltaic power plant;

- Estimate economic efficiency of solar energy sources implementation.

The results obtained in the project can be used to solve the similar tasks of remote objects power supply.

Key words

Renewable energy sources, photovoltaic power plant, polar circle, Midnight Sun, remote area, fuel savings.

Contents

List of abbreviations

DPP – Diesel Power Plant

DG – Diesel generator

USSR - Union of Soviet Socialist Republics

PVP - Photovoltaic panels

DC – Direct current

AC – Alternative current

SP – Solar panel

SC – Solar controller

ACB - Accumulator battery

I – Inverter

L – Load

C - Controller

AGM - Absorbent Glass Mat

NPV - Net Present Value

IRR - Internal Rate of Return

PI – Profitability Index

PP – Payback Period

Introduction

Nowadays in Russia remote areas without central power supply take about 70% of the country's territory with a population of up to 23 million people, where only diesel generators with using fuel are operated. And delivery of fuel to these remote areas is quite complicated, because rail roads are absent somewhere and usual roads can be not available because of snowpack. In this case, the fuel can be delivered only by helicopter that in turn has big influence on the final price of fuel. In addition, there is an increase in the tariffs of energy supply companies. Therefore the price for 1 kWh is about 100 RUB in remote areas, when the price in regular areas is about 4 RUB per 1 kWh now. Moreover, there are some risks, which also have influence on electricity power supply. It is fuel delivery and fuel discharge, because the weather is unpredictable on Far North. So, the use of alternative energy sources, especially solar energy can be a solution of this problem.

In this diploma thesis attention is focused on solar energy, in case of climatic feature of that area - the presence of a Midnight sun. The midnight sun lasts from 9^{th} of May to 4^{th} of August. Renewable energy is dynamically developing from technological and economic points and is being introduced around the world in modern world. Advantage of solar energy is obvious: sunlight is available anywhere in the world.

The purpose of the project is to develop the decentralized power supply system of a small village located in the territory behind the polar circle and prepare economic evaluation of decisions.

Throughout the work a reader will face the following structure. The thesis starts with providing information about technical and climatic features of the investigated object. After potential assessment of renewable solar energy for investigated region is presented. This part includes calculations of solar radiation in that area using two methods to confirm results. When data of solar radiation are got, it is be possible to calculate parameters of needed equipment for solar power plant, choose it and to design schematic diagram of the photovoltaic power plant. So, the reader can find this information in Chapter 3. Feasibility study will be given in the Finance model part and methodology for economic evaluation will be described next. Finally, in order to show expedience and sustainability of the work sensitivity analysis and comparative analysis of two power supply system operations will be provided. In turn I should also mention that energy economics is complex because of a number of factors [1]:

• The constituent industries tend to be highly technical in nature, requiring some understanding of the underlying processes and techniques for a good grasp of the economic issues.

• Each industry of the sector has its own specific features which require special attention.

• Energy being an ingredient for any economic activity, its availability or lack of it affects the society and consequently, there are greater societal concerns and influences affecting the sector.

• The sector is influenced by interactions at different levels (international, regional, national and even local), most of which go beyond the subject of one discipline.

The results will be discussed in the end.

Chapter 1

Technical and climatic features of the investigated object

1.1 Investigated object, characteristics, power supply requirements

The main goal of this work is the development of decentralized power supply system for the small village located in the territory behind the polar circle. Lack of large manufacturing, as well as the features of geographical location excludes the possibility of centralized power supply.

One of the most perspective directions of energy development in modern conditions is the integration of local renewable energy resources for energy purposes. Basically, it is the integration of combined solar-diesel power plant that combine renewable energy installations and diesel power plants (DPP). Moreover, climatic and territorial features of the village allow us to use alternative energy sources.

The investigated object is a small Popigay village in the territory behind the polar circle nearby to Khatanga village. Khatanga village is located in the Taimyr Dolgano-Nenetsk area of Krasnoyarsk region, and its coordinates are: 71^0 59 'N, 102^0 30'E. (Picture 1). It is 2.2 thousand km from the Khatanga village to the Krasnoyarsk regional center.

Popigay's installed energy production capacity is 100 kW, as the population of the village is 357 people. There is an elementary boarding school, a midwife office, a shop, a branch of the Federal post office of the Krasnoyarsk region, a rural house of culture, a library, a community of the Popigay KMN in the village [2].

Picture 1 - Location of the investigated object [2]

The category of village power supply reliability is the third one. For electrical receivers of the III category, electricity can be supplied from a single power source, on condition that the power supply interruptions must be repaired or the damaged power supply system element must be replaced do not exceed 1 day [3]. But since an alternative energy source depends on climatic conditions, it is also necessary to provide a reliable source of electricity - DPP.

1.2 Climatic features of the investigated object

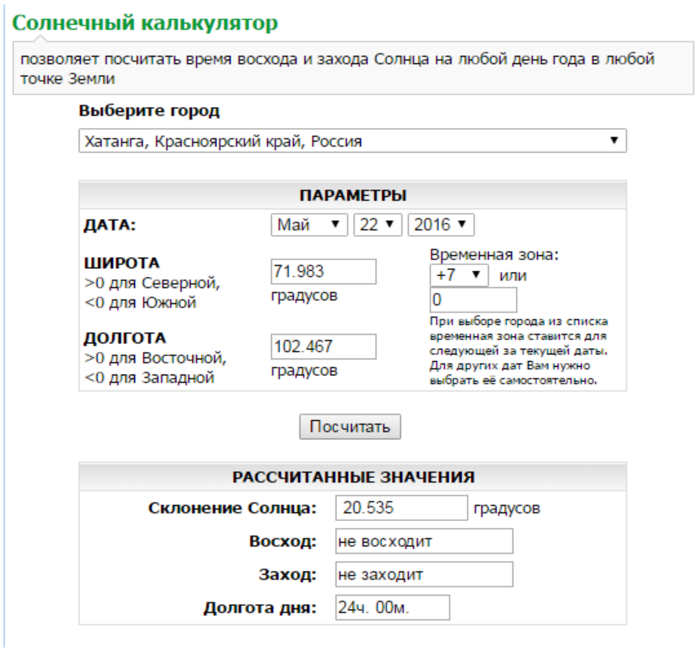
The main climatic feature of this village is the presence of a midnight sun and a polar night. The polar night at the Khatanga latitude lasts from 17th of November to 25th of January, the midnight sun lasts from 9th of May to 4th of August.

The polar night does not necessarily mean total darkness for all 24 hours. Its main feature is that the Sun does not rise above the horizon.

Since this village is below 72° 34'N, the polar night is nautical, i.e. at the time of the upper solstice twilight is observed. If we consider the whole polar night, then every day there are all types of twilight and periods without them [4].

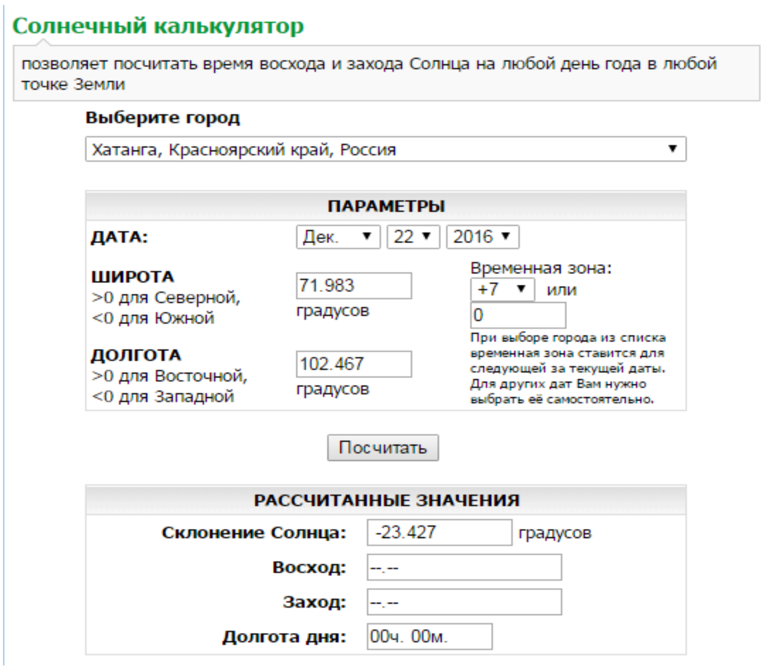
The Sun angle under the horizon is from 6° 50' to 12° in nautical twilight.

Using the specialized program Solar Calculator [5], it is possible to determine the duration of the day or night, the angle of the sun's declination relative to the horizon for any day during the year (Picture 2 and Picture 3).



Picture 2 - Duration of the day during midnight sun [5]

It can be seen on these pictures, that we fill out next parameters: investigated city, the day of observation, the coordinates of object like latitude and longitude. After that the program gives us next calculated values, like: sun's declination relative to the horizon, the time of sunrise and sunset and duration of the day or night. During midnight sun sun's declination relative to the horizon is 20.535 degrees, the sun does not set, and the duration of the day is 24 hours (Picture 2).



Picture 3 – Duration of the night during polar night [5]

During polar night sun's declination relative to the horizon is minus 23.427 degrees, the sun does not rise, and the duration of the day is 0 hours (Picture 3).

Therefore, it is possible to generate electricity using alternative energy sources - photoelectric power stations during the midnight sun. Electricity generation will be carried out within 24 hours for almost 3 months. But also electricity will not be produced within 2 months during the polar nights. Therefore, it is necessary to provide an additional electricity source, as well as accumulator batteries for the days of midnight sun.

In addition, it is necessary to take into account the cloudiness of this area, because even in the presence of a midnight sun, electricity generation may not be the maximum (Table 1).

The actual statistics data of cloudiness are taken from the RP5 site [6].

Table 1 - The actual statistics data of cloudiness [6]

Month	Cloudiness in %
January	40
February	50
March	40
April	40
May	50
June	50
July	50
August	50
September	60
October	60
November	50
December	40

It can be seen from the Table 1, that in general the cloudiness is 50%.

Consequently, only further calculations will help us to estimate the solar potential for a given cloudiness.

1.3 Diesel power plant characteristics

Three diesel generators (one is in reserve) are installed at the diesel power plant near the Khatanga village. Their type is ED 50-T400-3RN with a capacity of 50 kW each, and they are made in block-container version with 3 degrees of automation: automatic start-up of the diesel generator, network backup, automatic refueling of fuel and oil (Table 2). Unattended operation of the DPP is provided for more than 24 hours (Figure 4) [7].

Picture 4 – Diesel – generator [7]

The diesel power plant with technological equipment is located inside of the insulated block - container (starting and working of the diesel power plant up to -50°C). There are automatic load transfer - ALT, the common bus-bar, additional fuel tanks, refueling system, oil, fire extinguishing system, alarm and system remote monitoring inside of the insulated block - container [7].

Table 2 - Characteristics of diesel power plant [7]

Type of generator	P_{nom} *kW*	Fuel consumption (75% of load), *L/h*	Fuel tank, *L*	Generated current	f, *Hz*	Cost (RUB)
ED 50-T400-3RN	50	11,6	200	AC 3-phase current	50	630 000

According to the manufacturer's recommendations, the permissible overload of these types of generators is no more than 10% of the rated power for no more than 1 hour for every 8 hours of operation, no more than 200 hours per year, and the recommended load should be in the range of 75%

to 90% of the rated power. Work with a load of less than 25% is not allowed for more than 5 minutes [7].

1.4 Consumer load graphs

Popigay's installed energy production capacity is 100 kW, so, I can calculate the reactive power (Equation 1), and can get typical daily load graphs for each season during the year.

$$Q = P_{max} \cdot tg(\varphi) = 100 \cdot 0,3286 = 32,86,\ kVar, \qquad (1)$$

Where $tg(\varphi)$ – approximate power factor.

Approximate power factor corresponds to power factor 0.95 according to Russian quality standards in power systems engineering [8].

Table 3 - Popigay's installed energy production capacity

Active Power Pmax, *kW*	Reactive Power Qmax, *kVar*
100	32,86

According to statistic data from the book Budzko I.A. "Electric power supply of villages" [8], I know typical load graphs in percent, but I can easily rebuild them in named units using Popigay's installed energy production capacity (Table 3).

So, the active power, consumed every hour during the day, is calculated by the equation 2:

$$P_h = k \cdot P_c\ , \qquad (2)$$

Where P_h - power, consumed every hour during the day, kW,

P_c - calculated power, kW,

k - loading factor, %, [9, Table 3.3].

Consequently, the active power consumed in the winter from 00.00 to 01.00:

$$P_h = 0,25 \cdot 100 = 25\ kW\ .$$

The values of active power hourly consumption in winter, spring, summer and autumn are given in Table 4. In addition, further it will be taken into account that the maximum active capacity for the summer period is 30% less than for winter, and in spring and autumn are less from 10 to 20% [9].

Table 4 - Active power hourly consumption in each season of the year

Hour	P, kW			
	Winter	Spring	Summer	Autumn
1	25	20	14	23
2	25	20	14	23

Continue of table 4

3	25	20	14	23
4	25	20	14	23
5	25	20	18	23
6	35	28	21	32
7	50	36	28	41
8	60	40	32	50
9	40	32	28	36
10	30	24	21	27
11	30	24	21	27
12	35	28	21	32
13	40	32	25	36
14	30	24	21	27
15	30	24	21	27
16	30	24	21	27
17	40	24	21	27
18	70	32	21	36
19	100	40	25	63
20	95	56	28	90
21	70	80	49	77
22	50	16	70	54
23	35	40	42	36
24	35	24	18	27

Based on the calculations performed, we can construct daily load graphs for each season during the year for investigated object (Appendix A – Consumer load graphs).

To construct the annual active power graph, it is necessary to calculate the amount of power consumed monthly first, taking into account the seasonal coefficient [9, Table. 3.4].

Active power consumed in December:

$$W_{dec} = W_d \cdot k_s \cdot 31 = 1030 \cdot 1 \cdot 31 = 31930\ kWh. \quad (3)$$

Where W_d – daily consumption in calculated month, kWh,

k_s - seasonal coefficient.

Calculation is the same for the other months. The calculated data are presented in Table 5.

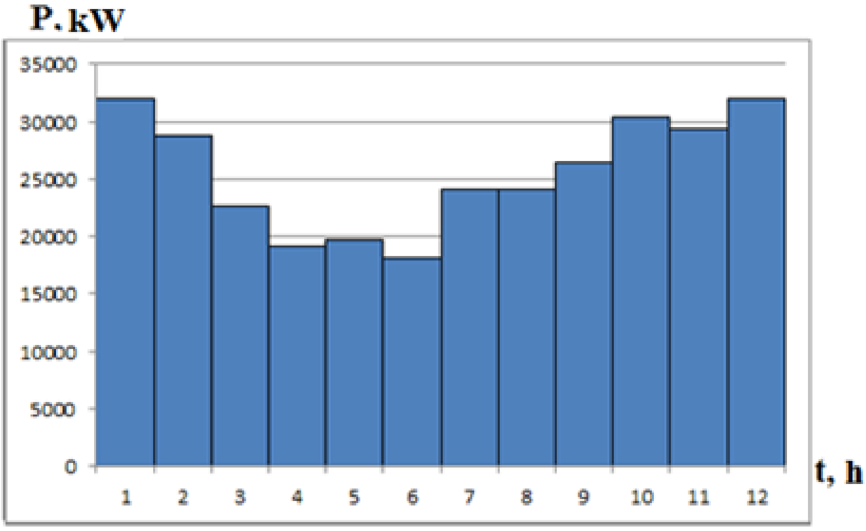
Table 5 – Total month active power load

Month	k_s	W, kWh
January	1	31 930
February	1	28 840
March	0,8	22 568
April	0,7	19 110

Continue of table 5

May	0,7	19 747
June	0,7	18 165
July	0,9	24 134
August	0,9	24 134
September	0,9	26 460
October	1	30 380
November	1	29 400
December	1	31 930

The annual load graph is on the picture 5, constructed on the calculated data.



Picture 5 - The annual load graph

In summary, it can be concluded that typical energy consumption graphs of small village in the territory behind the polar circle were obtained as a result of the made calculations. The annual electricity consumption of the village is 306797 kWh per year.

The final project goal is the choice of the optimal variant of power supply for the investigated object and an assessment of the effectiveness of solar sources in the hybrid power plant.

Chapter 2

Potential assessment of renewable solar energy for investigated region

Solar energy is the main source of energy coming from space to the Earth's surface. The sun is a natural constantly operating thermonuclear reactor.

The statistical data for the investigated region of solar potential are taken from the USSR Climate Data book [10].

There are 162 days without sun during the year, from mid-October to mid-February [4].

The total month solar radiation on the horizontal surface is shown in Table 6.

Table 6 – Total month solar radiation [10]

Month	Total solar radiation during the clear weather Q_c, kWh/m^2	Total solar radiation during an average cloudiness Q_c, kWh /m^2
January	-	-
February	-	-
March	52	21
April	111	86
May	170	159
June	242	153
July	260	154
August	243	99
September	183	43
October	98	18
November	40	3
December	-	-

It is known that there is an average cloudiness not below 40% during each month (Table 1). Thus, it is necessary to take into account in calculations the total solar radiation under average cloud conditions.

But further it is necessary to determine the optimal angle of solar panel inclination to make solar radiation is maximal. It is logical that the solar radiation will be maximal, when sunlight falls on the panel at a square corner of incidence.

2.1 The classical theoretical calculation of solar radiation

Three components of the radiation balance are taken into account, when I calculate solar radiation entering an inclined plane [11]:

$$Q_{incl} = S_{incl} + D_{incl} + R_{incl}, \quad (4)$$

Where,

Q_{incl} - total solar radiation falling on an inclined surface, W/m^2;

S_{incl} -direct solar radiation falling on an inclined surface, W/m^2;

R_{incl} – solar radiation reflected from the Earth's surface, W/m^2.

Reflected solar radiation is negligible in the warm season, because of lack of snow cover, so, it can be neglected [11].

Approximate estimation of declination value of the Sun according to Cooper's formula (28th of March) [12]:

$$\delta = 0{,}41 \cdot \sin\left(2 \cdot \pi \cdot \frac{284+N}{365}\right), \quad (5)$$

Where,

N - the ordinal number of the day in the year, counted from the first January.

So, $$\delta = 0{,}41 \cdot \sin\left(2 \cdot \pi \cdot \frac{284+87}{365}\right) = 0{,}042.$$

Next, determine the height of the sun and the angle of received solar radiation flux on the panel at various angles of inclination of the plane to the horizon according to the equation 6 [10]:

$$cos\theta = sin\delta \cdot sin\varphi \cdot coss - sin\delta \cdot cos\varphi \cdot sins \cdot cos\gamma +$$
$$cos\delta \cdot cos\varphi \cdot coss \cdot cos\omega + cos\delta \cdot sin\varphi \cdot sins \cdot cos\gamma \cdot cos\omega$$
$$+cos\delta \cdot sins \cdot sin\gamma \cdot sin\omega \quad (6)$$

Where,

$\varphi -$ Latitude of the investigated object, rad,

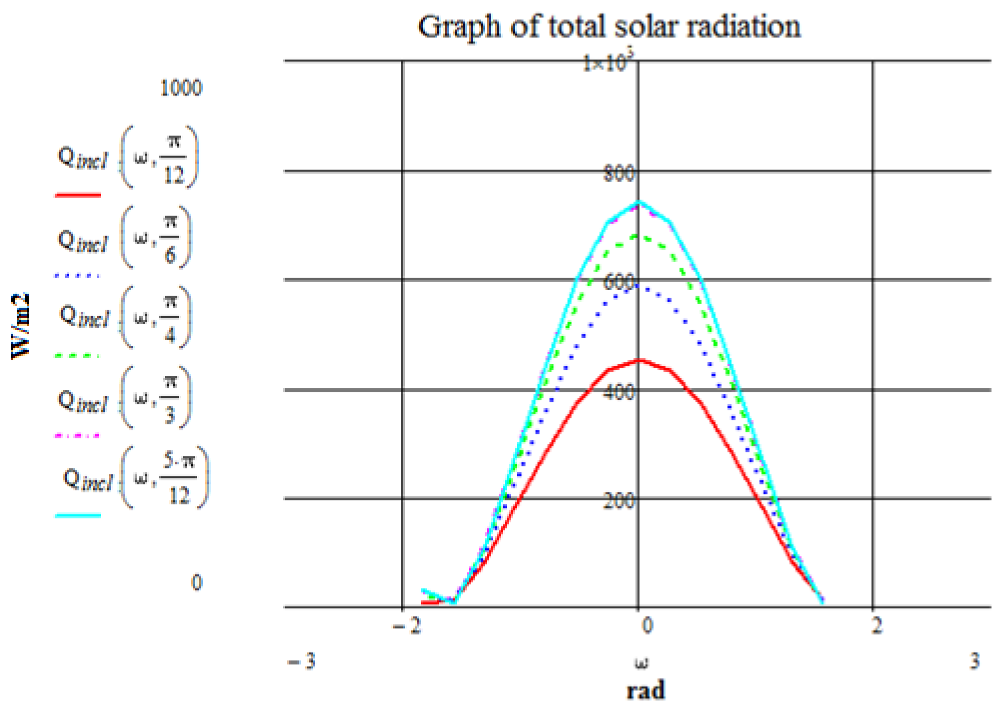
$\delta -$ Inclination of the Sun, rad,

s – Angle of inclination of the plane to the horizon, rad.

The next step is researching the total solar radiation flux incidences on an inclined plane at various angles of inclination of the solar panel to the horizon in clear weather:

$$Q_{incl}(\varphi, \omega, \gamma, s, N) = S_{incl}(\varphi, \omega, \gamma, s, N) + D_{incl}(\varphi, \omega, s, N) \quad (7)$$

The graphical solution is represented on the Picture 6.



Picture 6 - The graph of total solar radiation on a plane inclined at different angles on a spring clear day

As it can be seen from Picture 6, the maximum amount of solar radiation falls on the plane inclined to the horizon at 5π/12 angle.

After that I can determine the total radiation per day as an area under the solar insolation curve for the 5π/12 angle.

$$\int_{-2}^{2} Q_{incl}\left(w,\frac{5\pi}{12}\right)dw = 1344\ \frac{\mathrm{W}}{\mathrm{m}^2}\cdot \mathrm{rad, so,} \quad (8)$$

$$1344\cdot\frac{12}{\pi} = 5.134\ \frac{\mathrm{kW}}{\mathrm{m}^2}.$$

The next step is researching the total solar radiation flux incidences on an inclined plane at various angles of inclination of the solar panel to the horizon in the cloudiness weather [11]:

$$Q_{cloud}(\varphi,\omega,\gamma,s,N) = (S_{incl}(\varphi,\omega,\gamma,s,N) +$$

$$+D_{incl}(\varphi,\omega,s,N))\cdot(1-(a+bn)n) \quad (9)$$

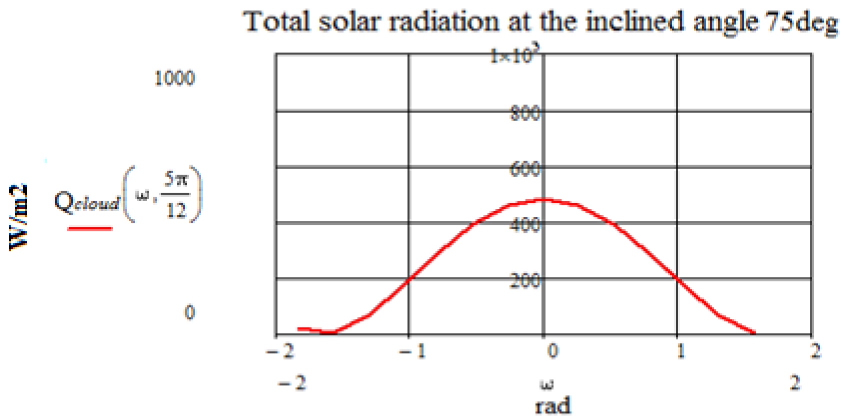
Where,

n - The number of clouds in unit fractions (n = 0 for a cloudless sky, n = 1 with an absolute cloudiness). Cloudiness is 40% in average in March.

b – Constant coefficient, which is equal 0.38,

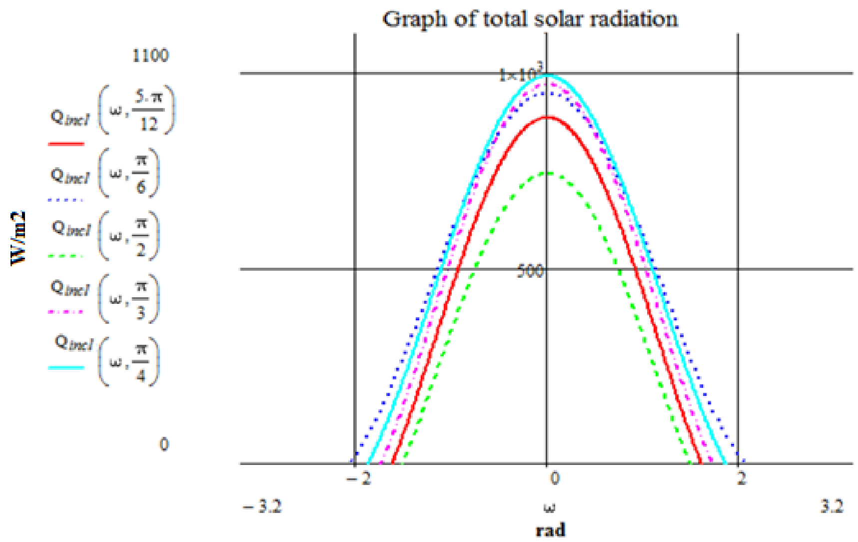
a – Coefficient, which depends on the environment (land or sea) and on latitude.

The graphical solution is represented on the Picture 8.



Picture 8 - The graph of total solar radiation at the inclined angle 75deg on a spring cloudiness day

The same algorithm of calculations is for summer day, when midnight sun is observed. The 18th of June is taken as a control day. The data obtained are presented below (Picture 9).



Picture 9 - The graph of total solar radiation on a plane inclined at different angles on a summer clear day

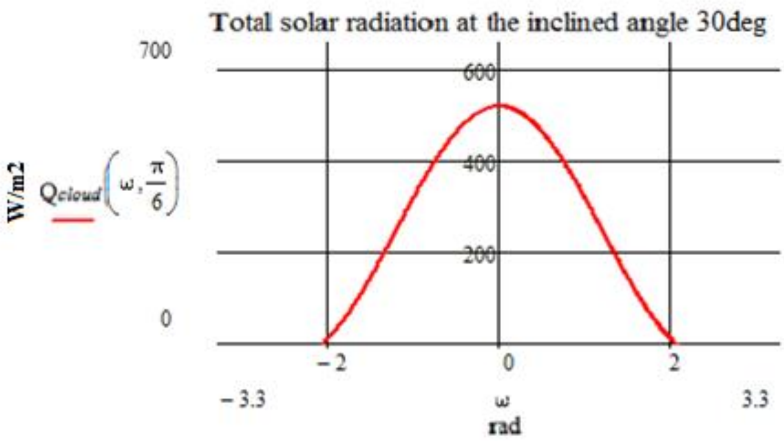
As it can be seen on Picture 9, the maximum amount of solar radiation falls on the plane inclined at an angle of π / 6 to the horizon.

So, the total radiation per day is an area under the solar insolation curve for the π/6 angle:

$$\int_{-3.14}^{3.14} Q_{incl}\left(w, \frac{\pi}{6}\right) dw = 2058 \ \frac{\mathrm{W}}{\mathrm{m}^2} \cdot \mathrm{rad, \ so,} \qquad (10)$$

$$2058 \cdot \frac{12}{\pi} = 7.861 \ \frac{\mathrm{kW}}{\mathrm{m}^2}.$$

Similarly is for a cloudiness day (Picture 10).



Picture 10 - The graph of total solar radiation at the inclined angle 30deg on a summer cloudiness day

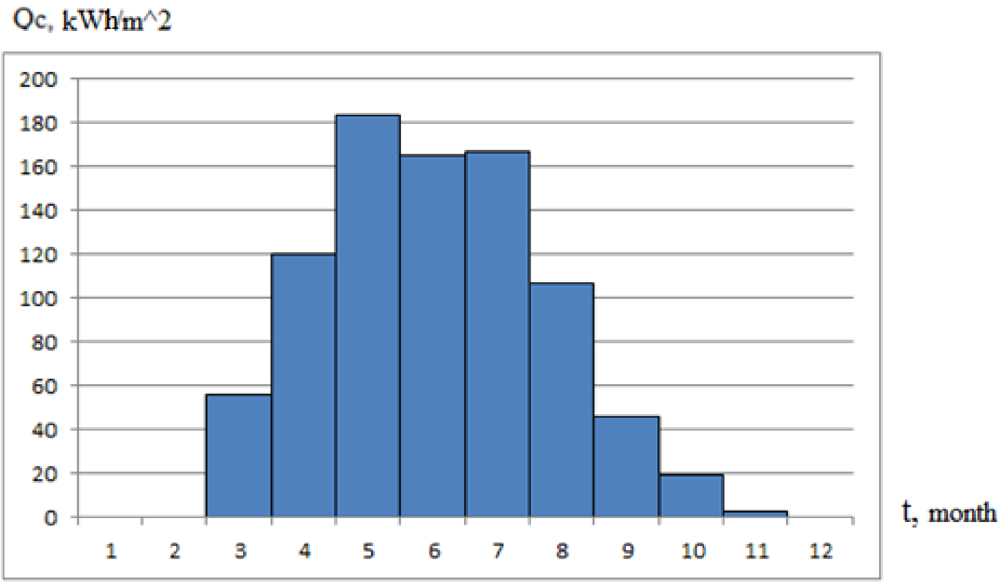
Firstly we use the statistics data from the USSR Climate Data book (Table 6), since those values are more accurate and take into account the presence of twilight during the midnight sun. The presence of twilight can also be taken into account by calculations, but only approximately. And to maximize the value of solar radiation, it is necessary to ensure the right angle of the solar panels relative to the angle of incidence of the sun's flux. It is not possible to provide this in all months, so we will take 30% losses for refraction of the sun's rays [13]. And I also take into account the greater production of solar radiation during the day in comparison with the data taken from the USSR Climate Data book (Table 5), multiplying by a factor of 1.5. Because the measurements from this book were carried out, when the instruments were placed directly on a horizontal surface land without any angle.

So, we have new table 7 based on data from the table 6.

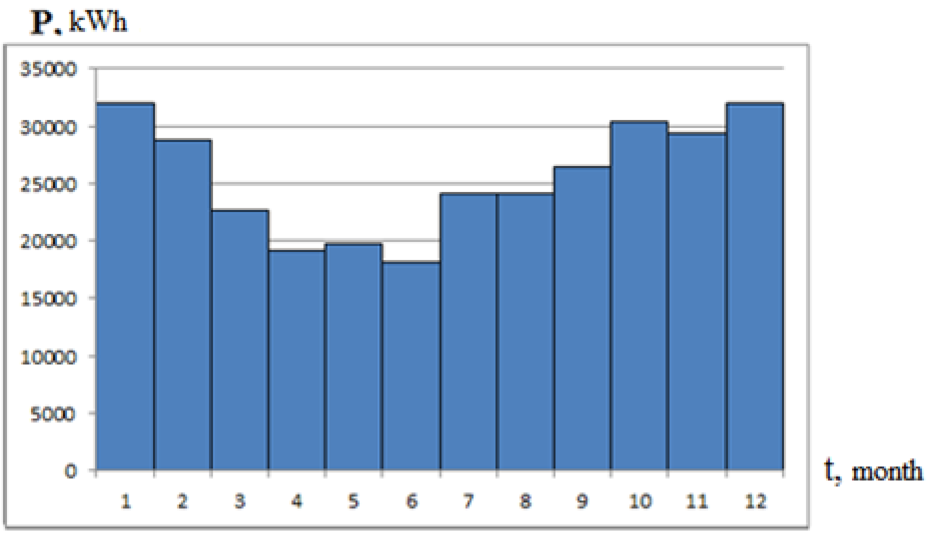
Table 7 – Total month solar radiation

Month	Total solar radiation during an average cloudiness Q_c, kWh /m^2
January	-
February	-
March	56
April	120
May	184
June	166
July	167
August	107
September	47
October	20
November	3
December	-

The solar activity of the investigated area and the electricity demand are shown in Pictures 11 and 12.



Picture 11 - The solar activity of the investigated area



Picture 12 – Electricity demand

Analyzing above graphs, I can make the following conclusions:

1) The most favorable months for the solar modules using are May, June and July, as midnight sun is observed during these months;

2) The minimum amount of total solar radiation and the maximum demand of electricity are observed from October to March. Village electricity supply is carried out with the diesel-generator;

3) Different volumes of fuel resources may be needed, depending on the total solar radiation in different months. It will save money in a result.

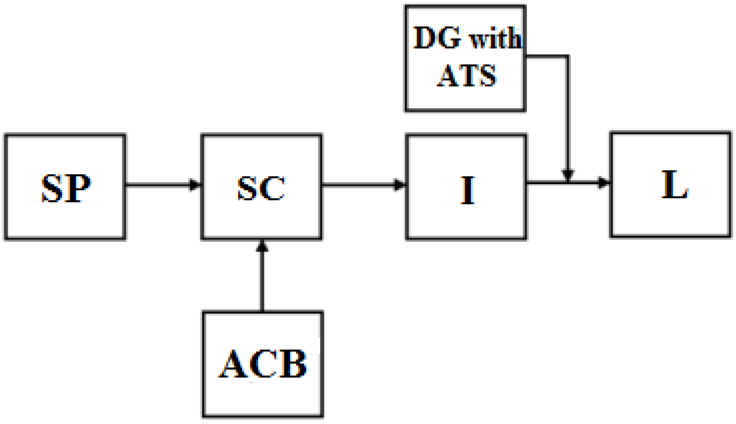
I will take into account all these features, when design photovoltaic power plant, and I will consider possibility to cover electricity demand fully in May and June, using solar energy.

2.2 Structural diagram of the power supply system

A hybrid power supply system should have at least two independent electricity sources in its structure [13]. In my case, this is the solar potential power plant and diesel fuel. Photovoltaic panels (PVP) will be used as the main energy source, and diesel generator (DG) is as a reserve source (Picture 13).

DG's power is turned on when the accumulated power is not enough to cover the load, or during the polar nights. It is necessary to charge the accumulator batteries during forced generator operation to provide working with the maximum efficiency.

The power supply system can be implemented using a single-phase or three-phase system. Typically, photoelectric mounting generates DC power at one voltage and charges the batteries through a charge controller. During maximum load periods, when the depth of accumulators discharge reaches the limit value, the DG must automatically start up and provide uninterrupted power supply of the electric receivers. There is an inverter in the system to convert DC to AC [13].



Picture 13 - Hybrid power supply system

On the Picture 13, DG with ATS is a diesel generator with automatic transfer switch, SP is solar panel, SC is solar controller, ACB is accumulator battery, I is inverter and L is load.

The designing of power supply schemes is proposed to be divided into two parts: power supply from renewable energy sources and power supply from diesel generators.

Chapter 3

Design of photovoltaic power station for the village behind the polar circle

3.1 Choice of solar modules

The choice of solar modules is based on the world practice of production and operation of solar cells. The most effective type is monocrystalline solar module. This type has efficiency from 14 to 16 percent. And it has good correspondence between quality, energy output and price [13]. That is why I have chosen monocrystalline solar modules HSE300-72M (Picture 14) made by Helios SolarWorks [14].

Picture 14 - Solar module HSE300-72M [14]

Technical characteristics are represented in the table 8.

Table 8 – Characteristics of solar modules [14]

Max power	300 W
Rated voltage	24 V
No-load voltage	44,6 V
Short-circuit current	8,74 A
Current at the point of maximum power	8,21 A
Operating temperature	-40…+85 ˚C
Dimension	1950 x 990 x 45 mm^2
Weight	24 kg
Structure	Single-crystal
Number of cells	72 (6x12) cells
Maximum system voltage	1000 V DC
Cost, RUB	22 680

However, I should take into account the gap between the elements, therefore I subtract 3% from the total area of the module and get the working area for further calculations [15].

$$S_{m1} = 1,95 \cdot 0,99 = 1,9305 \text{ m}^2,$$

$$S_{mw} = S_{m1} \cdot 0,97 = 1,873 \text{ m}^2.$$

It is needed to provide proper panels' orientation to the sun to increase the efficiency of solar panels. The optimal panels angle for summer and winter seasons were determined earlier.

Next, I will find the necessary number of solar modules to cover the demand for electricity in May, because the solar insolation in this month is the maximum. So, I take the meaning of demand for electricity in May and find necessary area of solar modules. The demand in May is 19 747 kWh.

$$S_{necess} = \frac{W_{necess}}{\eta \cdot Q_s} \qquad (11)$$

Where Q_s – total solar radiation, kWh/m^2,

η - efficiency of the solar module.

$$S_{necess} = \frac{19747}{183,34 \cdot 0,14} = 770\, m^2$$

Knowing the required area and area of one module, I can find the required number and cost of modules (Equation 13):

$$N = \frac{S_{necess}}{S_{mod}} \qquad (12)$$

Where,

S_{mod} - the area of one module, m^2.

$$N = \frac{770}{1,873} = 412$$

I take 432 solar modules in order to be able to connect them in series and parallel. So, there are 9 parallel branches of 8 solar panels in each, connected in series. And there are 6 separate photovoltaic blocks located territorially in one locality.

Depending on the amount of total monthly radiation, these modules will produce a different amount of electricity. Using equation 11, I will find the amount of electricity generated by the modules in each month (Table 9).

Table 9 - Electricity generated by solar modules

	March	April	May	June	July	Aug.	Sent.	Oct.
W_{mod} (kW)	6 421	13 840	21 176	19 125	19 263	12 308	5 355	2 226

Continue of table 9

Area of modules - S_{mod} (m^2)	809
Number of modules – N	432
Cost (RUB	9 797 760

Thus, in May and June, sufficient electricity will be generated to cover completely the demands of electricity. In other months, there is a shortage of electricity, so, it is necessary to use diesel generators as additional power supplies.

Table 10 - Electricity balance using solar modules

Month	Solar radiation Q_c (kWh/m^2)	Demand of electricity- W_{necess} (kWh)	Electricity from solar modules -W_{mod}(kWh)	Deficit of electricity – W_d(kWh)
March	56	22 568	6421	-16 147
April	120	19 110	13 840	-5 271
May	184	19 747	21 176	1 429
June	166	18 165	19 125	960
July	167	24 134	19 263	-4 871
August	107	24 134	12 309	-11 826
September	47	26 460	-	-26 460
October	20	30 380	-	-30 380

The solar panels are chosen for the summer season, when the solar activity is maximal at the minimum load, and the diesel-generator is chosen for the winter season, when the solar activity is minimal, and the load is maximal during the day. Some part of solar radiation will be used to reduce the consumption of diesel fuel in spring. In autumn, the power produced by the panels is not sufficient even to cover the load power, in this case only the diesel generator will work, because the photoelectric power plant operates separately with the diesel generator. But ACB will work during the whole year to maintain the battery charge during the winter and autumn periods in order to extend their service life [13]. But in autumn and winter seasons the load will be fully provided with a diesel generator.

3.2 Choice of accumulator batteries

The efficiency and reliability of the photovoltaic plant is increasing with using of accumulator batteries, because it will allow reserving of excess power produced by solar panels and using it in the future when solar activity is not so high.

I choose the DELTA DTM12200L battery [16]. It is also necessary to take into account the fact that to prolong operation life; the battery should always retain at least 40% of the charge [16].

Even in the presence of a midnight sun, there is twilight during the day, when solar activity is not so high. In this case, equipment operation will be considered for a typical days in May and June, when there is sufficient generation capacity to cover the required load. Daily characteristic loads are shown in Appendix B, Picture B.1-B.2.

It is also known hourly solar radiation from the USSR Climate Data book [10] for different months, but with assumption that according to proper corner of solar panels, insolation is increasing in 1.5 times, but 30% of losses is also present. The data are summarized in Table 11.

Table 11 - Hourly total solar radiation during an average cloudiness and power generation of solar panels

Time, hour	Solar insolation, kW/m^2		Power generation of solar panels (420 pc), kW	
	May	June	May	June
0-1	0,00	0,01	0,00	1,2
1-2	0,01	0,02	1,2	2,3
2-3	0,01	0,04	1,2	4,6
3-4	0,04	0,08	4,6	9,2
4-5	0,09	0,12	10,4	13,9
5-6	0,16	0,19	18,5	22,0
6-7	0,24	0,22	27,7	25,4
7-8	0,32	0,28	37,0	32,3
8-9	0,39	0,34	45,0	39,3
9-10	0,46	0,40	53,1	46,2
10-11	0,51	0,45	58,9	52,0
11-12	0,55	0,47	63,5	54,3
12-13	0,55	0,47	63,5	54,3
13-14	0,52	0,45	60,1	52,0
14-15	0,47	0,41	54,3	47,4
15-16	0,41	0,35	47,4	40,4
16-17	0,34	0,31	39,3	35,8
17-18	0,26	0,25	30,0	28,9
18-19	0,17	0,19	19,6	21,9
19-20	0,11	0,13	12,7	15,0
20-21	0,07	0,08	8,1	9,2
21-22	0,03	0,04	3,5	4,6
22-23	0,01	0,02	1,2	2,3
23-24	0,00	0,01	0,0	1,2

Data of hourly loads for typical days in May and June are presented in Table 12. And also the difference between the produced power and load power is there.

Table 12 – Hourly load data and produced power

Time, hour	Load, kW		Difference between produced and required capacities, kW	
	May	June	May	June
0-1	18	14	-18	-13
1-2	18	14	-17	-12
2-3	18	14	-17	-10
3-4	18	14	-13	-5
4-5	18	18	-7	-4
5-6	25	21	-6	1
6-7	32	28	-4	-3
7-8	35	32	2	1
8-9	28	28	17	12
9-10	21	21	32	25
10-11	21	21	38	31
11-12	25	21	39	33
12-13	28	25	36	30
13-14	21	21	39	31
14-15	21	21	34	27
15-16	21	21	27	20
16-17	21	21	19	15
17-18	28	21	2	8
18-19	35	25	-16	-3
19-20	49	28	-37	-13
20-21	70	49	-62	-40
21-22	14	70	-11	-66
22-23	35	42	-34	-40
23-24	21	18	-21	-17

Graphs of load capacity and solar insolation are presented in Appendix B, Picture B.3-B.4.

As it can be seen from Pictures B.3-B.4 in Appendix B, the solar insolation is maximal from 7 a.m. to 6 p.m., and the required load is completely covered. Moreover excessive energy is generated, which should be accumulated in batteries and used in those hours when it is necessary. The maximum excessive energy that should be stored is observed from 7 a.m. to 6 p.m., and it is 282.62 kWh. Daily graphs of load power and solar insolation for the other months are presented in Appendix B, Pictures B.5-B.10.

Technical characteristics of chosen battery are presented in Table 13.

Table 13 - Technical characteristics of accumulator battery [16]

Voltage	12 V
Capacity	200 Ah
Level of operating temperatures	Discharge: from -20˚C to +60˚C Charge: from -10˚C to +50˚C Storage: from -20 ˚C to +60 ˚C
Active material	Lead
Max charging rate	60 A
Battery fluid	High purity sulfuric acid
Dimension	522 x 238 x 223 mm
Weight	65,6 kg
Cost	23 520 RUB

Battery capacity is calculated according to the equation 13, taking into account the losses and the permissible depth of discharge [13]:

$$W_{ACB} = \frac{U \cdot C_I \cdot k_{d.ACB}}{1000}, \quad (13)$$

Where,

U – rate voltage, V;

C_I – rate capacity, Ah;

k_d - the battery discharge factor (discharge recommendation is up to 40%) [13].

So,

$$W_{ACB} = \frac{12 \cdot 200 \cdot 0,4}{1000} = 0,96 \text{ kWh}$$

The following number of batteries will be required in case of the charge-discharge losses (Equation 14) [13]:

$$n = \frac{Wexc}{W_{ACB} \cdot 1.1}, \quad (14)$$

So,

$$n = \frac{282.62}{0.96 \cdot 1.1} \approx 268 \text{ units}$$

Thus, I take for installation the 288 battery units. Twelve branches in parallel with 4 batteries each, connected in series. And there are 6 separate photovoltaic blocks located territorially in one locality.

3.3 Choice of solar controllers

The chosen type of accumulator batteries is recommended to be equipped with universal charge-discharge controllers Prosolar SunStar MPPT SS 24^{0C}X (Picture 15) [17].

Picture 15 - MPPT Battery charge controller for solar modules [17]

Such controllers provide the following options:

- Combines the built-in function MPPT (Maximum Power Point Tracking - monitoring the maximum power point of the solar battery), control the battery charge, display representation of information about the state of battery charge.

- Provide the maximum output power without reducing it at ambient temperatures up to 50°C.

- Can be used with lead-acid, gel and AGM-batteries, performs 2/3/4-stage charge with the ability to adjust all parameters and charging mode.

- Optimal connection of the photovoltaic module circuit is up to 192 V of DC (maximal voltage is 240 V).

- Ability to combine up to 16 controllers in one system to provide higher charge currents.

- Accurate charging of 12V/24V/36V/48V batteries.

- Built-in temperature compensation functions for safe and full charging of batteries.

- Can charge lead-acid batteries: with liquid electrolyte, gel, AGM and also lithium LiFePO4 batteries [17].

I take 6 controllers for the installation.

3.4 Choice of inverters

The choice of inverters is based on the following important characteristics:

1. Input voltage.

In my case the output controller's voltage is 48 V, and output power is more than 1500 W, it is recommended to use this voltage in order to reduce losses [18], so, I choose an inverter with an input voltage 48 V.

2. Rate and peak output power.

Inverter's rate output power must be equal to the sum power of all loads. However, rate power is determined as the maximum load power to simplify calculation. So,

$$P_{\max.calc} = P_{calc} = 100,\ \text{kW}.$$

3. Shape of the output voltage.

The form of the output voltage must be pure sinewave in order to provide receivers with high-quality electric power.

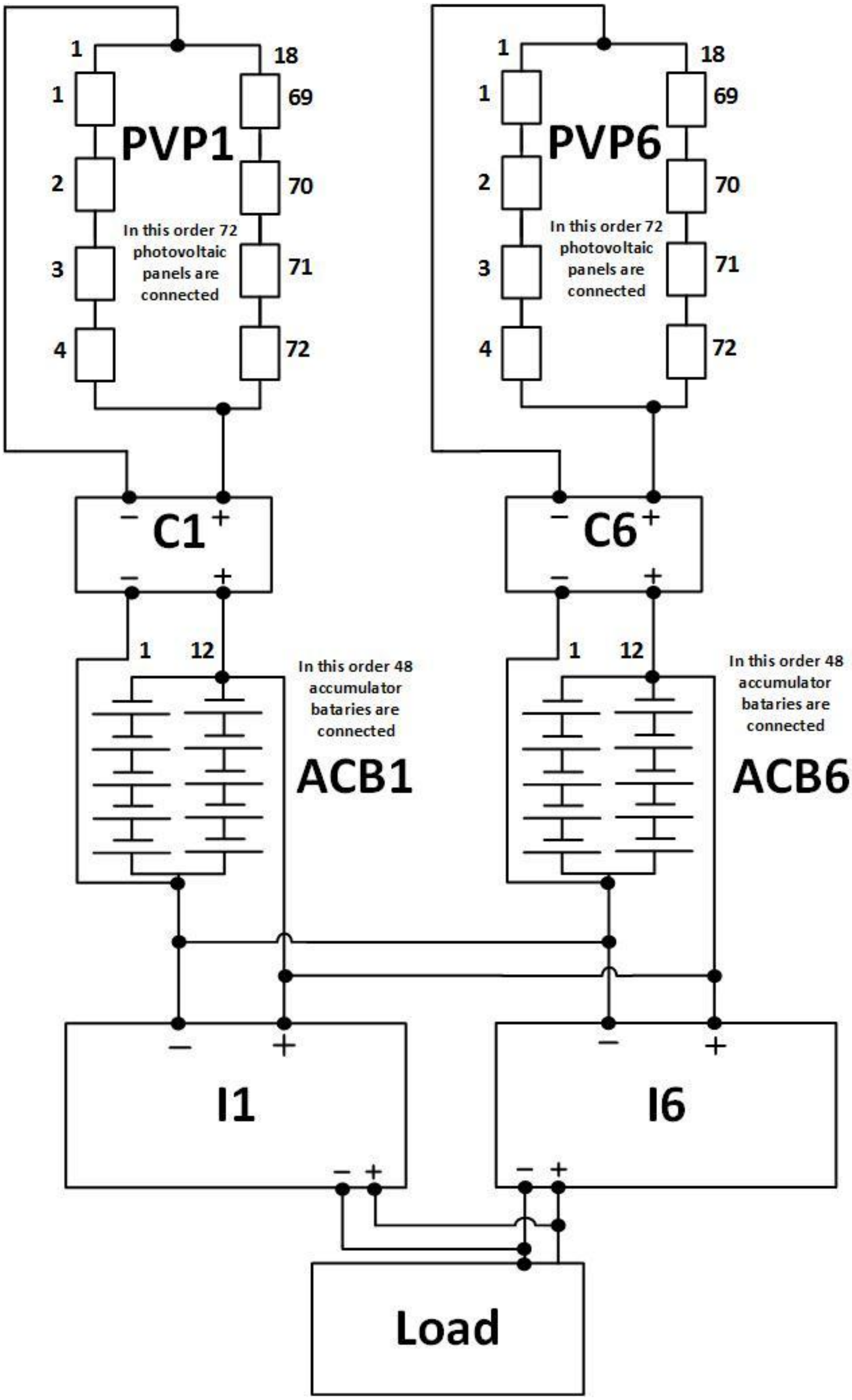
Since the maximum load power is 100 kW, I take 6 Dominator power inverters of 20 kW each by MicroArt [19]. Technical characteristics of the taken inverters are presented in Table 14.

Table 14 – Technical characteristics of the inverters [19]

Rate power	20 kW
Input voltage	48 V
Output voltage	220 V
Frequency	50 Hz
Output signal	Pure sinewave
Efficiency rate	92-96
Min / Max capacity of ACB	800/2400 Ah
Dimension	550 x 217 x 153 mm
Cost	222 700, RUB

Also the MAP Dominator inverter has such an important advantage as: the ability to synchronize not only with the 220V network (or with an electric generator), but also in parallel between other MAP Dominator inverters (up to 10 pcs in parallel) [19].

3.5 Schematic diagram of the Photovoltaic Power Plant



Picture 16 - Schematic diagram of the photovoltaic power plant

Chapter 4

Financial model

4.1 Theoretical background

There are some most important investment criteria in financial model. It is [20]:

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

I will write more detailed about each criterion further.

4.1.1 Net Present Value

The difference between a project's value and its cost is Net Present Value (NPV) [21].

NPV is used in capital budgeting to analyze the profitability of a projected investment or project.

The following is the formula for calculating NPV [22]:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0, \quad (15)$$

Where

C_t - net cash inflow during the period t;

C_o - total initial investment costs;

r - discount rate;

t - number of time periods.

Net Present Value Rule says that investments should be made only for positive NPV values [22].

4.1.2 Internal Rate of Return

The discount rate that makes NPV 0 is the rate of return [21].

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{CF_i}{(1+IRR)^i} = 0 \quad (16)$$

Where

CF_i - cash flows (both inflow and outflow);

C_o - total initial investment costs;

NPV – net present value;

T - number of time periods.

And the rule of IRR says: "Accept investment opportunities offering rates of return in excess of their opportunity costs of capital." [21]

4.1.3 Profitability Index (PI)

Profitability index is the value which illustrates the ratio of project's future cash flows in the present value over investments. The formula is showed below [21]:

$$PI = \frac{\sum_{i=1}^{T} DCF_i (1+r)^i}{INV}, \tag{17}$$

Where

DCF – discounted cash flow;

r – discount rate;

INV – investments;

T – lifetime period.

"The rule of profitability index" claims: if a project has profitability index higher that one, it should be accepted, otherwise – the better way is to avoid it [23].

4.1.4 Payback period

A project's payback period is found by counting the number of years it takes before the cumulative cash flow equals the initial investment.

The payback rule states that a project should be accepted if its payback period is less than some specified cutoff period. Moreover, the payback rule ignores all cash flows after the cutoff date [21].

As it was mentioned before, simple payback period is the period of time which is needed to return the investments. The simple description is represented below:

$$(C_i - C_0)_1 + (C_i - C_0)_2 + \ldots + (C_i - C_0)_T = \sum_{i=1}^{T} (C_i - C_0)_t \geq C_0 \tag{18}$$

Where

Co – cash outflow;

Ci – cash inflow.

4.2 Economic parameters

4.2.1 Inflation

Inflation is a sustained increase in the general price level of goods and services in an economy over a period of time [24], but government controls increasing of prices in some fields. So, according to Scenario conditions of socio-economic development of the Russian Federation the inflation rate is 4% [25].

4.2.2 Tax shield

It is government project, so, no any taxes in this case.

4.2.4 Depreciation

There are two main methods of depreciation in financial management:

1. Straight-Line Method;

2. Accelerated Method.

The Straight Line Method is the simplest method. This amortization method based on the basic equation:

$$D = \frac{INV}{T}, \tag{19}$$

Where

INV – investments of each item,

T – item's lifetime.

Accelerated methods used in accounting for higher values of depreciation in the beginning of the lifetime period [26]. So, these methods had good impact on cash flow if the project would have a few amount of money in the earlier years.

In my project Straight-Line Method will be used. But the different lifetime is for the different equipment, so, the depreciation will be also changed.

4.2.4 Discount rate

Discount rate is the interest rate that is used to re-evaluate the value of future capital at the current time [27].

It is government project, so, according to Decree of the Russian Federation Government №1470 [28], the next value of the discount rate for the investment money into the new technology is there. It is 18-20%, I take 18%.

4.3 Financial model

To calculate financial model I need as technical data as data of economic parameters. I have described found economic parameters above. As for technical parameters and costs of equipment, the data from previous chapters are presented in the table 15.

Table 15 – Collected Data for the financial model

Item	Units of each item
Installed Power, kW	129,6
Investment per 1 kW, RUB	392 126
Tmax, hours	692
Tl of photovoltaic panels, years	20
Tl of accumulator batteries, years	7
Tl of controllers, years	10
Tl of inverters, years	10
Discount rate, %	18
Operation cost, RUB	1%
Existing price, RUB	100
Escalation rate, %	4

4.3.1 Net Present Value (NPV)

In my model I got negative NPV and its result is -42,8 million rubles with price for electricity 95 RUB (Appendix C, Table C.1).

4.3.2 Internal Rate of Return (IRR)

The value of IRR in my project is absent, because the project is absolutely not economic effective.

4.3.3 Profitability Index (PI)

The value of profitability Index is presented below:

$$PI = \frac{18303034}{47288732} = 0,39.$$

According to “the rule of profitability index” it is better to avoid this project, because PI is less, than one.

4.3.4 Payback Period (PP)

Payback Period is bigger than lifetime of the project that is why this project should not be accepted.

All calculation results of financial model are presented in the Appendix C. The minimum price for 1 kW is 579 RUB, when NPV is 0, but now the existing price is 100 RUB [13], that means absolutely not economic effective project. To estimate this project fully, it is necessary to do sensitivity analysis.

Chapter 5

Financial analysis

Most common financial analysis are:

- Sensitivity analysis;
- Scenario.

5.1 Sensitivity analysis

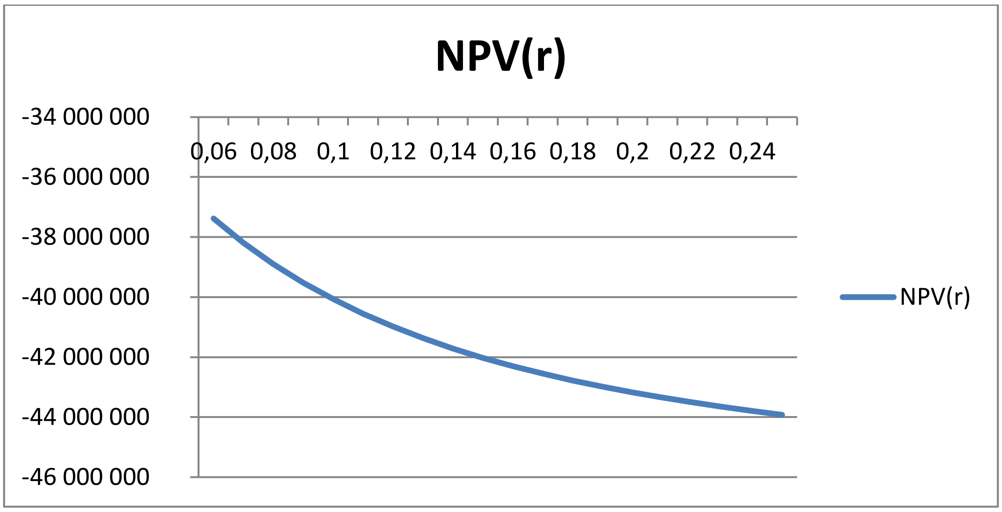
Financial analysis includes financial model and sensitivity analysis. Sensitivity analysis shows influence of changing of input parameters on NPV and helps to estimate which parameters have bigger influence [29].

In this chapter sensitivity analysis will be done for:

- Dependence NPV on discount rate;
- Dependence NPV on electricity price;
- Dependence NPV on useful life;
- Dependence NPV on escalation.

To estimate this project better, I assume that price for 1 kW is 95 RUB, not 579 RUB as I have calculated minimum price before to be more competitive with electricity price generated by diesel generators.

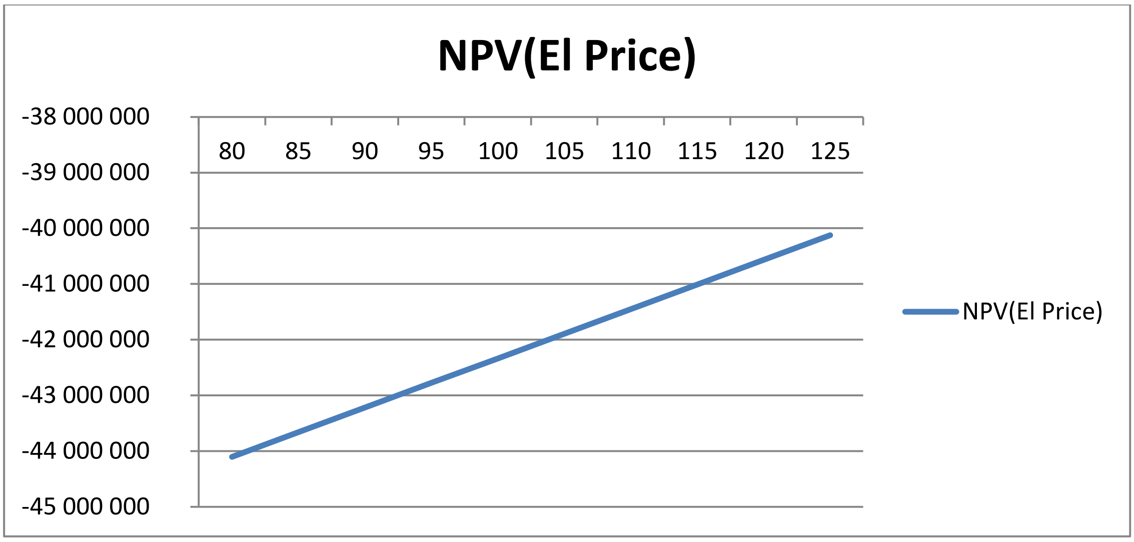
5.2 Dependence NPV on discount rate



Picture 17 - Dependence NPV on discount rate

NPV is decreasing with the increasing of discount rate. The picture 17 shows that the value of IRR – intersection of curve with the horizontal axe (the axe of discount rate) is absent. It means that there is no such value of discount rate, which could make the project economic effective.

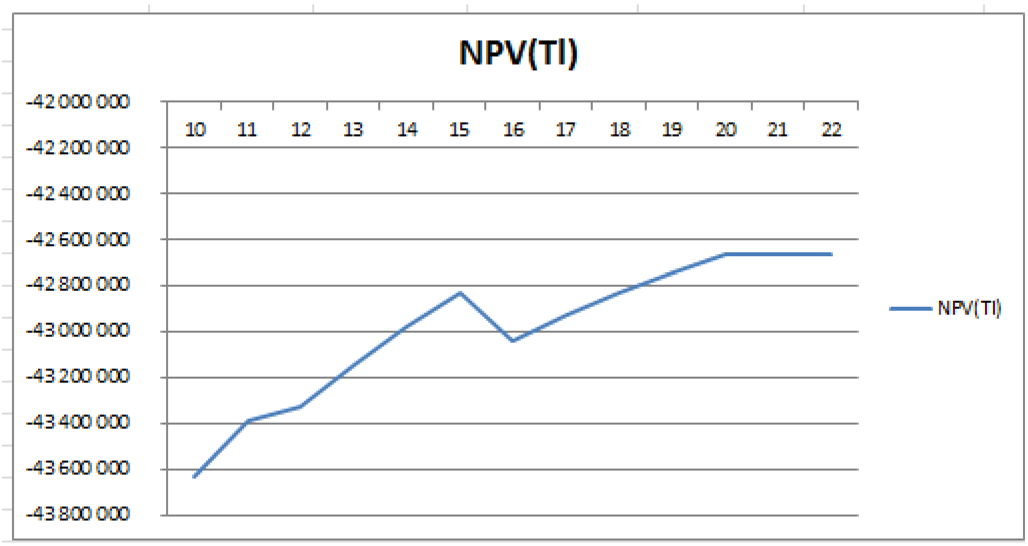
5.3 Dependence NPV on electricity price



Picture 18 - Dependence NPV on electricity price

Picture 18 represents the linear dependence NPV on price; the price is higher, the NPV is bigger. It also shows that the minimum price for electricity is too high to cover all production costs. It even does not intersect the curve with a horizontal axe. The value of minimum price is approximately 579 RUB, but the market price is 100 RUB.

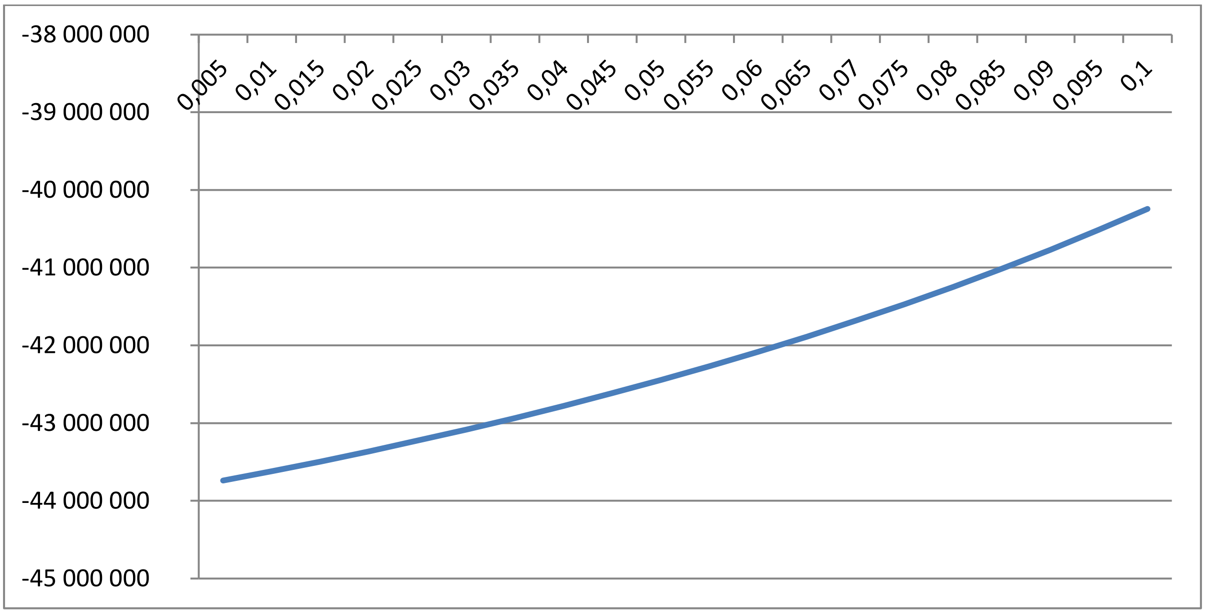
5.4 Dependence NPV on useful life of solar panels



Picture 19 - Dependence NPV on useful life of solar panels

The NPV value depends on lifetime period as well. According to picture 19, NPV value is rising with increasing of lifetime. So, if project's lifetime is bigger, the project is more profitable. But in my case the intersection of curve with a horizontal axe is absent, so, it means that with this price it is not possible to cover all costs and investment. And moreover, it is needed to do additional investments at 8th year, 11th and 15th, because lifetime of equipment is different.

5.5 Dependence NPV on escalation



Picture 20 - Dependence NPV on escalation

With increasing of escalation, NPV will be increasing also, because the revenues is much bigger than cost of expenses, so, it has bigger influence on NPV. But still there is no such escalation, when NPV would be positive

Sensitivity analysis showed that this project is not economic effective absolutely, because the investment is much bigger than the profit from produced energy by photovoltaic panels. And lifetime of such equipment as accumulator batteries, inverters and controllers is less than the lifetime of solar panels that will require additional investments during the whole life time of the project. I will calculate economic effectiveness of this project on the example of saved fuel for the diesel generators in the next chapter.

Chapter 6

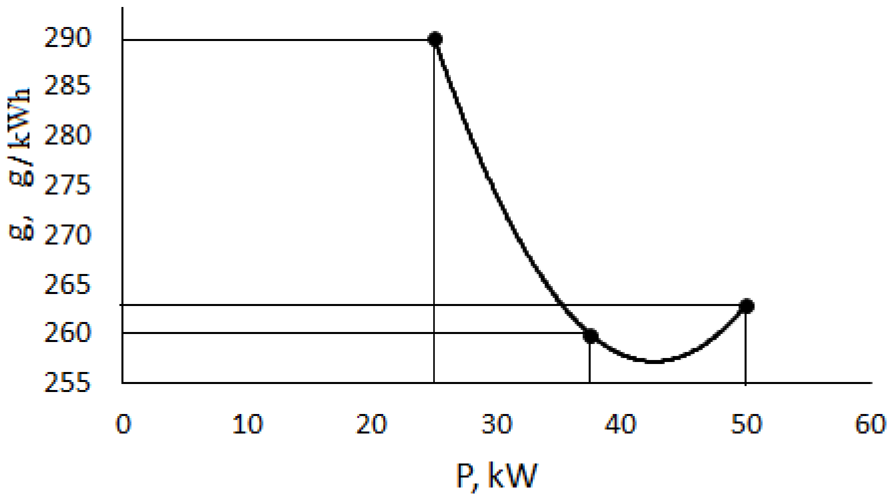
Comparative analysis of two power supply system operations

I will present a comparative analysis of two power supply system operations. The first variant includes photovoltaic panels, storage batteries and diesel generators. The second variant includes only diesel generators. Comparative analysis will be carried out according to the amount of fuel consumption.

The final cost of diesel fuel on the far North is 52.0 RUB / liter according to the prices of supplier [30].

6.1 Diesel generators power supply

I will define the total fuel consumption when only diesel generators operate. The fuel consumption at the nominal load is known from the passport data [7], but since the generator is loaded in each hour differently depending on the season, it is necessary to calculate the fuel consumption for a given load value. I know consumption of fuel from the passport data in three points: when the load is 50%, 75% and 100%. So, the curve of consumption and equation of this dependence are presented on the picture 21.



Picture 21 - Dependence of fuel consumption on load

From the picture 21 it is obtained that the minimum consumption (257 g/kWh) will be, when the load is 85%. So, according to this curve I can calculate fuel consumption for different loads in each month. Data of loads are taken from table 4. The table with calculated results of fuel consumption depending on load is presented in Appendix D.

The calculated monthly consumption of fuel and its prices are presented below.

Table 17 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	234	7254	52	377 208

Continue of table 17

February	234	6552	52	340 704
March	242	7502	52	390 104
April	242	7260	52	377 520
May	242	7502	52	390 104
June	213	6390	52	332 280
July	213	6603	52	343 356
August	213	6603	52	343 356
September	290	8700	52	452 400
October	290	8990	52	467 480
November	290	8990	52	467 480
December	234	7254	52	377 208
Totally	-	**89600**	52	**4 659 200**

The total cost of fuel per year is 4.659 million rubles.

6.2 Power supply from photovoltaic panels and diesel generators

In the second variant of power supply, the load will be covered by the photovoltaic panels partly. During the polar nights and autumn, the fuel consumption will be the same as in the first variant. Data of generated power by PV panels and the amount of operating hours are taken from Appendix B, Pictures B.5-B.10. The calculated data are presented in Table 18.

Table 18 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	31 930	7254	52	377 208
February	28 840	6552	52	340 704
March	16 147	6704	52	348 608
April	5 271	3216	52	167 232
May	-	0	52	-
June	-	0	52	-
July	4 871	2042	52	106 184
August	11 825	4670	52	242 840
September	21 105	8700	52	452 400
October	28 154	8990	52	467 480
November	29 400	8990	52	467 480
December	31 930	7254	52	377 208

Continue of table 18

Totally	-	**64372**	52	**3 347 344**

So, the difference in total cost is 1.311 million rubles. Economy of fuel in liters is 25 228.

It means that the government could save only 1.311 mln rubles per year using PV power plant, but the whole investment for 20 years is 39.2 mln rubles. So, it takes about 30 years to cover all investments without any profit, but after 20 years it will be necessary to change equipment on new one that will require additional investment again. So, the project is not economic effective from the point of saving fuel costs also.

But it was realistic scenario when both of consumption and fuel cost are according to expected value. And to make financial analysis better it is recommended to do other scenarios also.

Chapter 7

Scenarios

Scenario analysis allows seeing, how project's outcomes change, if several assumptions will suddenly change. Therefore it shows how the project will going on if it happens [21].

However, scenario analysis has several drawbacks. Scenario analysis limited to outcomes. In other words, there is no strict description of realistic or pessimistic scenarios [31].

For this project three different scenarios are assumed. They are:

1) Realistic;

2) Pessimistic;

3) Optimistic scenario;

According to study presented by researchers, realistic scenario includes expected all inputs at the expected level, so called real values [31]. In this case, as a realistic scenario the option with expect cost of fuel and consumption of fuel are adopted.

Further, pessimistic scenario is. This option is estimated as a worse variant. In pessimistic scenario most inputs values are at the lower level, than expected [31]. In this variant cost of fuel is higher, than it is and consumption of fuel is also higher, than it is.

An optimistic scenario is determined as the best option [31]. In other words, it shows the highest possible savings of money. For the work it could be an option with expected cost of fuel (less, than it is) and consumption of fuel (also less, than it is).

7.1 Optimistic scenario

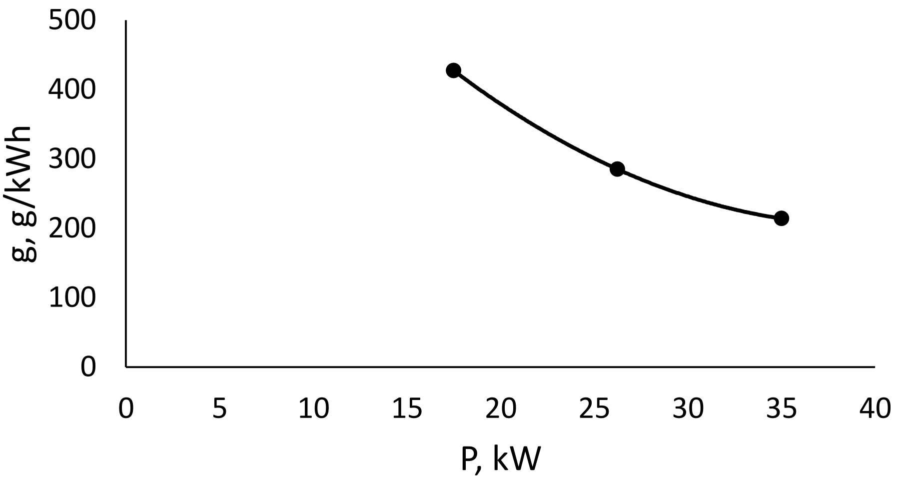
In this case I assume that because of economic situation on Russian market 1 RUB could be more stable and could have bigger value as currency. So, the price on fuel is assumed to be less on 20% than it is now. It is 42 RUB per liter. And electricity demand is also less on 20%, because of changes in population of this village.

But if load is less on 20%, it means that it will be also necessary to install new diesel generators with less installed capacity. Two new diesel generators are AD-35 (MMZ D-243) [32]. Characteristics of new diesel power plant are below.

Table 19 - Characteristics of new diesel power plant [32]

Type of generator	P_{nom} *kW*	Fuel consumption (75% of load), *L/h*	Fuel tank, *L*	Generated current	f, *Hz*	Cost (RUB)
AD-35 (MMZ D-243)	35	8.9	200	AC 3-phase current	50	495 000

And its curve of consumption and equation of this dependence are presented on the picture 22.



Picture 22 - Dependence of fuel consumption on load

The calculated monthly consumption of fuel, when demand is covered only with diesel generators, is presented below. And prices of consumption are presented below also.

Table 20 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	272	8432	42	354 144
February	272	7616	42	319 872
March	230	7130	42	299 460
April	230	6900	42	289 800
May	230	7130	42	299 460
June	218	6540	42	274 680
July	218	6758	42	283 836
August	218	6758	42	283 836
September	262	7860	42	330 120
October	262	8122	42	341 124
November	262	7860	42	330 120
December	272	8432	42	354 144
Totally	-	**89 538**	42	**3 760 596**

The total cost of fuel per year is 3.760 million rubles.

In the second variant of power supply, the load will be covered by the photovoltaic panels partly.

Table 21 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	25 544	8432	42	354 144
February	23 072	7616	42	319 872
March	12 918	6333	42	265 986
April	4 217	3612	42	151 704
May	-	0	42	-
June	-	0	42	-
July	44	3101	42	130 242
August	9 460	4602	42	193 284
September	16 884	7860	42	330 120
October	22 524	8122	42	341 124
November	23 520	7860	42	330 120
December	25 544	5841	42	245 322
Totally	-	**63 379**	42	**2 661 918**

So, the difference in total cost is 1.098 million rubles. Economy of fuel in liters is 26 159. It means if demand of electricity and price of fuel are less, than it is expected, government could save less money with using PV modules, but investments are still big. Therefore it is even more not economic effective, than it was in realistic scenario, in spite of covering almost all demand with PV in July also, not only in May and June. In this case it is more profitable to use diesel-generators.

7.2 Pessimistic scenario

In this case I assume that because of economic situation on Russian market 1 RUB could be less stable and could have less value as currency. So, the price on fuel is assumed to be higher on 20% than it is now. It is 63 RUB per liter. And electricity demand is also higher on 20%, because of changes in population of this village.

The calculated monthly consumption of fuel, when demand is covered only with diesel generators, is presented below. And prices of consumption are presented below also.

Table 22 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	392	12152	63	765 576
February	392	10976	63	691 488
March	290	8990	63	566 370
April	290	8700	63	548 100
May	290	8990	63	566 370

Continue of table 22

June	253	7590	63	478 170
July	253	7843	63	494 109
August	253	7843	63	494 109
September	338	10140	63	638 820
October	338	10478	63	660 114
November	338	10140	63	638 820
December	392	12152	63	765 576
Totally	-	**115 994**	63	**7 307 622**

The total cost of fuel per year is 7.308 million rubles.

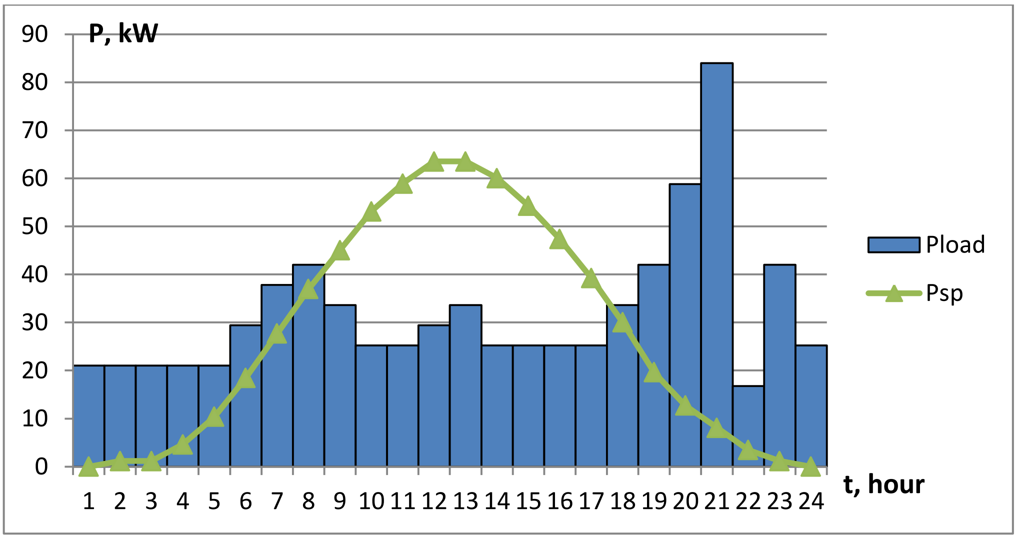
In the second variant of power supply, the load will be covered by the photovoltaic panels partly.

Table 23 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	38 316	12152	63	765 576
February	34 608	10976	63	691 488
March	20 661	8468	63	533 484
April	9 092	5549	63	349 587
May	2 520	2377	63	149 751
June	2 673	1669	63	105 147
July	9 698	4449	63	280 287
August	16 652	7480	63	471 240
September	25 326	10140	63	638 820
October	33 785	10478	63	660 114
November	35 280	10140	63	638 820
December	38 316	12152	63	765 576
Totally	-	**96 030**	63	**6 049 890**

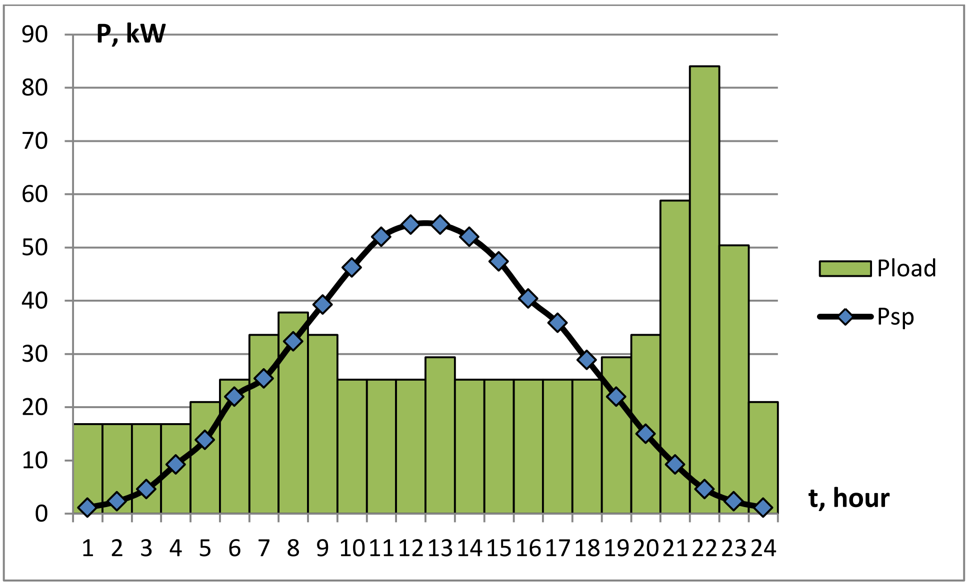
So, the difference in total cost is 1.258 million rubles. Economy of fuel in liters is 19 964. But this amount of PV modules even could not cover demand of electricity even in May and June, as it was in realistic scenario.

New graphs of load capacity and solar insolation in May and June are presented below.



Picture 23 - Graphs of load capacity and solar insolation in May

In May it will be possible to cover demand by PV only from 9 a.m. to midnight.



Picture 23 - Graphs of load capacity and solar insolation in June

In June it will be possible to cover demand by PV from 9 a.m. to 2 a.m.

In this case it is more profitable to use diesel-generators.

Other variants of scenarios with combination optimistic price and realistic consumption, for example, are also calculated. Results are presented in the Table 24. Saving of fuel consumption and savings in RUB are at the intersection. Full calculations are in Appendix E.

Table 24 – All variants of scenarios

Cost of fuel\ Fuel consumption	Optimistic (less than it is)	Realistic	Pessimistic (more than it is)
Optimistic, 42 RUB	1,098 million rubles; 26 159 liters	1,059 million rubles; 25 228 liters	0.839 million rubles; 19 964 liters
Realistic, 52 RUB	1,360 million rubles; 26 159 liters	1,311 million rubles; 25 528 liters	1,038 million rubles; 19 964 liters
Pessimistic, 63 RUB	1,648 million rubles; 26 159 liters	1,589 million rubles; 25 228 liters	1,258 million rubles; 19 964 liters

If demand of electricity is higher on 20%, as it is in pessimistic scenario, government could save less fuel of consumption, because PV modules could not cover demand absolutely even in May and June.

Conclusion

The initial aim of this Master's thesis was to design parallel photovoltaic power plant of village behind the polar circle and estimate economic feasibility of the project. The whole work was divided into seven main chapters with several subparts in each of them.

The first chapter was devoted to technical and climatic features of the investigated object. As for technical features, the category of village power supply reliability is third. Installed power capacity is 100 kW that have helped to build typical daily load graphs for each season during the year, taking into account statistic data [8]. The annual electricity consumption of the village is 306797 kWh per year. Moreover, three diesel generators (one is in reserve) are installed at the diesel power plant. As for climatic features, investigated village locates in the territory behind the polar circle. It means that the main climatic feature of this village is the presence of a midnight sun and a polar night. The polar night at the Khatanga latitude lasts from 17th of November to 25th of January, the midnight sun lasts from 9th of May to 4th of August. But potential assessment of renewable solar energy is presented in the second chapter.

In the second chapter calculation of solar radiation was made with two methods. The first method is connected with using statistical data from the USSR Climate Data book [9], which had being collected during fifty years. The second method is connected with using classical theoretical calculation of solar radiation [10]. So, I got total month solar radiation, combining these two methods. Analyzing obtained information, I made the following conclusion: the most favorable months for the solar modules using are May, June and July, as midnight sun is observed during these months. Structural diagram of the power supply system was also made in this chapter.

The third chapter was about designing of photovoltaic power plant for the village behind the polar circle. In this chapter choice of all necessary equipment was realized. So, photovoltaic power plant includes 432 solar modules, 288 accumulator battery units, 6 controllers and 6 power inverters. Schematic diagram of the photovoltaic power plant is also in this chapter.

The aim of the fourth chapter was economic analysis. Precisely, the main financial indicators: NPV, IRR, IP, PP. In my model I got negative NPV and its result was -42,8 million rubles with price for electricity 95 RUB. The value of IRR in my project was absent, because the project is absolutely not economic effective. As for PI, it is equal to 0.39. According to "the rule of profitability index" it is better to avoid this project, because PI is less, than one. Payback Period was bigger than lifetime of the project that is why this project should not be accepted. The minimum price for 1 kW is 579 RUB, when NPV is 0, but now the existing price is 100 RUB [12], that means absolutely not economic effective project.

But sensitivity analysis was made in the fifth chapter to estimate this project fully. Sensitivity analysis showed that this project is not economic effective absolutely, because the investment is much bigger than the profit from produced energy by photovoltaic panels. And lifetime of such equipment as accumulator batteries, inverters and controllers is less than the lifetime of solar panels that will require additional investments during the whole life time of the project.

In next sixth chapter I calculated economic effectiveness of this project on the example of saved fuel for the diesel generators. I presented a comparative analysis of two power supply system operations. The first variant includes photovoltaic panels, storage batteries and diesel generators. The second variant includes only diesel generators. Comparative analysis was carried out according to the amount of fuel consumption. So, the difference in total cost is 1.311 million rubles. Economy of fuel in liters is 25 528. It means that the government could save only 1.311 mln rubles per year using PV power plant, but the whole investment for 20 years is 39.2 mln rubles. So, it takes about 30 years to cover all investments without any profit, but after 20 years it will be necessary to change equipment on new one that will require additional investment again. So, the project is not economic effective from the point of saving fuel costs also. But it was realistic scenario when both of consumption and fuel cost are according to expected value. And to make financial analysis better it is recommended to do other scenarios also, what has been done in the last seventh chapter.

In seventh chapter I did nine different scenarios, where combinations of realistic, pessimistic and optimistic fuel consumption with realistic, pessimistic and optimistic fuel were presented. I assumed that both of fuel price and fuel consumption could be less or more from the expected value on 20%. I obtained that depending on these changes, government could save more or less money, but it is still not enough to cover investments and to get profit. So, it is more profitable to use only diesel-generators.

To sum up, integration of photovoltaic power plant is not economic effective in that region, despite of midnight sun presence during three months. Investments are too huge to be covered by saved fuel expenses. My recommendation is to use only diesel-generators.

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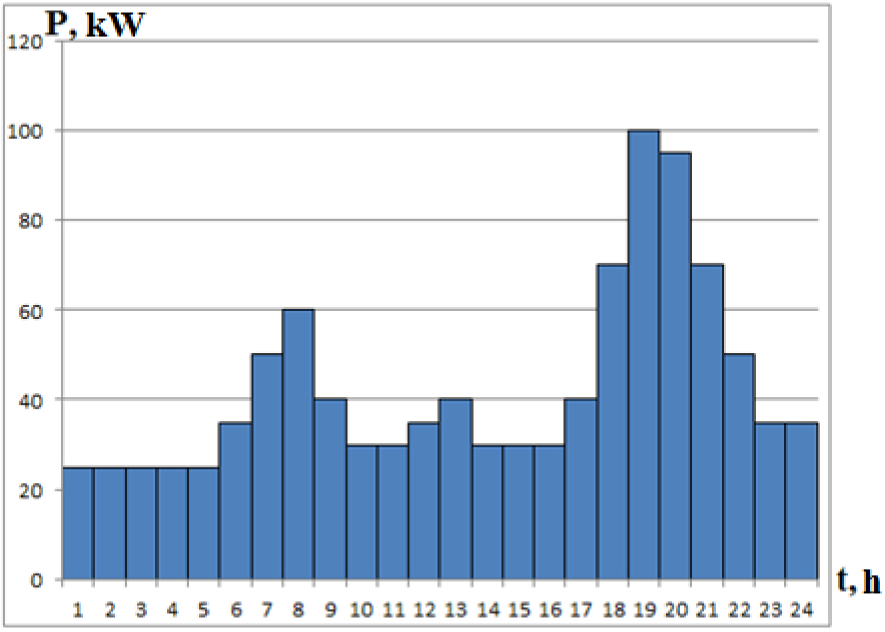
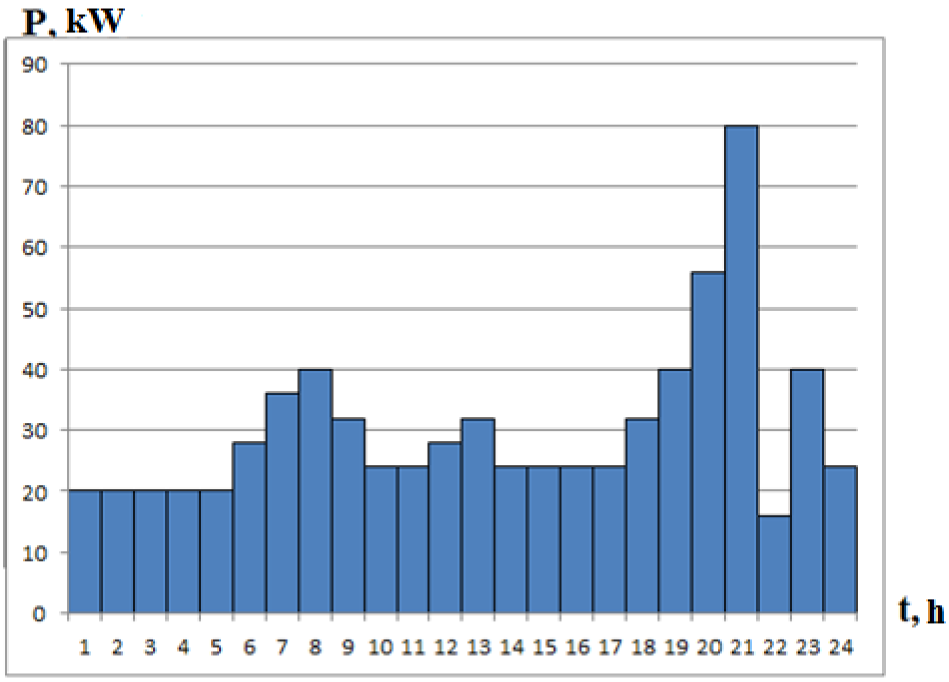
Appendices

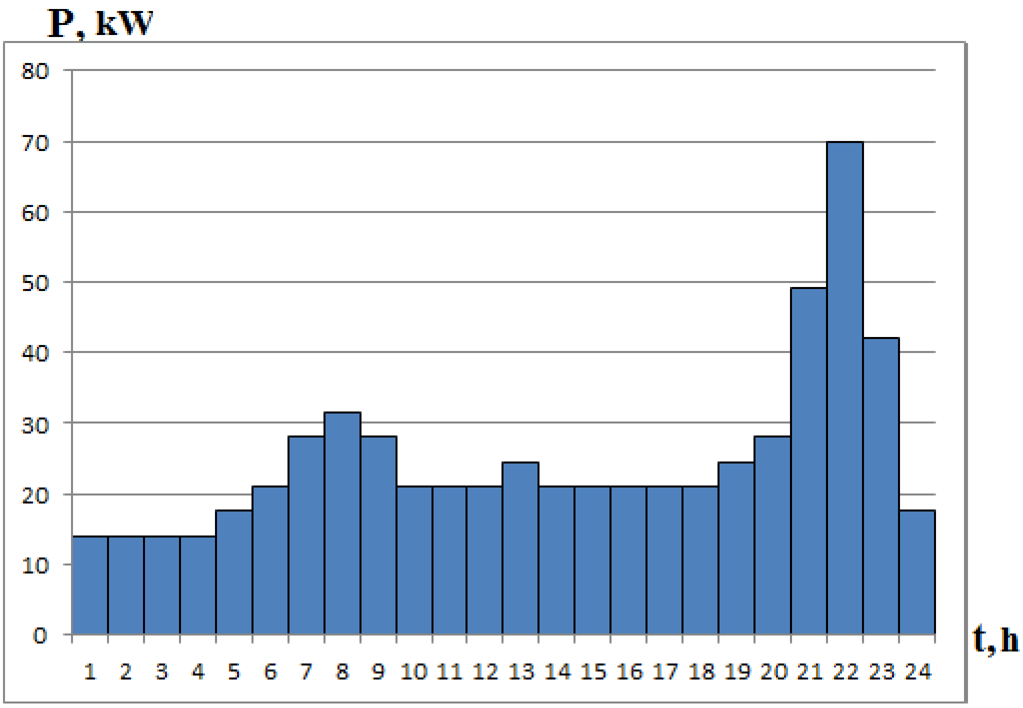
Appendix A – Consumer load graphs



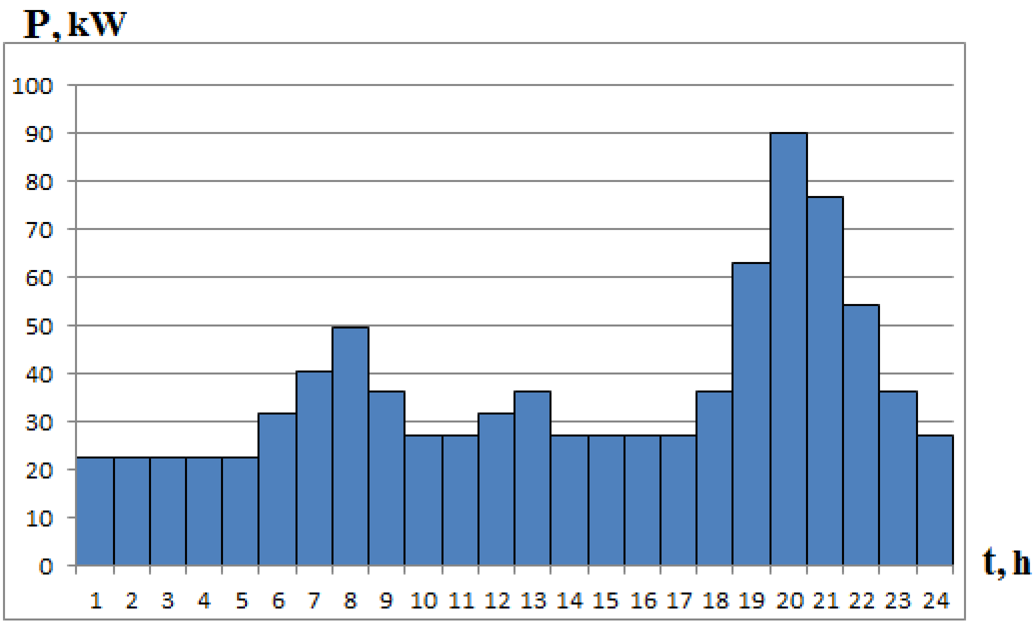
Picture A.1 – Graph of winter daily active power consumption (December)



Picture A.2 – Graph of spring daily active power consumption (March)

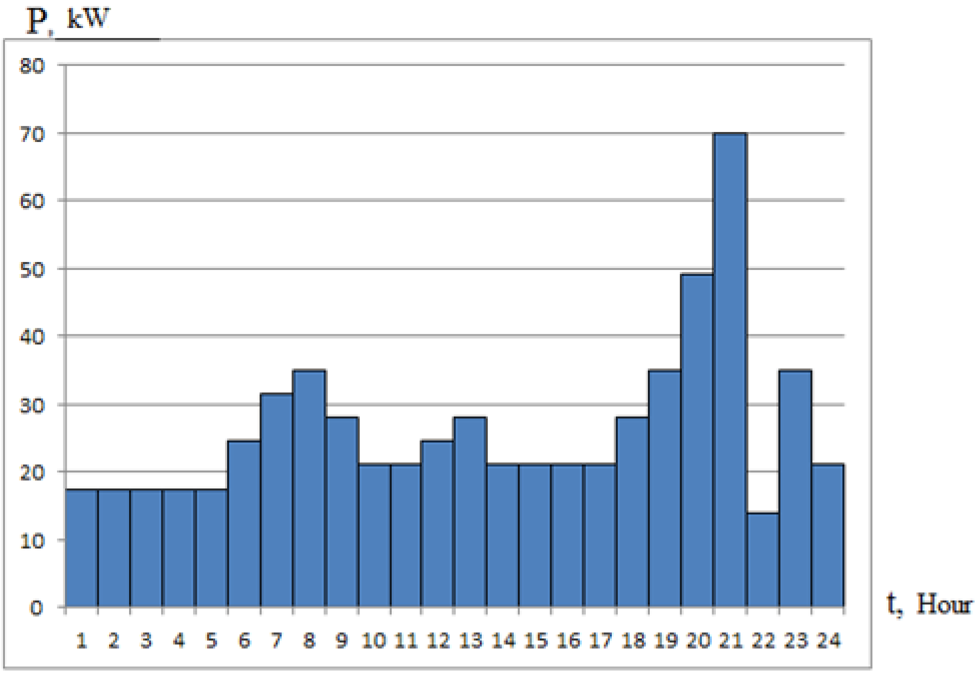


Picture A.3 – Graph of summer daily active power consumption (June)

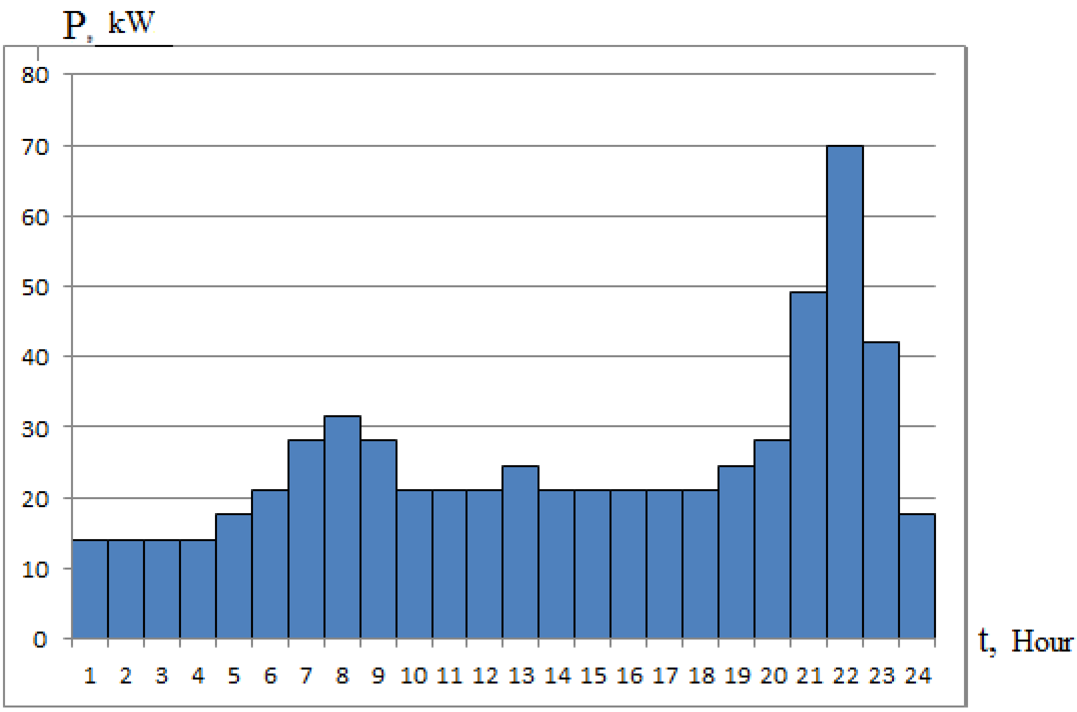


Picture A.4 – Graph of autumn daily active power consumption (September)

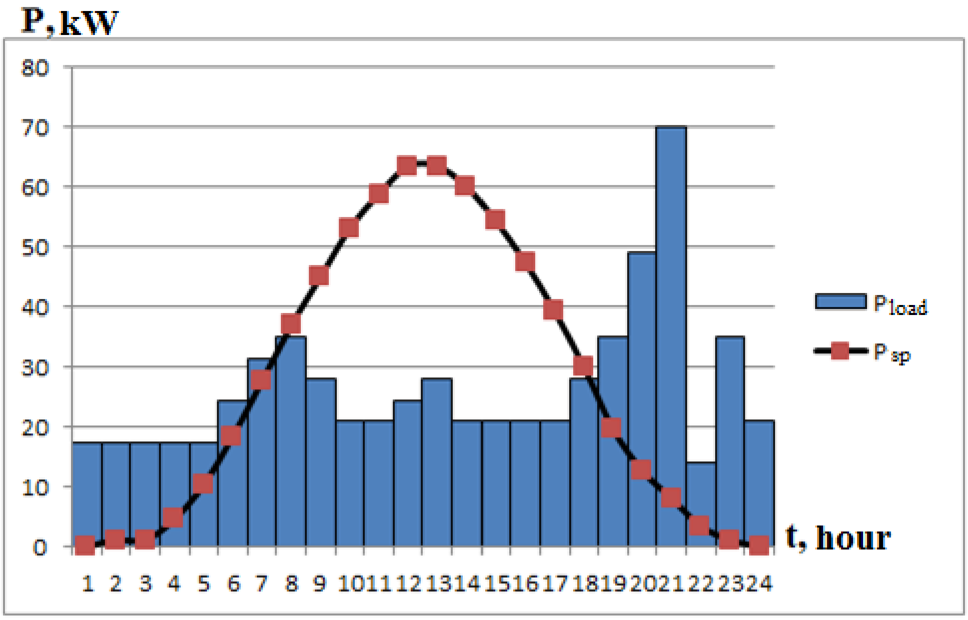
Appendix B – Choice of accumulator batteries



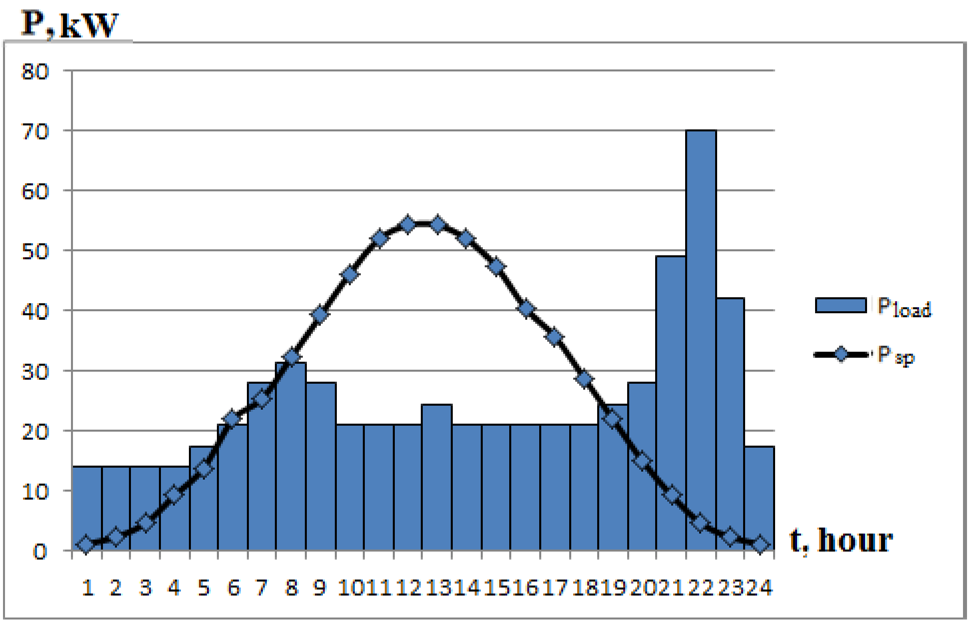
Picture B.1 – Graph of daily active power consumption in May



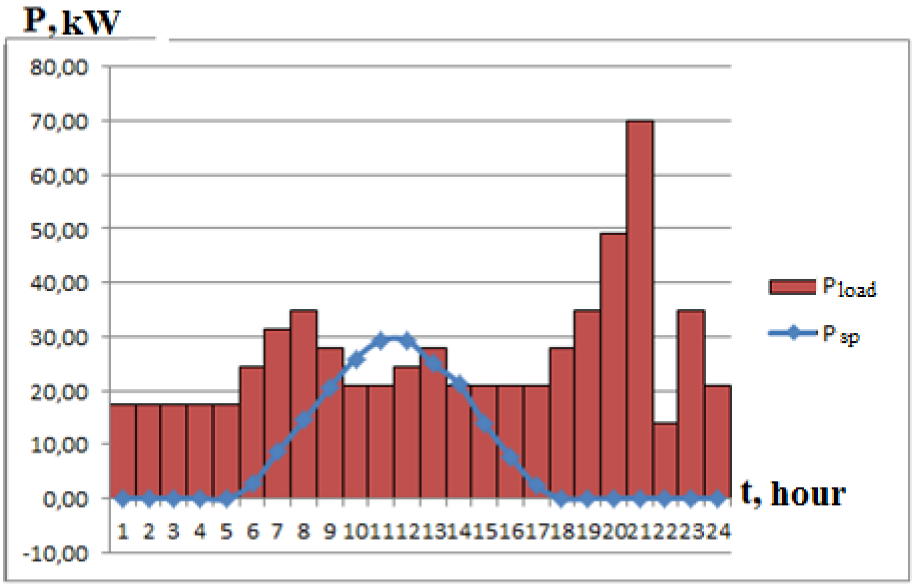
Picture B.2 – Graph of daily active power consumption in June



Picture B.3 – Graph of load capacity and solar insolation in May

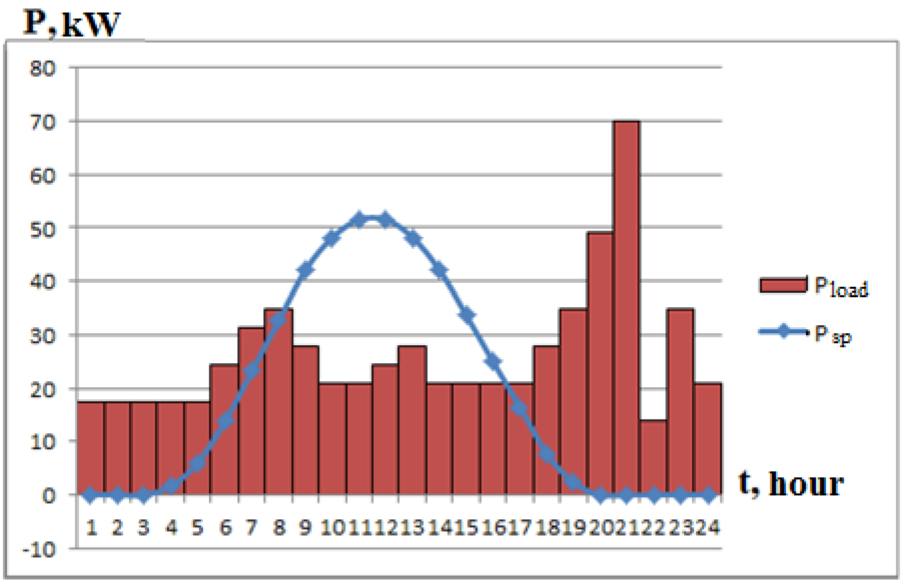


Picture B.4 – Graph of load capacity and solar insolation in June



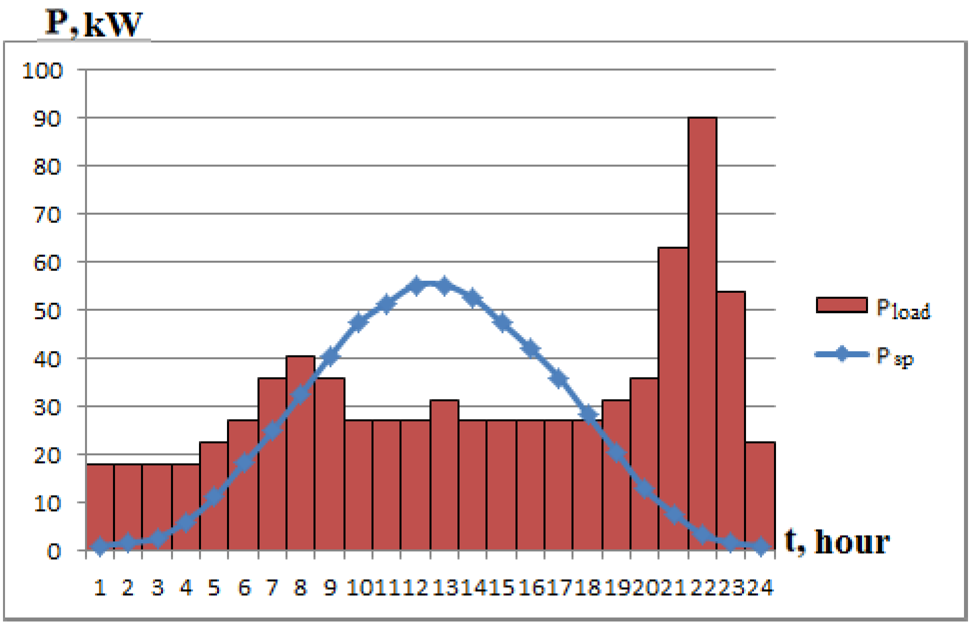
Picture B.5 – Graph of load capacity and solar insolation in March

Solar insolation exceeds the load only from 10 a.m. to 13 p.m hours of the day. Therefore, the diesel generator can be switched off for 3 hours to save fuel.



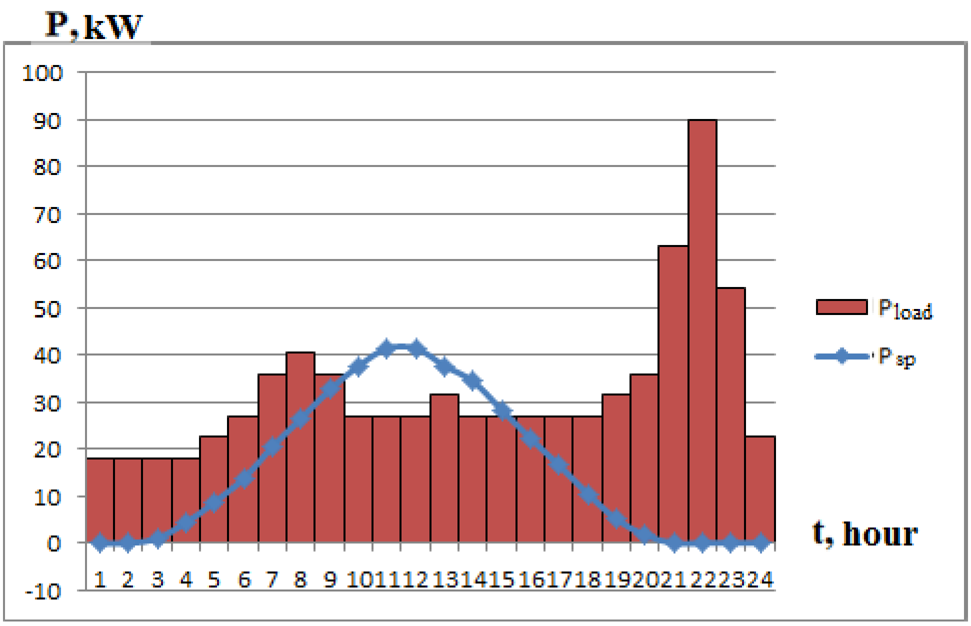
Picture B.6 – Graph of load capacity and solar insolation in April

Solar insolation exceeds the load only from 9 a.m. to 16 p.m. hours of the day. Therefore, the diesel generator can be switched off for 8 hours to save fuel. Moreover 156.77 kWh can be stored and used in the future for another 4 hours. Thus, the diesel generator will be switched off from 9 a.m. to 9 p.m.



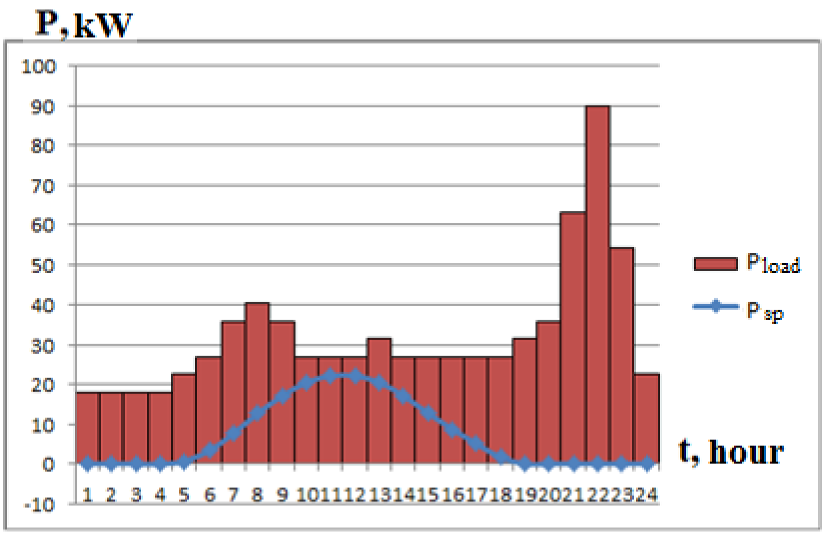
Picture B.7 – Graph of load capacity and solar insolation in July

Solar insolation exceeds the load only from 9 a.m. to 18 p.m. hours of the day. Therefore, the diesel generator can be switched off for 10 hours to save fuel. Moreover 172.97 kWh can be stored and used in the future for another 3 hours. Thus, the diesel generator will be switched off from 9 a.m. to 10 p.m.



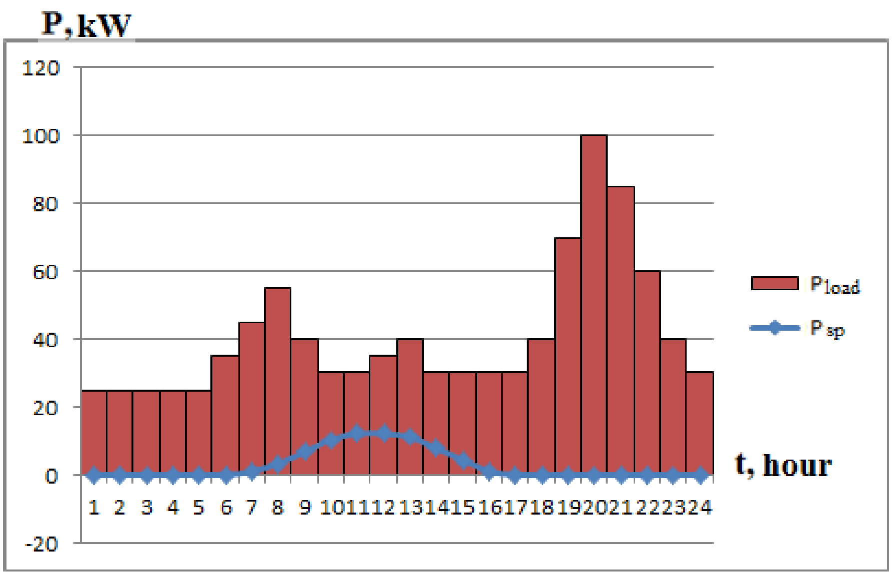
Picture B.8 – Graph of load capacity and solar insolation in August

Solar insolation exceeds the load only from 10 a.m. to 15 p.m. hours of the day. Therefore, the diesel generator can be switched off for 6 hours to save fuel. Moreover 54.49 kWh can be stored and used in the future for another 2 hours. Thus, the diesel generator will be switched off from 10 a.m. to 18 p.m.



Picture B.9 – Graph of load capacity and solar insolation in September

Solar insolation is not enough to cover demand of electricity, so, diesel generator will not be switched off, and so, there is no fuel economy.



Picture B.10 – Graph of load capacity and solar insolation in October

Solar insolation is not enough to cover demand of electricity, so, diesel generator will not be switched off, and so, there is no fuel economy.

Appendix C – Results of Financial model

Table C1 – NPV of financial model with price of electricity 95 RUB

	0	1	2	3	4	5	6	7	8	9	10
Investment	- 39 212 556								- 3 090 119		
Revenue		1 277 986	1 329 105	1 382 269	1 437 560	1 495 062	1 554 865	1 617 059	1 681 742	1 749 012	1 818 972
Operation Cost		- 392 126	- 407 811	- 424 123	- 441 088	- 458 731	- 477 081	- 496 164	- 516 010	- 536 651	- 558 117
Depreciation1		-1 960 628	- 1 960 628	- 1 960 628	-1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628
Depreciation2										- 441 446	- 441 446
Depreciation3											
TAX		-	-	-	-	-	-	-	-	-	-
CF	- 39 212 556	885 860	921 294	958 146	996 472	1 036 331	1 077 784	1 120 896	- 1 924 388	1 212 361	1 260 855
NPV	- 42 777 902										

Table C2 – Cash Flows of financial model with NPV = 0

	0	1	2	3	4	5	6	7	8	9	10
Investment	- 39 212 556								- 3 090 119		
Revenue		7 787 584	8 099 087	8 423 051	8 759 973	9 110 372	9 474 786	9 853 778	10 247 929	10 657 846	11 084 160
Operation Cost		- 392 126	- 407 811	- 424 123	- 441 088	- 458 731	- 477 081	- 496 164	- 516 010	- 536 651	- 558 117
Depreciation1		-1 960 628	- 1 960 628	- 1 960 628	-1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628
Depreciation2										- 441 446	- 441 446
Depreciation3											
TAX		-	-	-	-	-	-	-	-	-	-
CF	- 39 212 556	7 395 458	7 691 277	7 998 928	8 318 885	8 651 640	8 997 706	9 357 614	6 641 799	10 121 195	10 526 043
NPV	- 0										

Continue of Table C3 - Cash Flows of financial model with NPV = 0

11	12	13	14	15	16	17	18	19	20
- 919 670				- 4 066 386					
11 527 526	11 988 627	12 468 173	12 966 899	13 485 575	14 024 998	14 585 998	15 169 438	15 776 216	16 407 264
- 580 442	- 603 659	- 627 806	- 652 918	- 679 035	- 706 196	- 734 444	- 763 822	- 794 374	- 826 149
- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628	- 1 960 628
- 441 446	- 441 446	- 441 446	- 441 446	- 441 446	- 441 446	- 441 446	- 441 446	- 441 446	- 441 446
	- 91 967	- 91 967	- 91 967	- 91 967	- 91 967	- 91 967	- 91 967	- 91 967	- 91 967
-	-	-	-	-	-	-	-	-	-
10 027 415	11 384 968	11 840 367	12 313 982	8 740 154	13 318 802	13 851 555	14 405 617	14 981 841	15 581 115

Appendix D

Table D.1 – Fuel consumption depending on realistic load

Winter	P, kWh	g, g/kWh	G, kg/h	Spring	P, kWh	g, g/kWh	G, kg/h	Summer	P, kWh	g, g/kWh	G, kg/h	Autumn	P, kWh	g, g/kWh	G, kg/h
	25	290	7,25		16	350	5,6		14	370	5,18		22,5	305	6,8625
	25	290	7,25		20	310	6,2		14	370	5,18		22,5	305	6,8625
	25	290	7,25		20	310	6,2		14	370	5,18		22,5	305	6,8625
	25	290	7,25		20	310	6,2		14	370	5,18		22,5	305	6,8625
	25	290	7,25		20	310	6,2		17,5	340	5,95		22,5	305	6,8625
	30	272	8,16		20	310	6,2		17,5	340	5,95		31,5	270	8,505
	30	272	8,16		24	290	6,96		21	308	6,468		40,5	259	10,489
	30	272	8,16		24	290	6,96		21	308	6,468		49,5	290	14,355
	30	272	8,16		24	290	6,96		21	308	6,468		36	264	9,504
	30	272	8,16		24	290	6,96		21	308	6,468		27	285	7,695
	35	265	9,275		24	290	6,96		21	308	6,468		27	285	7,695
	35	265	9,275		24	290	6,96		21	308	6,468		31,5	270	8,505
	35	265	9,275		24	290	6,96		21	308	6,468		36	264	9,504
	35	265	9,275		28	275	7,7		21	308	6,468		27	285	7,695
	40	258	10,32		28	275	7,7		21	308	6,468		27	285	7,695
	40	258	10,32		32	270	8,64		24,5	290	7,105		27	285	7,695
	40	258	10,32		32	270	8,64		24,5	290	7,105		27	285	7,695
	50	290	14,5		32	270	8,64		28	275	7,7		36	264	9,504
	50	290	14,5		36	264	9,504		28	275	7,7		63	270	17,01
	60	272	16,32		40	259	10,36		28	275	7,7		90	259	23,31
	70	265	18,55		40	259	10,36		31,5	270	8,505		76,5	260	19,89
	70	265	18,55		40	259	10,36		42	258	10,836		54	285	15,39
	95	261	24,795		56	262	14,672		49	262	12,838		36	262	9,432
	100	268	26,8		80	259	20,72		70	265	18,55		27	285	7,695
Totally			**279.1**				**202,6**				**178.9**				243,57
Totally, l/h			**234**				**242**				**213**				**290**

Appendix E – Calculation results of scenarios

E.1 Realistic Cost of fuel and Optimistic fuel consumption

Table E.1.1 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	272	8432	52	438 464
February	272	7616	52	396 032
March	230	7130	52	370 760
April	230	6900	52	358 800
May	230	7130	52	370 760
June	218	6540	52	340 080
July	218	6758	52	351 416
August	218	6758	52	351 416
September	262	7860	52	408 720
October	262	8122	52	422 344
November	262	7860	52	408 720
December	272	8432	52	438 464
Totally	-	**89 538**	52	**4 655 976**

Table E.1.2 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	25 544	8432	52	438 464
February	23 072	7616	52	396 032
March	12 918	6333	52	329 316
April	4 217	3612	52	187 824
May	-	0	52	-
June	-	0	52	-
July	44	3101	52	161 252
August	9 460	4602	52	239 304
September	16 884	7860	52	408 720
October	22 524	8122	52	422 344
November	23 520	7860	52	408 720
December	25 544	5841	52	303 732
Totally	-	**63 379**	52	**3 295 708**

E.2 Pessimistic Cost of fuel and Optimistic fuel consumption

Table E.2.1 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	272	8432	63	531 216
February	272	7616	63	479 808
March	230	7130	63	449 190
April	230	6900	63	434 700
May	230	7130	63	449 190
June	218	6540	63	412 020
July	218	6758	63	425 754
August	218	6758	63	425 754
September	262	7860	63	495 180
October	262	8122	63	511 686
November	262	7860	63	495 180
December	272	8432	63	531 216
Totally	-	**89 538**	63	**5 640 894**

Table E.2.2 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	25 544	8432	63	531 216
February	23 072	7616	63	479 808
March	12 918	6333	63	398 979
April	4 217	3612	63	227 556
May	-	0	63	-
June	-	0	63	-
July	44	3101	63	195 363
August	9 460	4602	63	289 926
September	16 884	7860	63	495 180
October	22 524	8122	63	511 686
November	23 520	7860	63	495 180
December	25 544	5841	63	367 983
Totally	-	**63 379**	63	**3 992 877**

E.3 Optimistic Cost of fuel and Realistic fuel consumption

Table E.3.1 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	234	7254	42	304 668
February	234	6552	42	275 184
March	242	7502	42	315 084
April	242	7260	42	304 920
May	242	7502	42	315 084
June	213	6390	42	268 380
July	213	6603	42	277 326
August	213	6603	42	277 326
September	290	8700	42	365 400
October	290	8990	42	377 580
November	290	8990	42	377 580
December	234	7254	42	304 668
Totally	-	89600	42	**3 763 200**

Table E.3.2 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	31 930	7254	42	304 668
February	28 840	6552	42	275 184
March	16 147	6704	42	281 568
April	5 271	3216	42	135 072
May	-	0	42	-
June	-	0	42	-
July	4 871	2042	42	85 764
August	11 825	4670	42	196 140
September	21 105	8700	42	365 400
October	28 154	8990	42	377 580
November	29 400	8990	42	377 580
December	31 930	7254	42	304 668
Totally	-	**64372**	42	**2 703 624**

E.4 Pessimistic Cost of fuel and Realistic fuel consumption

Table E.4.1 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	234	7254	63	457 002
February	234	6552	63	412 776
March	242	7502	63	472 626
April	242	7260	63	457 380
May	242	7502	63	472 626
June	213	6390	63	402 570
July	213	6603	63	415 989
August	213	6603	63	415 989
September	290	8700	63	548 100
October	290	8990	63	566 370
November	290	8990	63	566 370
December	234	7254	63	457 002
Totally	-	**89600**	63	**5 644 800**

Table E.4.2 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	31 930	7254	63	457 002
February	28 840	6552	63	412 776
March	16 147	6704	63	422 352
April	5 271	3216	63	202 608
May	-	0	63	-
June	-	0	63	-
July	4 871	2042	63	128 646
August	11 825	4670	63	294 210
September	21 105	8700	63	548 100
October	28 154	8990	63	566 370
November	29 400	8990	63	566 370
December	31 930	7254	63	457 002
Totally	-	**64372**	63	**4 055 436**

E.5 Optimistic Cost of fuel and Pessimistic fuel consumption

Table E.5.1 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	392	12152	42	510 384
February	392	10976	42	460 992
March	290	8990	42	377 580
April	290	8700	42	365 400
May	290	8990	42	377 580
June	253	7590	42	318 780
July	253	7843	42	329 406
August	253	7843	42	329 406
September	338	10140	42	425 880
October	338	10478	42	440 076
November	338	10140	42	425 880
December	392	12152	42	510 384
Totally	-	**115 994**	42	**4 871 748**

Table E.5.2 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	38 316	12152	42	510 384
February	34 608	10976	42	460 992
March	20 661	8468	42	355 656
April	9 092	5549	42	233 058
May	2 520	2377	42	99 834
June	2 673	1669	42	70 098
July	9 698	4449	42	186 858
August	16 652	7480	42	314 160
September	25 326	10140	42	425 880
October	33 785	10478	42	440 076
November	35 280	10140	42	425 880
December	38 316	12152	42	510 384
Totally	-	**96 030**	42	**4 033 260**

E.6 Realistic Cost of fuel and Pessimistic fuel consumption

Table E.6.1 - The monthly consumption of fuel and its prices

Month	Per day, l	Per month, l	Price, RUB	Total cost, RUB
January	392	12152	52	631 904
February	392	10976	52	570 752
March	290	8990	52	467 480
April	290	8700	52	452 400
May	290	8990	52	467 480
June	253	7590	52	394 680
July	253	7843	52	407 836
August	253	7843	52	407 836
September	338	10140	52	527 280
October	338	10478	52	544 856
November	338	10140	52	527 280
December	392	12152	52	631 904
Totally	-	**115 994**	52	**6 031 688**

Table E.6.2 - Data of the fuel and energy savings due to the PV panels operating

Month	Demand per month, kWh	Per month, l	Price, RUB	Total cost, RUB
January	38 316	12152	52	631 904
February	34 608	10976	52	570 752
March	20 661	8468	52	440 336
April	9 092	5549	52	288 548
May	2 520	2377	52	123 604
June	2 673	1669	52	86 788
July	9 698	4449	52	231 348
August	16 652	7480	52	388 960
September	25 326	10140	52	527 280
October	33 785	10478	52	544 856
November	35 280	10140	52	527 280
December	38 316	12152	52	631 904
Totally	-	**96 030**	52	**4 993 560**