Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management and Humanities

USAGE OF SOLAR TRACKERS TO IMPROVE EFFICIENCY OF PV SYSTEMS

Master thesis

Study program: Electrical engineering, Power Engineering and Management

Field of study: Economy and Management of Power Engineering

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Usage of solar trackers to improve efficiency of PV systems

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Usage of solar trackers to improve efficiency of PV systems

Pokyny pro vypracování:

- analyze and identify key parameters of stand-alone energy systems
- identify and describe ways to improve efficiency of stand-alone energy systems
- design and propose possible technical solutions of energy supply for given location using PV system with solar trackers
- perform technical and economic evaluation of proposed PV system with solar trackers

Seznam doporučené literatury:

BOXWELL, Michael. Solar electricity handbook: a simple practical guide to solar energy : how to design and install photovoltaic solar electric systems. 2015 edition, Ninth edition. ISBN 9781907670459.
Y. A. SHINYAKOV, Y. A. SHURYGIN, and O. E. ARKATOVA, ?Povyshenie energeticheskoy effektivnosti avtonomnyh fotoelektricheskih energeticheskih ustanovok - Improving the energy efficiency of autonomous photovoltaic power plants,? vol. 2, no. 22, pp. 102?107, 2010.
A. V. OHORZINA, M. V. KITAEVA, A. V. YRCHENKO, and A. V. SKOROHODOV, ?Sun tracking systems with using photoelectrical sensor,? Polzunovsky Vestn., pp. 213?217, 2012.

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Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání Podpis studenta

DECLARATION

“I hereby declare that this master’s thesis is the product of 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

The thesis considers the usage of solar trackers as the way to increase efficiency of PV systems in a decentralized area in the south-eastern part of Russia. Implementation of solar trackers is presented in the case study of the thesis. The case study examines three possible technical solutions to power supply the object of investigation: a petroleum based generator power plant; optimally tilted PV system in assembly with the petroleum generator; PV system in assembly with a dual-axis solar tracker and a petroleum generator. In order to determine the power output of PV systems, the technique which allows to calculate the total solar radiation falling on the plane oriented in any direction is used. The considered variants are evaluated from both technical and economic points of view. The net present value and minimum electricity price are the main indicators for economic evaluation. The sensitivity analysis on most important parameters is conducted.

KEY WORDS

Decentralized energy supply, renewable energy source, solar energy, photovoltaic system, solar tracker

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LIST OF ABBREVIATIONS

RES – Renewable energy sources

DES – Decentralized energy supply

PV – Photovoltaic

IEA – International Energy Agency

STC – Standard Test Conditions

DG – Diesel generator

STC – Standard test conditions

CVC – Current-voltage characteristic

DC – Direct current

AC – Alternating current

PWM – Pulse width modulation

MPPT – Maximum power point tracking

HSAT – Horizontal single axis tracking

VSAT – Vertical single axis tracking

TSAT – Tilted single axis tracking

AADAT – Azimuth-altitude dual axis tracking

TRDAT – Tilt-roll dual axis tracking

ATS – Automatic transfer switch

NPV – Net present value

CAGR – Compound annual growth rate

KWH – Kilowatt hour

MW – Megawatt

CONTENTS

INTRODUCTION

Energy consumption has been rapidly increasing in the world over the last decades. The growth is mainly explained by population increase and the economic development of countries. Almost 81% of the world energy consumption is obtained by combustion of fossil fuels [1]. The energy based on fossil fuels affects the environment and humanity, for instance, oxygen and water consumption, gas and toxic emissions, depletion of fossil fuels reserves, and global warming. Therefore, all these factors are leading to an unsustainable situation in the future. In modern conditions, there are two options to decrease the above-mentioned harmful impacts. The first option is the active usage of energy-saving technologies. The second option is an intensive introduction of renewable energy sources including biomass, wind, hydro, geothermal and solar energy. At the moment, RES make a significant contribution to the energy supply. Thus, these sources have already a great potential to replace fossil fuels and can meet the future required demand of energy.

In comparison with all available non-conventional energy sources, solar energy looks as one of the most promising directions of renewable energy development. Solar energy utilization is characterized by the following advantage factors: inexhaustible resource, environmentally friendly and widespread distribution. Today, among the diverse types of solar energy technologies, the photovoltaic system is one of the perspective directions to produce electrical energy. The most relevant and cost-effective way of utilization of PV systems is as a power supply of decentralized objects in remote areas. The substitution of diesel generators for PV systems, in this case, allows to solve energy as well as ecology problems, and in a number of cases it is economically feasible.

However, photovoltaic systems have a number of drawbacks. Along with the high investment cost and low efficiency of photocells, there is one of the major problem in PV system utilization: a decrease in their efficiency when the solar panels are disoriented to the Sun. Presently, the majority of PV panels are inclined at a fixed optimal angle during the whole operational period. Therefore, PV systems do not use the whole potential of the incoming solar radiation. This results in a lower power output of the overall PV system.

The power output of the PV system reaches its maximum value when the solar panels are perpendicular to the Sun’s rays. Therefore, the solution to this problem is the usage of a sun tracking system or a solar tracker. A solar tracker is a device that is designed to orient the PV panel toward to the Sun’s position. These devices change their orientation throughout the day to follow the Sun’s path in order to maximize energy capture. Thus, a solar tracker can significantly increase the power output by up to 30 – 55% compared to stationary PV panels [2]. But the major constraint factor of solar tracker utilization is the significant cost of trackers due to more complex technology and moving parts. Thereby, whether solar trackers are beneficial and recommended is dependent on various factors. The reasonable question about the viability of Sun tracking is arising.

Therefore, the objective of the thesis is to identify whether the usage of solar trackers in PV systems is reasonable from both technical and economic points of view.

1. THE PROBLEM OF POWER SUPPLY IN DECENTRALIZED AREAS

1.1. WORLD

The constant growth of the world's population is the reason why the problem of electrification will always exist. Today, the world population is about 7.4 billion and continues to grow. According to the "World Population Data Sheet", the population will reach 8.5 billion in 2030. The increase of population leads to the growth of world economy. The increase of economic growth yields an increase in energy demand. Electricity expansion growth will have to double to meet the 100 percent access target by 2030 [3].

At the moment, there are a number of countries that have a problem associated with access to energy services. According to the IEA, about 1.2 billion people (that is about 17% of the global population) or more than a fifth of the world's population, live without electricity, and about 1 billion people more have only an unreliable and unsustainable power supply. More than 95% of people who live without access to electricity are in sub-Saharan Africa and in developing Asia, where most live in rural areas (around 80% of the world total). India with one-sixth of the world's population accounts for only 6% of global energy use and one in five of the population – 237 million people – still have a lack of access to electricity [4].

In developing countries, access to acceptable, secure and reliable energy services is fundamental. It helps to decrease poverty and improve health, to increase productivity and competitiveness, and to promote the growth of the economic sector of the country. Moreover, access to energy involves important factors such as clean water and healthcare, the provision of reliable and efficient cooking, heating, lighting, transportation and telecommunications services. Table 1 shows the situation with the world electrification.

Table 1 – Electricity access in 2015 - Regional aggregates [5]

Region	Population without electricity, millions	Electrification rate, %	Urban electrification rate, %	Rural electrification rate, %
Developing countries	1 200	78%	92%	67%
Africa	635	43%	68%	26%
North Africa	*1*	*99%*	*100%*	*99%*
Sub-Saharan Africa	*634*	*32%*	*59%*	*17%*
Developing Asia	526	86%	96%	78%
India	*237*	*81%*	*96%*	*74%*
Latin America	22	95%	98%	85%
Middle East	17	92%	98%	79%
WORLD	1 201	83%	95%	70%

As it was mentioned before, the majority of the population lives in rural areas. The problem of electrification can be caused by the following technical and economic reasons: improper and rough geographical conditions, economically inapplicable installations, lack of funding and investment. In the case when there is no possibility to be connected to the central grid from either technical or economic reasons, the alternative variants which correspond to energy requirements can be used. In other words, alternative variants mean decentralized energy supply (DES) systems.

DES systems are systems that generate energy from a power source without connection to the central grid, so-called "off-grid" or "stand-alone" systems. These systems are flexible, modular and located close to the object of supply. There are several ways of decentralized energy supply. It can be classified by conventional, non-conventional and hybrid energy systems. Where conventional systems run on fossil fuel (typically diesel, petroleum), non-conventional systems run on renewable energy sources, hybrid systems run both on conventional and renewable sources.

At present, DES systems play a vital role in providing energy services. In such countries as Denmark, Germany, USA, China, stand-alone energy systems based on RES are already able to replace or supplement traditional power systems in the areas without connection to the centralized power supply. Based on experience from countries it is already proven that the off-grid systems are an available, reliable and cost-effective way to supply decentralized consumers [6].

1.2. RUSSIA

According to experts' estimations, about 70% of the Russian territory belongs to the decentralized power zone supplying a population of about 20 million people, or approximately 14% of the total population of Russia [7]. Most of these decentralized territories are located in areas with severe climatic conditions. Thus reliable energy supply of the population in these areas is the most important economic problem for many constituent units of the Russian Federation. The decentralized areas of Russia are presented in Figure 1.

The Russian Federation is a typical example of a country with an already developed system of centralized power. At the same time, Russia has a substantial need for the decentralized energy supply systems. Most of the territory of Russia is characterized by low population density and long distances between centralized power systems and consumers. The population density on the Russian territory is presented in Figure 2.

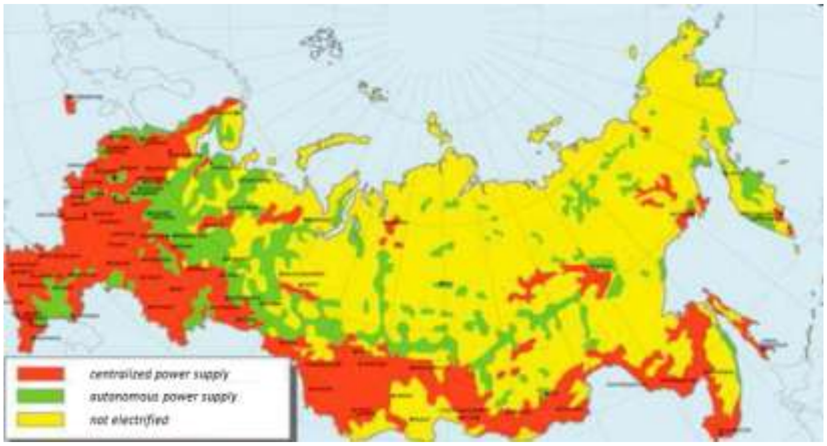

Figure 1 – Decentralized areas of Russia [8]

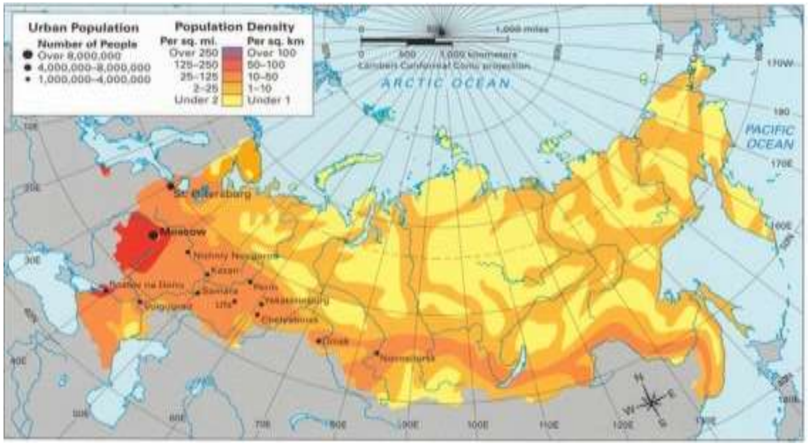

Figure 2 – Population density on the Russian territory [9]

Figure 1 shows that more than half of the territory of Russia is not electrified at all. It can be seen from Figure 2, that there is a low population density with low electrification rate in the Far East, North and East Siberia [10]. According to the maps, it can be concluded that Russian potential for decentralized energy supply is enormously high. Table 2 presents a statistical overview about the population in areas without centralized power supply.

Table 2 – Information about the population in areas of decentralized power supply [11]

Number of people living in the settlements	Number of settlements, units	Population in the location
Up to 50	13 500	172 600
From 51 to 500	11 100	2 400 000
From 501 to 3 000	5 700	5 900 000
From 3001 to 10 000	580	2 600 000
Total		11 072 600

A number of these non-electrified regions (settlements) face problems such as high poverty, unemployment, low living conditions, the under-development of agricultural goods and products. The power supply to such consumers, in general, can be carried out either through centralized electricity supply or the creation of decentralized energy supplies. However, it’s obvious that the construction of power lines to the centralized system is an option but it requires significant investment costs, and time, thereby, it is not economically feasible [11]. Therefore, the creation of decentralized energy supply systems is a proper and viable solution to these problems.

At the moment, most of decentralized energy supply in Russia is based on diesel power plants which have been widely applied as the main source. For example, the Republic of Yakutia, which extends to 2.2 million kilometers of territory and encompasses 150 thousand people, is provided with electricity by 129 autonomous diesel power plants [12].

There are some statistics that shows more than five thousand diesel generators operating in the country and which produce about 1.8 billion kWh of electricity with an annual fuel consumption of 6-8 million tons. These 6-8 million tons of fuel are delivered by rail or road and sometimes by helicopter. Such kinds of supplies are very expensive and unreliable. Additionally, it is noticed that the fuel is becoming more expensive and prices will only continue to grow in the future. An increase in fuel prices leads to an increase in transportation tariffs. Thus, the costs of transportation are increasing as well. As for the current situation, the cost of generated electricity is up to 25-40 RUB per kWh, while the average cost of electricity for the population in the centralized areas is RUB 2.5-3.5 per kWh. In some specific regions, the cost can be 125 RUB per kWh [13].Apart from fuel and transportation costs, one more influential reason of such significant numbers is the cost for required maintenance and repair of diesel generators.

Based on the discussion provided above, it is reasonable to pay attention to decentralized energy supply systems based on renewable energy sources. There is a number of scientific literature that widely addresses the analysis of stand-alone systems for decentralized areas in Russia. According to the results, it can be concluded that the remote areas of Russia are an excellent starting platform to implement renewable energy source into DES.

1.3. STAND-ALONE ENERGY SYSTEMS

Based on discussion in the previous subchapter, the decentralized energy systems based on fossil fuel as well as renewable energy sources are the current practical solutions for remote customers without connection to the electricity grid. The necessity in stand-alone energy systems exists due to such factors as independence on electricity grid, no payment for connection and construction costs of power lines, independence on global energy crisis, etc. Therefore, it is necessary to introduce the key parameters of these systems. The modern stand-alone systems should have following key parameters:

- The required level of reliability of energy supply
- Parameters of produced energy should correspond to the requirements
- Full-automation of technological process of energy production
- Efficiency of energy production
- Quick response of operation (switching between sources, etc.)
- Simplicity of the supply system
- Scaling (available range of operating installed capacities)
- Controllability of power source (or maneuverability)

Apart from the above-listed parameters, the most important parameters which characterize the stand-alone energy systems are availability of power sources and the load diagram of the object of investigation. According to the case study of the thesis, the object of investigation is the meteorological station (weather station). The meteorological station is located in the east-south part of Russia, Republic of Buryatia. The object has 1.4 kW of the maximum load and its load diagram is presented in Figure 19. More detailed description of the object is presented in 4.2.

It is obvious that the diesel/petroleum generator power plant is automatically considered as the potential power source of the object. Despite the number of problems described earlier, these power plants have more powerful advantage factors such as reliability and stability of power output, high efficiency factor, automatization of processes, quick start and high maneuverability, simplicity of the plant and its installation and low investment costs. In the result, the diesel/petroleum power plant corresponds to all key parameters of stand-alone systems. Also there is no any technical and funding restrictions to install the generator power plant. From another side, the main disadvantages of the power plant are the high operating costs, emissions from burning of fuel and negative social effect.

Since that there is a chance to supply the object not only on the basis of diesel/petroleum generator set, the decentralized energy supply system based on RES will be considered. Based on the information provided in the subchapter 1.2, the utilization of RES in composition of DES systems can make a significant contribution to solving the problems of decentralized consumers. These systems are divided by the type of RES:

- wind power
- biomass energy
- geothermal energy
- small hydropower
- solar energy

However, the crucial question about the availability of such sources is arising. Therefore, the potential of renewable energy sources in Russia and in the region of the object will be examined in the next subchapter.

1.4. THE POTENTIAL OF RENEWABLE ENERGY IN RUSSIA

The potential of RES in the Russian Federation is significantly high. Russia has a number of various resources – hydropower, bioenergy wind power, geothermal power, biomass and solar power. Most of the regions possess at least one or two options of RES that are commercially feasible, while some of these areas are abundant in all forms of RES. Despite its energy and economic state of RES and the existing scale of fossil fuel extraction, at the moment, the Russian Federation uses a small part of its huge potential. About 21% of Russian electricity is produced by hydropower, and less than 1% of total installed energy capacity in the country is produced by other renewable energy sources [13].

By the end of 2015, the total installed renewable power generation capacity reached 53.5 GW, where around 20% of Russia's total installed power generation capacity (253 GW). Most of that capacity is represented by hydropower with (51.5 GW), by bioenergy (with 1.35 GW). Installed capacity for photovoltaic and the wind is about 460 MW and 111 MW, respectively [14]. According to the "Renewable Energy Policy in Russia" report [15], Russia prepared a detailed projection of energy usage and intends to reach 4.5% of all electricity generation and consumption from renewable sources by 2020. This step has sent positive signals to the potential development of this sector.

The power potential of renewable energy sources in Russia can be estimated in different ways depending on technical and economic aspects of their usage. From each point of view, it is necessary to find the gross potential, technical potential and economic potential of RES.

The gross potential is an amount of energy produced by a given type of energy resource in case of complete and full utilization. The technical potential is a part of the gross potential. It is useful energy which is reasonable under the certain level of technical development. Economic potential is a part of a technical potential. It is useful energy which is economically feasible under specific economic conditions (price on fuel, electricity, and heat, price on equipment and materials, transport and labor power). Table 3 presents the assessment of the potential RES of Russia according to the Russian experts' estimations.

Table 3 – Assessment of the potential renewable energy sources of Russia [16]

Resources	Gross potential, million tons of reference fuel/year	Technical potential, million tons of reference fuel/year	Economic potential, million tons of reference fuel/year
Wind	$26 \cdot 10^3$	2000	10
Small hydropower	360,4	124.6	65,2
Solar	$2,3 \cdot 10^6$	2300	12,5
Biomass	$10 \cdot 10^3$	53	35
Low-temperature heat	525	115	36
Total	$2,34 \cdot 10^6$	4593	273,5

Taking into account the economic potential, the extent of RES is estimated approximately 30% of the total energy production, the technical potential is estimated to be more than five times bigger compared with total primary energy production of Russia [17]. Therefore, the following RES such as wind, biomass, geothermal, small hydropower and solar which are widely available in Russia will be considered further in more details as the potential source of power.

1.4.1. Wind power

The highest wind energy potential in Russia is concentrated along the coastal areas and islands of the Arctic and Pacific Oceans. Also, the proper zones for wind energy development are located in the Northern regions, Far East, Kamchatka Peninsula, where the average wind speed exceeds 6 meters/second. Distribution of average wind speeds on the territory of the country is represented on the map (Appendix 1). Average wind speeds vary significantly in the daily and annual cycles. Consequently, wind energy has unstable characteristics and rapid fluctuations which are accompanied by abrupt changes in the power output. According to the wind cadaster of Russia, only 40% (include above-described regions) of Russian territory can be used to generate electricity. By comparing the maps presented in Appendix 1 and Figure 2, it can be seen that the majority of wind potential is found in those regions, where the population density is low (less than one person per 1 km^2). Wind power usually is estimated by using an average wind speed in the location. Since the object of investigation has small installed capacity, the range of minimum required wind speed is 2.5 – 3 m/s [7]. According to the statistical data [18], the data of low average annual wind speed (low than 2.4 m/s) is obtained. Thus, it can be concluded that the usage of wind power for electric supply is inefficient in the region of the meteorological station.

1.4.2. Biomass energy

The potential of large-scale and efficient usage of biomass is quite high in some regions of Russia. According to “Intersolar center”, a Russian company which deals with renewable energy sources, Russia produces about 15 billion tons of biomass annually, which is about 8 billion ton of reference fuel in the energy equivalent [13]. However, there are severe limitations of using biomass to produce energy. The problem of efficient processing and combustion of biomass is still relevant. This is because biomass is composed of low-grade fuels with high moisture content (up to 85%). Therefore, it requires additional costs for drying and pretreatment (grinding, pressing, etc.). The most common method of producing energy from biomass is combustion. The combustion process has its difficulties: firstly, different types of biomass require different firing devices, and secondly, installations for the direct combustion of biomass is relatively inefficient and unsustainable energy system. Furthermore, the environmental parameters of the furnaces must comply with applicable standards of emissions. Also, biofuel production is justified if the restocking cheap raw material is used intermittently. Examples of stocks cheap raw material can be animal waste, sawdust, municipal waste, straw cereals, etc. It is very important to assess the possible flows of the respective raw materials. If there are no raw materials, its collection can be technically and economically challenging. Apart from that, the special infrastructure for processing biofuel is required to construct a power system. Therefore, the biomass energy for supplying the object is not considered.

1.4.3. Geothermal energy

In recent years, Russia has made progress in the development of geothermal energy. At this time, almost all territories of Russia are well explored, and the investigation shows a number of the regions with large reserves of geothermal resources. According to the map in Appendix 2, the red color shows high-temperature geothermal resources (150 °C <), which are suitable for producing electricity; the green color shows low-temperature geothermal resources (90-100 °C), which are suitable for centralized heat supply and agriculture; the pink color represents medium temperature geothermal resources (90-100 °C – 150 °C), which are suitable for binary power plants. It can be seen that only the Kamchatka Peninsula, the Kuril Islands, and the North Caucasus have enough geothermal energy to produce electricity [13]. The Republic of Buryatia, where the object is located, possess only low-temperature geothermal resources (90-100 °C) therefore the geothermal energy becomes unacceptable variant.

1.4.4. Small hydropower

In Russia, hydropower is the most developed industry for renewable energy. Small rivers account for approximately 46% of the total hydropower potential. Most of hydropower sources are located in Eastern Siberia, Far East, North Caucasus and the western part of the Urals. Appendix 3 shows the current situation of hydropower resources in Russia [7]. It is obvious that small hydropower plays a leading role in the energy supply of decentralized regions of Russia, but it should be noticed that water resources can be absent in areas. Additionally, the areas must be proper for the construction of a power plant. An important factor is that energy production of power plants is proportional to the quantities of water flows. The water flow should be large and fast enough to ensure reliability. This can't be always obtained. However, small hydropower plants have a great number of advantages. The construction of small hydropower for the weather station is not considered due to a long distance from available hydropower resource to the object and load diagram of the object. The closest possible hydropower source (river "Hilok") is located in 30 km away.

1.4.5. Solar energy

Russia is located between 41 and 82 degrees of north latitude, and solar radiation levels vary significantly within the vast territory of the country. Nonetheless, Russia has a huge potential for the development of solar energy. It is estimated that solar radiation in the remote northern regions is 810 kWh/m^2 per year, whereas, in the southern regions, it is more than 1400 kWh/m^2 per year. The average solar insolation is equal to 1200 – 1500 kWh per year [13].

There is a misconception about the utility of the usage of solar energy in the Russian Federation, due to the insufficient level of its incident solar radiation. Figure 3 maps the annual distribution of average daily solar radiation on the territory of Russia, developed by High Temperatures RAS using Russian solar radiation stations. Thus, State Institution of Science "Joint Institute for High Temperatures" of the Russian Academy of Sciences can refute such opinions according to the obtained data.

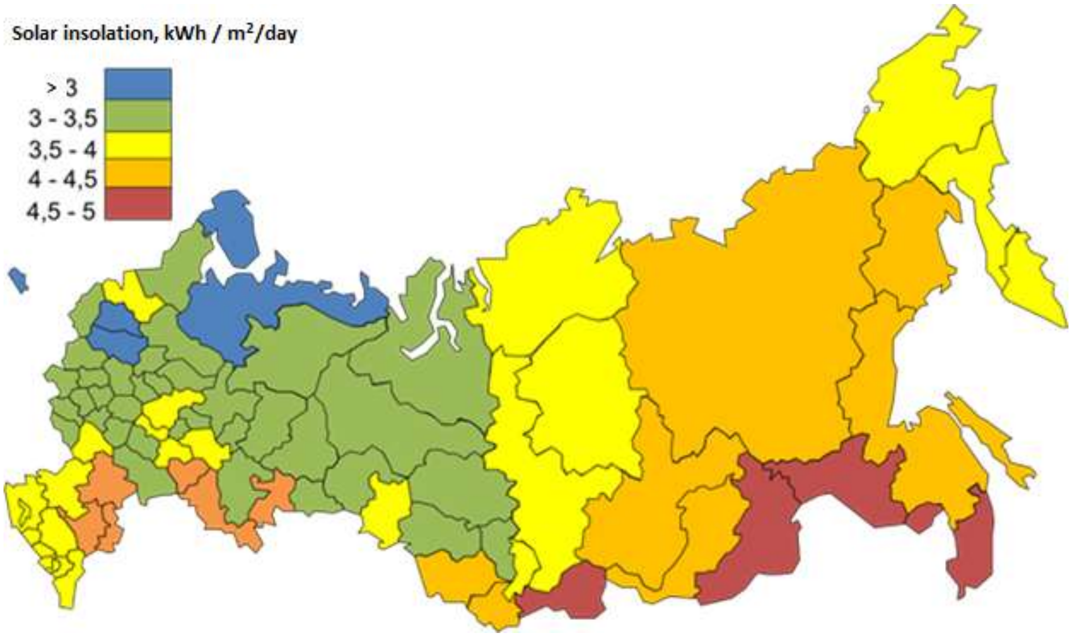

Figure 3 – Annual distribution of average daily solar radiation on the territory of Russia [8]

The highest potential of solar energy is in the South-West (the North Caucasus, the Black Sea, and the Caspian Sea), Southern Siberia and the Far East. Kalmykia, Stavropol Region, Rostov region, Krasnodar, Volgograd Region, Astrakhan region and other regions in the South - West, as well as

Altai, Primorsky region, Chita region, Republic of Buryatia and other regions in the South – East, have the greatest solar resources. For example, in Irkutsk (52 degrees north latitude), the amount of solar energy reaches 1340 kWh/m^2 per year, and in the Republic of Saha-Yakutia (62 degrees north latitude) - 1290 kWh / m^2 per year [19].

According to the results of the following research [20],[21],[22],[23] it can be concluded that solar power plants are already justified for implementation in the Russian Federation. There are some good examples of solar power plants which currently operating in Russia. In May 2015, a 5 MW capacity solar power plant was opened in Orenburg region. In October, a 10 MW capacity solar power plant was established in the Republic of Bashkortostan. Also, one of the biggest solar power plants was opened in Orsk with a total capacity of 25MW. Additionally, new solar power plants started to operate in the Republic of Khakassia, Altai, and Yakutia. Solar plants projects are developing in the Krasnodar region, and the Astrakhan region as well.

Taking into account the region of the object, research shows that the Republic of Buryatia is one of the most promising regions in Russia to create small and large-scale (more than 10 MW and above) photovoltaic systems for the production of electrical energy. Moreover, the Russian company "Avelar Solar Energy" is already in agreement for construction of 6 photovoltaic power plants with a total capacity of 105 MW in the Republic of Buryatia.

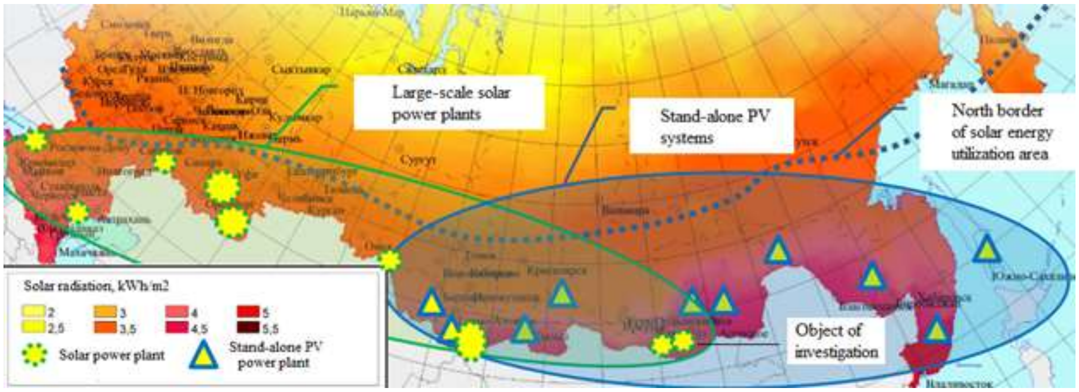

Figure 4 – Potential zones for construction of solar power plants on the territory of Russia [8]

Solar energy has the highest potential to be adopted in the region. With the high potential and the presence of free space on the territory, the future analysis of the cost reduction of PV cells and renewable energy policy of the country, it was identified that the east-south part of Russia is considered the appropriate place for construction of PV systems in order to operate as autonomous power supply system.

Photovoltaics perspective

Solar energy seems to be genuine solution addressing energy and environmental challenges. In the present time, among the diverse types of solar energy technologies and devices being developed, photoelectric conversion of solar radiation is one of the perspective ways to produce electrical energy. The recognition of these systems is caused by the current dynamics of a volume of generated energy. The figure below represents the worldwide capacity of photovoltaic systems where a substantial growth of PV systems can be noted. A.P. Landsman, Lidorenko, V.S. Vavilov, V.K. Subashiev, J.I. Alferov, V.S. Strebkov and many others authors made a great contribution to the development of photovoltaic systems [24].

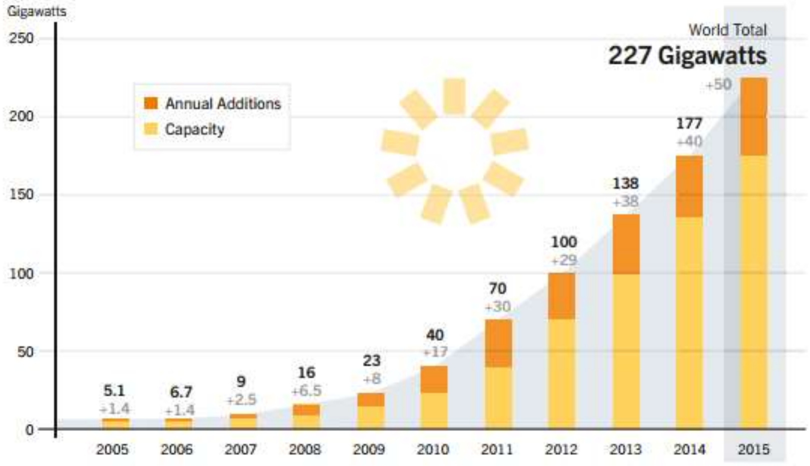

Figure 5 – Worldwide capacity of photovoltaic systems, 2005-2015 [25]

Only in the last five years, the annual production growth rate of required solar photoelectrical element reaches about 30%. The solar energy market has been growing rapidly. The global prices for PV modules have fallen about 80%. It’s obvious that the changing of prices in the world has a significant impact on the Russian solar energy market. Therefore, it can be concluded that the current development rate of solar energy and falling of prices make the PV industry more accessible for all purposes in Russia and the photovoltaic system is becoming more practiced and its application increasingly competitive.

“Total installed solar PV capacity is estimated to reach 2.7 GW by 2030. Up to 2024, Russia aims to implement a total solar PV installation capacity of 1 520 MW in its wholesale market, only. Between 2024 and 2030, another 1 180 MW will need to be implemented.” [14]

The potential of each available renewable energy sources was investigated in order to define the possible solutions to supply by power the object of investigation. Among all above-explored options of power sources, it can be concluded that the PV stand-alone energy system is the most appropriate power source. Therefore, based on discussion with supervisor, it was decided to take PV systems for further more detailed investigation.

2. INTRODUCTION OF PHOTOVOLTAIC SYSTEMS

The photovoltaic system is one of the fastest growing renewable energy technologies and it will play a leading role in the future energy generation. This section of thesis will consider the main components with key parameters of the PV system. Moreover, the advantages of PV systems and its constraint factors that have an impact on the performance of the system will be presented. Finally, this chapter will identify the ways to improve the efficiency of PV systems notably highlighting the effectiveness of solar trackers.

The PV system is an installation that supplies the power of a given load by converting solar energy into electricity through the photovoltaic effect. A typical PV system is a set of PV panels and an additional equipment needed for the power supply. The structure of PV systems is very flexible, and the final composition of the system is determined by energy loads. There are two main types of PV systems: grid-connected (on-grid) and off-grid (or autonomous, stand-alone) systems. As it was discussed in 1.4.5, the most relevant and cost-effective way of utilizing of PV systems is the power supply of decentralized consumers. Stand-alone PV systems are identified as an ideal solution for these purposes. Thus, this work will focus further on stand-alone PV systems.

2.1. STAND-ALONE PV SYSTEMS

The low quality of the grid power supply, frequent interruptions, frequency fluctuations, low voltage, tariffs that are much higher than the actual cost of supply, and the location of consumers residing in decentralized, remote areas are the reasons for utilizing stand-alone PV systems. The off-grid PV systems are designed to operate independently from the centralized grid. Electricity generated by this system is not transferred to the grid. This system feeds only the objects that are directly connected. Central component of the stand-alone PV system is the PV module, the other several elements such as a controller or an inverter are also required. Since the PV panel produces power during the day, the battery is necessary to use for storage of energy for the night time and on cloudy days. Usually, the off-grid PV system has a backup generator unit which provides a higher degree of reliability of the system. The main components of stand-alone PV systems are presented in general schematic structure of Figure 6, the next subchapter will consider them in more details.

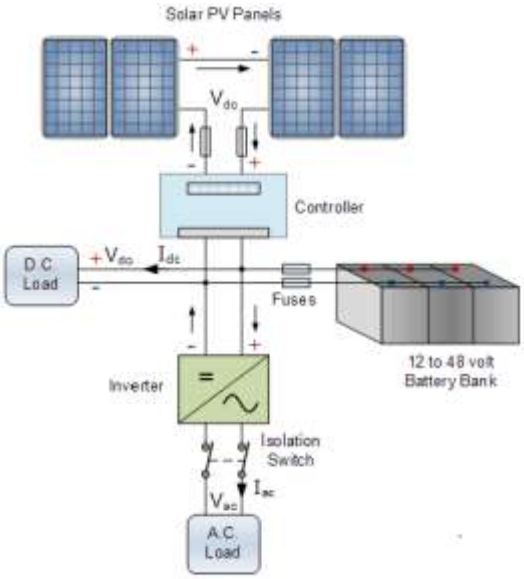

Figure 6 – General schematic structure of stand-alone PV system [26]

2.2. MAIN COMPONENTS AND PARAMETERS OF PV SYSTEMS

2.2.1. Photovoltaic module

PV module (or PV panel) converts solar energy into direct current (DC) of electricity. PV module is an assembly of photovoltaic cells, also known as solar cells. The solar cell is a device which is produced from semiconductor materials such as silicon, gallium arsenide, and cadmium telluride, etc. PV modules can be connected in series to increase the voltage of the system, it can be connected in parallel to increase the current of the system, and it can be connected in series-parallel to increase both current and voltage. Different connections are necessary to achieve the needed current, voltage and power output values of the system. This group of connected PV modules is called a PV array. The important characteristics of PV panels are as follows: open-circuit voltage – the maximum voltage that panels provides under no load operation; short-circuit current – the maximum current of a panel when the output connectors are shorted together; maximum power point of PV panel – the point where power is at a maximum; fill factor – the relationship between the actual maximum power under operating conditions and the product of the open-circuit voltage times the short-circuit current; efficiency – the ratio of the maximum power that panel can generate to compare with solar radiation hitting the panel. The performance of PV panels is usually rated according to their maximum power output under Standard Test Conditions. STC are determined by a panel operating temperature of 25 °C, and incident solar radiation level of 1000 W/m^2 and air mass of AM 1.5. Since PV panels are not always operating under such conditions, their actual performance is usually dropped by 10% to 15% of the STC [27].

2.2.2. Inverter

The inverter is the second main component of photovoltaic systems. The off-grid inverter is designed for off-grid PV system with a battery backup, where the inverter draws its DC power from batteries or PV panels and converts it to AC power. The off-grid inverter involves a variety of sizes and output waveforms which are dependent on the installed equipment of the consumer. The pure sine form inverter is used to reach the best power output. The inverter does not only transform DC to AC power, it also affects the overall performance of the PV system. At the same time, it controls and monitors the system, adjusts the frequency of AC power output and controls the value of the voltage output. The important characteristics of the inverter are power output, its reliability, protection functions and efficiency. The inverter efficiencies are range from 90% to 96% to the full load [27].

2.2.3. Battery

In PV systems, the battery stores energy that is produced by PV panels during the day, and supplies it to electrical loads when it is needed (at the night and during periods of cloudy weather). Besides storing energy, the primary functions of batteries are: to supply power to electrical loads a stable voltage and current in order to protect loads from damage and to supply peak operating currents to some electrical loads. The important characteristics of batteries are: indicated capacity which is represented in Ampere hours (Ah), nominal voltage which is specified by manufacturers (usually 3V, 6V, 12V, 24V), charge and discharge current, the depth of discharge, the lifetime or number of charge/discharge cycles and self-discharge [28].

2.2.4. Controller

Controllers manage the flow of energy between the PV panels, the storage of energy, and the electrical loads. They regulate the voltage and current level from the PV panels to the batteries to prevent overcharging and over-discharging. Also, they protect batteries from damage and expand their lifetime. There are two main types of technologies that have been introduced into the design of controllers. The first one is pulse width modulation (PWM). PWM technology uses a pulse-width converter in the final stage of battery charging. When the voltage of the battery reaches a certain value, the PWM algorithm gradually reduces the charging current to prevent overheating, swelling or boiling of the batteries. At the beginning of the charging process, the solar panel is connected directly to the battery. The second type is maximum power point tracking (MPPT). This technology allows battery charging with a rated voltage lower than the nominal voltage of the solar panel. In this mode, it is possible to charge the batteries in low-illuminated conditions (for example, in cloudy weather, at the beginning and end of the day). The MPPT controller continuously monitors the current and voltage on the solar panel then sums up their values and determines what current and voltage value at which the power of the solar panel will be at its maximum. Therefore, the PV panels operate at the maximum power, independently of battery voltage. This allows the power output to be increased by 10 – 25% in comparison with PWM. The important characteristics of the controller are: input voltage and current, regulation set point – the maximum voltage level that controller allows the battery to reach; low voltage disconnect point – the voltage level at which the load is disconnected from battery.

2.3. ADVANTAGES AND DRAWBACKS OF PV SYSTEMS

The versatility of stand-alone PV systems makes them an ideal solutions for any area that receives enough sunlight to make the system feasible. But it should be noticed that there are a few factors that may have an effect on the utilization of the system. Therefore, the advantages and disadvantages of a stand-alone PV system must be taken into account.

Advantages:

- Inexhaustibility and environmentally friendly
- Durability and availability
- No need for maintenance and noiselessness
- No use of fuel and water
- Innovative technologies and wide implications
- Ability to provide electricity to consumers with different power
- The possibility of full automation

On the other side, the photovoltaic systems have following disadvantages: the instability of produced electric energy that is associated with temporary variability of solar radiation and its diffusion; the dependence on the weather and geographic location; the necessity to accumulate energy, therefore, investment costs are increasing. Along with above-listed factors, there are two major constraints:

- High initial investment costs
- Low efficiency of solar cells

All PV technologies have a few common needs: to increase the efficiency of PV panels and to make them more competitive, to ensure a sufficient return, to reduce the use of fossil fuels, thus solving the problem of scarcity. Therefore, it is important to examine the ways to improve the performance of PV systems.

2.4. WAYS TO IMPROVE THE EFFICIENCY OF PV SYSTEMS

Nowadays, there is an active search for new methods and devices which efficiently convert solar energy into electricity as well as ways to improve the productivity of already existing technologies. Specialists in many countries, including Russia, are intensively conducting ways to reduce the impact of factors such as high cost and low efficiency for the further development of PV systems. Therefore, the following subchapters will identify and describe the ways to improve the efficiency of photovoltaic systems.

2.4.1. Development of manufacturing technology of solar cells

Development of manufacturing technology of solar cells allows cost reduction and an increase in efficiency factor. The high investment cost of PV panels is explained by the high investment cost of solar cells. The high investment cost of solar cells mainly depends on manufacturing technology. There has been great progress in the manufacturing technology of solar cells that are used as photovoltaic material to produce electricity from sunlight. It is possible to outline the crystalline silicon solar cell technology that has been improving dramatically in the past years, and today it is the dominant solar cell technology. The work to reduce the cost of panels is in progress. The specific cost of solar cells has been especially decreasing at a high rate. Table 4 shows the specific cost reduction of silicon solar panels over 65 years [29].

Table 4 – Specific cost reduction of silicon solar panels [30]

Year	1950	1960	1970	1980	1990	1995	2000	2010	2015
Specific cost, $/Wp	1000	500	100	20	10	6	5	1.4 – 2.2	1.05 – 1.08

The decrease in the production cost of solar panels has happened mainly due to the decline in the price of polysilicon material, world technological improvements and economies of scale, where market penetration of Chinese manufacturers with the lowest cost has been playing an essential role. It is obvious that the dynamics of such tremendous cost reduction will only grow in the future. Therefore, day by day cost reduction of solar cells explains the reason behind the cost-reduction of PV systems, and there is a high potential for the cost reduction of PV system's components as well (controller, inverter, supporting structure and tracking systems).

In addition, the work to improve the efficiency of PV systems is also in progress. The efficiency factor of the system depends on photocell material. There is a broad range of different solar cell technologies on the market using various types of materials. Usually, solar cell technologies are classified into three generations. First generation PV systems use the wafer-based crystalline silicon (c-Si) technology, either monocrystalline (sc-Si) and polycrystalline (mc-Si). The second generation uses thin-film technologies which include cadmium telluride (CdTe) and copper indium selenide (CIGS) etc. The third generation uses technologies such as concentrating and organic PV cells. These types are not widely commercialized. In the last 40 years, the efficiency of semiconductor silicon solar cells has increased. In the 1930, solar cell efficiency barely reached 1%. At present, commercial PV system covers energy with an efficiency ranging from 7% to 17%. The maximum lab cell efficiency is 25.6% for monocrystalline elements and 20.8% for polycrystalline elements. As for thin film technology, the efficiency is about 21% for CdTe and 20.5% for CIGS solar cells. Today the high concentration multi-junction solar cells have achieved an efficiency of up to 46.0 %. The record efficiencies show the potential for further efficiency growth at the production level [31].

Despite the exploitation of different types of solar cells, the crystalline silicon element has been dominating photovoltaic technology development from the beginning and today it occupies around 93% of the market. This is due to the high prevalence of silicon in nature and its relative cheapness. Furthermore, the development of the industry that produces semi-conductor silicon-based devices affects the cost of the silicon solar panel. According to Fraunhofer-Institute for Solar Energy Systems [32], it has predicted that a successful development of the PV industry would include an annual 22% growth rate of the market linked to an annual 6% cost reduction rate. As a result, the development of manufacturing technology of solar cells is an efficient way to improve the performance of PV systems [31].

2.4.2. Optimization of the solar cell structure

Optimization of the solar cell structure is necessary in order to achieve the minimum heating of it. The high solar radiation and high ambient temperatures are the reasons why PV panels (cells) get overheated. The maximum power output of solar cells, like most other semiconductor devices decreases as the cell temperature increases. The efficiency of photocells declines due to a high sensitivity to the temperature. Additionally, the situation becomes more complicated when the sensitive surface of the fragile solar cells is covered by a protective glass or transparent plastic. The result is a kind of "greenhouse" which increases overheating. Therefore it is necessary to take all actions to reduce the heat. There is lack of information about the research on the effectiveness of specific operations or devices for forced cooling of photovoltaic solar panels [33].

However, one of the ways to cool PV panels is a hybrid photovoltaic/thermal solar system. This system contains PV panel in combination with a cooling system. Water is circulated around the solar panel in order to reduce the temperature of the solar cells. The warm water returns to the water tank by a pump where it is mixed with cool water. According to results of the paper [34], a combination of panels with a cooling system can be the solution of the problem of overheating.

2.4.3. Usage of solar radiation concentrators

The usage of solar concentrators in PV systems allows to increase the specific flow of solar energy contacting the solar cell, thereby reducing the area of the photovoltaic elements and finally reducing the cost of PV system. The concentrated radiation increases the efficiency factor of a solar cell. Concentrated solar systems produce power by using the mirrors or lenses to focus a large area of the sun’s rays onto a small area. The concept of systems has appeared as an attempt to decrease the cost of PV technology. In these systems, savings are achieved by the reduction of the solar cell area which is compensated by the increase in the intensity of sunlight on the device through less expensive optical components [35].

However, there are some common drawbacks: the need for special technical means and measures to intensify abstracted heat from the solar cell; complicated construction and operation of the power plant, the metal and material consumption, the complexity and high cost of solar concentrators, and solar energy losses connected with the reflection coefficient of the concentrating system. Additionally, it also requires a solar tracking system which must operate with high accuracy. All these factors lead to an increase in weight, higher investment costs, reliability reduction, etc. At the same time, it is also necessary to employ the third-party specialists who can eliminate possible troubleshooting in the installation process, to use special technical means for intensification of heat removal from solar cells. It also should be noted that relatively cheap silicon solar cells, in most cases, are not designed to operate under a highly concentrated radiation, the other types of solar concentrators are used in this case, where the cost of them is significantly higher.

2.4.4. Implementation of the maximum power take-off mode

PV systems are used in different operating conditions. They are strongly influenced by the environment. The current-voltage characteristics (CVC) of the solar panel is characterized by nonlinearity and instability. The volt-watt characteristics have a strongly pronounced maximum point of generated power, the position of which varies depending on the operating conditions (temperature, illumination). With the change of the operating temperature (+ 70 °C to -30 °C), the voltage of the optimum operating point of the silicon solar cell increases approximately in 1.5 times (photocell voltage varies in the range of 0.5 - 0.75 V). As for the current of a solar cell, it slightly depends on the temperature [33]. Therefore it is necessary to maintain the optimum performance of PV panels in order to gain maximum energy from the panel when the temperature and light conditions are being changed. This can be achieved by using the extreme power control mode. In other words, the search and maintenance of the optimal energy mode for more energy to be received thereby increasing the energy efficiency of the PV system.

The so-called “step type extreme control system” is most widespread. The step type extreme control system includes the power sensor which processes the solar panel’s voltage and current information at the operating point. Then the power sensor generates the output voltage which is proportional to the current value of the power produced by a solar panel. The synchronizing generator signals, the resulting value of power that is stored in the sample and hold device. After the next signal of the generator, the operating point along the CVC curve is shifted by an action of the correction device. Then, the measured value of PV’s power is compared with the previous value of power by using a comparison device. The output signal of the comparison device influences the correction device in order to define the direction of shifting of the operating point. The correction device periodically moves the operating point along the curve of the CVC, and then, focusing on the power sensor readings, it adjusts the mode of the PV panel. For example, when the power generated by the solar panel is reduced the correcting device changes the direction of shifting. Simultaneously, sample and hold devices remember the new current value of the panel’s power. Then, the process is repeated continuously. Thus, the maximum power mode of a solar panel is performed when constant "searching" voltage fluctuations of the solar panel around the optimum point occur. Theoretical analysis shows that the energy efficiency with the extreme power control mode can reach 50% [33].

2.4.5. Usage of solar trackers

The generated power of a PV system is based on the amount of solar insolation received by the PV panel. The sun's position in the sky is changing with the seasons and the time of day. At the moment, the majority of PV panels are set at a fixed optimal angle. Therefore, the PV system does not use the whole potential of the incoming solar radiation because of a disordered orientation of PV panels to the sun. This results in a lower power output of the overall PV system.

The solution to this problem is sun tracking system or solar tracker. The solar tracker is a device that is designed to orient a PV panel towards the sun's position. These devices change their orientation throughout the day to follow the sun's path and thereby, to maximize energy capture. The usage of solar trackers in PV systems provides the highest solar radiation income on the surface of the solar panel. Thus, solar tracking systems can significantly increase the power output by up to 20 – 55% compared to the stationary PV panels. Therefore it makes solar trackers the most appropriate and efficient way to improve the energy efficiency of photovoltaic systems. Due to this fact, further investigation will be dedicated to solar trackers.

2. SOLAR TRACKER

3.1. MAIN COMPONENTS OF SOLAR TRACKER

Literature review demonstrates that there are many different designs of trackers with diverse components on the market. But the main elements of a tracker can be classified. The main elements of sun tracking system are a tracking device, an algorithm of tracking, a control unit, a system of positioning, a driving mechanism and sensing devices. In the figure below the typical components of solar tracker are presented.

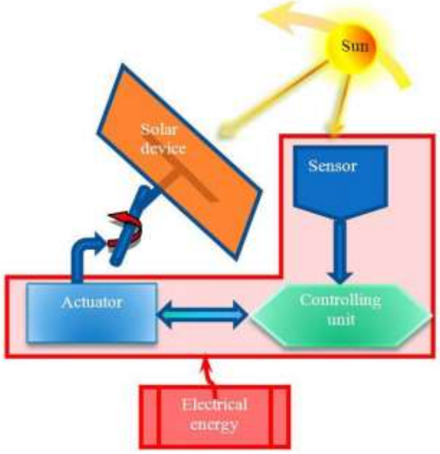

Figure 7 – The main components of solar tracker [36]

- The algorithm of tracking calculates the sun’s position angles (azimuth and zenith) which are used in order to rotate the PV panels to the sun’s direction.
- The control unit carries out the algorithm of tracking and coordinates the positioning system’s movement.
- The positioning system moves the PV modules in order to face perpendicularly the sun’s rays. This positioning system consists of motor and mechanical linking elements. There are a number of existing motion actuators (DC motors, stepper motors, linear actuators and servo motors). The standard DC motor has imprecise tracking since they are free spinning. In this case, stepper motors are the most appropriate solution.
- The driving mechanism (actuator) is responsible for moving the tracking device to the position determined by the positioning system.
- The sensing devices (sensor) are a group of sensors and measurements that collect data and processes it before actuation. For instance, the ambient conditions, the intensity of light for real-time, wind load, etc.
- The electrical system provides energy to the motors when the power output of PV panels is limited due to weather conditions.
- The supporting frame consists of a foundation and support base for PV panels. The frame is a fixed part that is responsible for supporting the system’s weight and stabilizing the modules as it rotates according to the sun’s position.

3.2. TYPES OF SOLAR TRACKING SYSTEMS

Solar tracking systems can be classified by a number of criteria. The first classification is the type of tracking system. Sun tracking systems are divided into systems with partial (single-axis) and full (dual-axis) orientation. Since the majority of PV panels are oriented at a fixed optimal angle, the PV systems that have such position of panels can be considered as a type of tracking system. Therefore, the first type of tracking is a fixed panel system.

3.2.1. Fixed panel system

PV systems with invariable orientation of solar panel are widely used due to their simple design and reliability. However, these systems have a low efficiency of power generation due to the non-perpendicularity of the sun's rays falling on the surface of the PV panel because the fixed orientation of the panels does not include the azimuth and zenith movement of the sun across the sky. Non-perpendicularity causes the reduction of incoming solar energy due to the reduction of its active area. Consequently, it leads to underutilization of the solar radiation.

3.2.2. Single-axis tracking system

“Single axis system have one degree of freedom that acts as the rotation axis.” [36] In such type of systems, the PV modules change their position according to the sun’s movement and try to be at a perpendicular angle to the sunlight only using one axis (coordinate). For example, in the single

axis trackers which are located in the northern hemisphere, the panels are oriented at the optimum angle to the south thus the panels could not always be perpendicular to the direction of the sun since the north-south direction is not taken into account. Figure 8 illustrates the sun's movements within a year. There are several common implementations of single-axis tracking systems. They include trackers with the horizontal axis of rotation (HSAT), with the vertical axis of rotation or azimuth solar tracker (VSAT), and with the tilted axis of rotation (TSAT). [36]

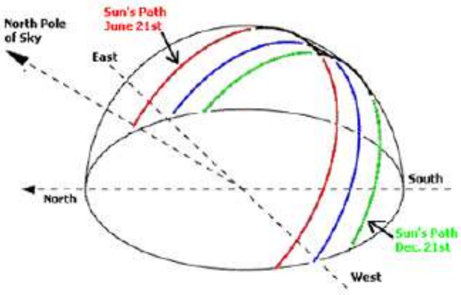

Figure 8 – The path of sun during the different seasons [37]

Tilted single-axis tracker

In TSAT, the rotation axis is inclined from the horizon by an angle which is oriented along the north-south direction. Also, the trackers with axes of rotation between horizontal and vertical are considered as tilted single axis trackers. This type of trackers is presented in Figure 9.

Horizontal single-axis tracker

HSAT have a rotation axis that is horizontal to the ground and oriented along the east-west or north-south direction [36]. The axes of rotation of each row of solar panels are parallel to each other. In this type of system, the long horizontal tubes are supported on bearings that are mounted on pylons. Panels are mounted on the tube, and the tube is rotated around its axis to track the sun. Usually, usage of this type is found in tropical regions where the sun gets high at noon and the days are short.

Vertical single-axis tracker

VSAT usually have a design that the modules are oriented at an angle about the axis of rotation. Vertical type trackers are most common in high latitudes where the sun does not get very high and the summer days can be long. In these systems, it is necessary to take into account the shading from adjacent rows to avoid unnecessary energy losses and maximize the available working space.

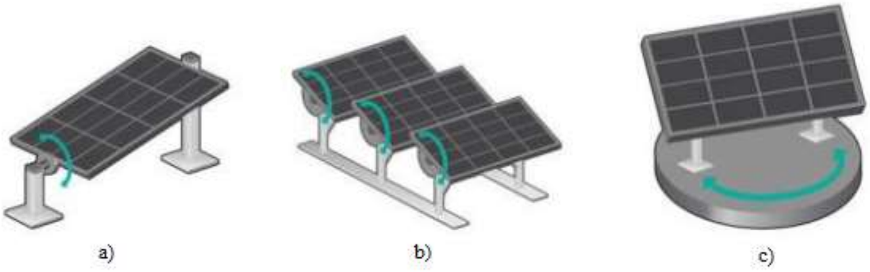

Figure 9 – a) TSAT b) HSAT c) VSAT [38]

3.2.3. Dual-axis tracking system

“Dual-axis tracking systems have two degrees of freedom that act as axes of rotation.”[36] In this case, dual-axis orientation systems are tracking both the azimuth and zenith angles. This system allows setting the PV panels perpendicularly to the sun’s rays throughout the year. There are two well-known types of dual axis tracking systems: tilt-roll (or polar) and azimuth-elevation systems.

Tilt-roll dual axis tracker

Trackers with two axes of rotation on the pole are called tilt-roll dual axis trackers (TRDAT). They are named in this way because an array with panels is mounted on the top of the pole. This tracker is shown in Figure 10. The movement of the tracker is driven by turning the panels around the top of the pole. A mechanism, which is set at the top part of the rotating bearing, provides a vertical rotation of the panels and provides the main mounting points for the panels. In a tilt-roll tracking system, a rotating panel track the sun from the east to the west where the tilt angle of panels is also moving due to the yearly changing of the sun’s path. Hence, one axis of rotation is aligned parallel to the polar axis. Therefore, the tilt angle equals the local latitude angle. The second axis is perpendicular to this polar axis. The tracking angle about the polar axis is equal to the sun’s hour angle. As for the tracking angle about the perpendicular axis, it depends on the declination angle. [39]

Azimuth-altitude dual axis tracker

Trackers with two axes of rotation and a reference plane are called azimuth-altitude dual axis tracker (AADAT), in which the primary axis is vertical to the ground. It is presented in Figure 10. They are similar to TRDAT, but the difference between them is the way of array rotating. Instead of rotating around the top of the pole, the AADAT usually uses big rings mounted on the ground or platform. The whole system is mounted on rollers or a large platform with bearings.

The main advantage of this arrangement is that the weight of the panels is distributed over the parts of the ring, unlike TRDAT where the loading point of the pole is focused at one point. This helps to support many more solar panels. However, AADAT systems could not be placed closer to each other than the ring diameter. This can lead to a reduction of the system's density, especially when inter-track shading occurs. In the case of the azimuth-altitude system, the solar panel must have freedom to rotate about the azimuth and elevation axes. The primary tracking axis (azimuth) must be parallel to the zenith axis. The secondary axis (elevation) is always orthogonal to the primary axis and parallel to the surface of the earth. In such systems, the tracking angle of the azimuth axis is referred to the solar azimuth angle, the tracking angle of the elevation axis is referred to the solar elevation angle [36].

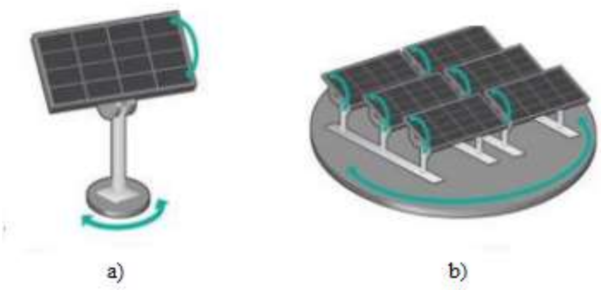

Figure 10 – a) TRDAT b) AADAT [38]

3.3. CONTROL METHODS OF TRACKING SYSTEM

The second classification can be made depending on the methods of tracking. They can be divided into three categories: passive, active and manual control.

3.3.1. Passive method

The passive method is based on the movement of the system by utilizing a low boiling compressed gas fluid. Passive solar tracking systems include two identical cylindrical tubes filled with a pressurized fluid (usually Freon or on shape memory alloys). The two cylindrical tubes are actuators working in opposite directions to each other. The passive tracker is moving due to an imbalance in the pressure between two points at both ends of the system. The low boiling compressed liquid under the influence of the sun's heat pass into the gas state then they begin to move. The center of mass shifts, therefore, the system finds an equilibrium position, meaning that the PV panels changes their position. A passive tracker is not complex thereby the system is reliable, but has low efficiency of tracking [37].

3.3.2. Active method

In most of active tracking systems, the position of the sun in the sky during the day is continuously determined by utilizing of programmable controllers, microprocessors and time based, electro-optical sensors, control devices of GPS navigation.

The PC controllers and time-based active tracking calculates the angles regarding the date and time using algorithms and mathematical functions, and send signals to the control unit in order to rotate the mechanism and position the system. A program with a combination of movements of the sun is already given to the control unit where the program includes the latitude and longitude of the object and angle of declination. Thus a PV panel changes its position by using the predetermined program. The theory behind it is that the sun moves across the sky at a fixed rate. This method of tracking is the most accurate [37].

Also, tracking can be performed in the functions of solar radiation. This method is based on the imbalance of incident solar radiation throughout the surface area of a PV panel. These systems have sensors that detect the deviation of the position of the sun. The system during operation receives the information from the sensors about the position of the photoelectric converter relative to the sun. By differential illumination of the sensors, a differential control signal occurs. The differential control signal is used to drive the motor to orient the installation in a direction where the illumination of the sensors is equal. Then a PV panel changes position by a rotational mechanism [40].

Rotational mechanisms of active tracking can be divided into analog and digital. Analog drive control based on the information obtained from the sensor, which determines the position of the brightest point in the sky. The digital drive is performed by the microprocessor control, which determines the position of the sun at any given time by the tables in memory [41].

3.3.3. Manual control

Another way of tracking is manual control. In this method, by controlling the actuators, an operator sets and directs the tracking system at the optimum angle during the seasons. This method is the most reliable and requires low maintenance, but it has the lowest efficiency.

3.4. TECHNICAL REQUIREMENTS OF SOLAR TRACKERS

PV systems require that PV panels be perpendicular to the sun's rays with minimal error as much as possible. Therefore, the design of a solar tracker should take into account static and dynamic deformation in order to provide high performance. If the deformation of the solar tracker is within the acceptable error range, the tracker's structure should be designed with a proper level of stiffness. Within this in mind, the solar tracker should satisfy the following technical requirements:

- Low level of energy consumption in order to maximize efficiency of solar installation and optimum performance-cost ratio.
- Operation reliability and mechanical strength in order to withstand dust, wind loads, snow, rain, temperature differences, additional weight, etc.
- Simple movement solution (sensors, motors, gears) in order to enhance feasibility and reduce the cost.

3.5. CLASSFICATION OF TRACKERS FOR DECENTRALIZED OBJECTS

In this step of work, a short overview and analysis of the sun tracking systems which are proper for decentralized consumers are provided according to [42]. After review, the rationally acceptable solar tracking system used for decentralized energy supply will be determined.

3.5.1. Tracking system based on thermal regulation

1) The solar installation pictured below consists of a base plate, solar panels and telescopic tubes filled with fluid and includes a high coefficient of volume expansion (Figure 11). Operation principle: rotation of the panel is carried out by expanding the heated liquid which is inside of the telescopic tube, when the sunlight penetrates the panel.

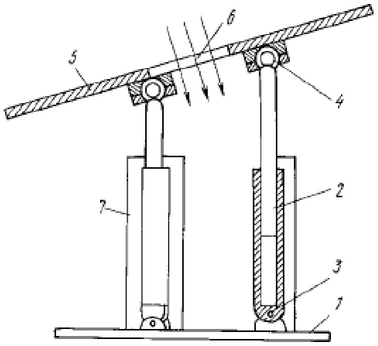

Figure 11 – Solar installation with the tracking system [42]

Where: *1 - the base plate; 2 - telescopic tube; 3 - cylindrical joint; 4 - ball joint; 5 - panel; 6 - round hole; 7 - reflective screen*

2) The solar installation is equipped by an axis of rotation with a solar panel, two-tier gear, telescopic thermal actuators (Figure 12). Operation principle: the thermal actuators provide the rotation and longitudinal movement of the solar panel via the transfer mechanism. This occurs because of the temperature difference in the light-absorbing surface of thermal actuators when the sunlight contacts it to equalize the temperature on both thermal actuators. The longitudinal movements of the solar panel along the axis (without its rotation) compensate daily and the seasonal fluctuations of air temperature.

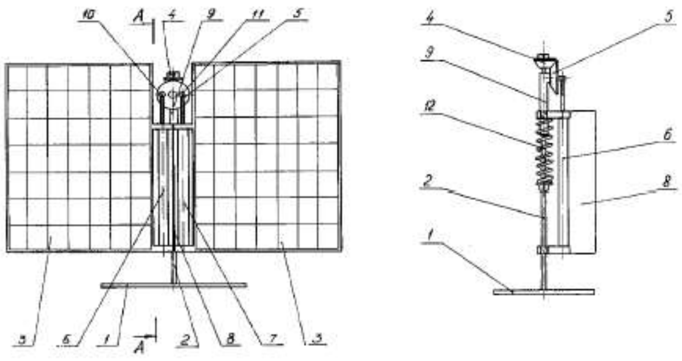

Figure 12 – General view (a) and front section of the installation with tracking system 2 (b) [42]

Where: *1 - the basis; 2 - fixed axis of rotation; 3 - solar panel; 4, 5 - pair of bevel gears; 6, 7 - thermal actuators; 8 - the screen; 9 - the plug; 10, 11 - the stops; 12 – spring*

3) Below is an example of an autonomous sun tracking system (Figure 13) which uses thermal actuators in the form of torsion bars made from metal with a shape memory effect and is mutually deformed by rotation in opposite directions. Automatic orientation (both axes - zenith and azimuth) of the panel is provided by unfolding some torsions bars and folding other torsion bars due to the temperature difference that occurs in the case of different degrees of illumination of torsion bars.

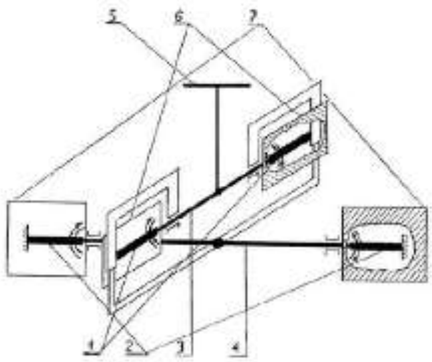

Figure 13 – The autonomous system of tracking the movement of the sun [42]

Where: *1, 2 - torsion bars; 3, 4 - the axis of rotation; 5 - oriented panel; 6, 7 – screens*

To sum up the tracking systems based on thermal regulation some advantages can be found: simple construction and low maintenance, reliability, no energy consumption. Disadvantages include: the low accuracy of orientation characterized by high fluctuating wind loads and low ambient temperatures.

3.5.2. Tracking system based on electrical regulation

1) The solar installation showed in Figure 14 has vertical and horizontal shafts needed for azimuth and zenith rotation of the solar panel. The automatic orientation system consists of the zenith and azimuth tracking drives, which include command photocells of control relays and drives of

reversing motors. The azimuthal rotation shaft is provided by an additional command photocell which sends a signal to the drive of the vertical shaft to return the system to the starting position after sunset.

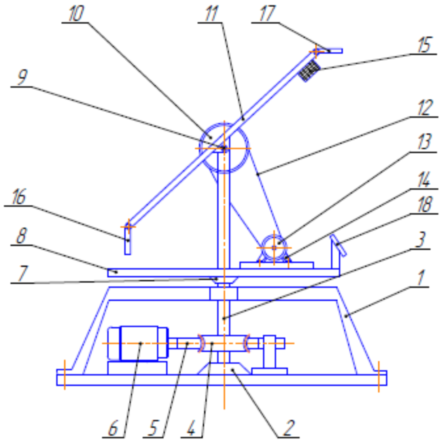

Figure 14 – Solar power plant [42]

Where: *1 - the frame; 2 - support bearing; 3 - the vertical shaft; 4 - the driving gear; 5 - the screw shaft; 6, 14 - reversing DC motors; 7 - coupling; 8 - the horizontal platform; 9 - horizontal shaft; 10 - pulley; 11 – solar panel; 12 - belt drive; 13 - wheel; 15 - left and right command photocells; 16 - the bottom and top 17 solar cells; 18 - back photocell*

2) Among the numerous types of tracking systems produced on an industrial scale, it is possible to note the company “Traxle Solar”, which develop and manufactures solar tracking systems “Traxle”. This company is proven in the European market. The main part of the tracker is pipe inclined to the horizon and the rails where the solar panels are attached. The DC motor which rotates entire system through screw transmission gear is embedded in the tube. The gearbox is self-braking and protects against the wind. The electric motor receives the energy from the double-sided solar module installed in the bottom of the tube. Also, a double-sided solar module is considered as a sensor which sends a signal to turn the system. [43]

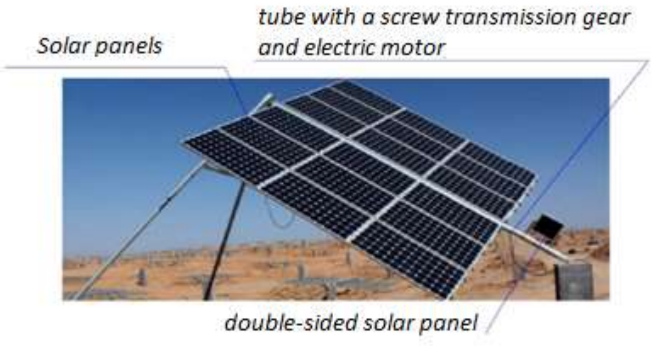

Figure 15 – Solar power plant with sun tracking system “Traxle” [43]

3) There are known tracking systems of the company "Seltek" (Figure 16). They consist of external and internal rotators of a controller which provide automatic rotation of the system. In accordance with a signal received from the controller, the full orientation is performed by two electric drives. The base control of solar installation is carried out by a microcontroller that implements the algorithm based on the trajectory of the ыun’s movement. The tracking program is performed on the basis of the season and for operation in any location point [44].

а) б)

Figure 16 – "Seltek" firms device [44]
Where: *a - external rotating device; b - control unit*

Taking into account the severity of natural and climatic conditions with significant annual and daytime temperature changes in large part of the Russian Federation, tracking systems should be performed primarily by electrical automation. The advantages of tracking systems based on the electrical automation equipment unlike systems based on thermal regulation include high precision of tracking and less susceptibility to environmental influences. The disadvantages are the complexity of installing the construction that leads to a reduction of reliability and therefore to a high investment cost of PV systems. Thus, in the conditions of decentralized energy supply, which is currently experiencing a shortage of working cadres and their low qualification, it is more expedient to use the electrified tracking systems.

According to the research provided in [45], it is indicated that single axis tracking of PV panels increases the power output by 23%, and the dual-axis tracking increases by 32% regarding Tomsk region [2]. The calculations which were made for the natural environment of Western Siberia show that the system with single-axis tracking makes it possible to increase the efficiency of power generation by 30%, the dual-axis tracking - up to 40% [46]. In [42], it is found that the efficiency of the PV systems with the sun tracking system in the conditions of the Republic of Bashkortostan increases power output by 39% in the summer and by 26.3% during the spring months, compared with fixed position of solar panels [46].

4. CASE STUDY

Modern weather forecasting has a great importance for the adoption of managerial decisions and the operation of economic and infrastructure facilities, as well as for the population. In the present time, a small number of meteorological stations remain in Russia which have been making continuous observations throughout the 20th century. In some regions (Arctic, the Central regions of Siberia and the Far East), the density of meteorological stations is reduced by dozens, especially in the Eastern part of Siberia. It is one of the main reasons behind the inaccurate weather forecasting on the vast territory of Russia. In this regard, there is serious work currently in progress to expand the network of meteorological stations and modernize the equipment of meteorological stations. This will substantially improve the accuracy of weather forecasting. In 2016, the accuracy was estimated at 89%, and it will grow up to 92% by 2018. At the end of 2010, the Strategy for Hydrometeorology Activities for the period up to 2030 was adopted. According to the strategy, the number of weather stations should reach 5400 units by the year 2030. But today there is only half of this number. Figure 17 below shows the distribution of meteorological stations in Russia [47].

Figure 17 – The distribution of meteorological stations in Russia [47]

The Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet non-profit organization) is the only reliable producer and supplier of hydro-meteorological information for hydro-meteorological safety in Russia. The Roshydromet organization ensures systematic collection of hydro-meteorological information which provides hydro-meteorological security and contributes to sustainable social and economic development [48].

Based on the above described situation, this case study will use the meteorological station as an object of investigation.

4.1. OBJECT OF INVESTIGATION

The object of investigation is the meteorological station (or weather station), which is located in the south-east part of Russia, about 115 km from the center of the town Ulan-Ude, Republic of Buryatia. The exact coordinates of the object are 51.07 degrees of north latitude and 107.3 degrees of east longitude.

The weather station carries out 24 hours regular observations of the atmosphere and atmospheric processes, including changes of meteorological elements such as temperature, pressure, humidity, wind speed and direction, cloud cover and precipitation, etc. There is an observation site where the central meteorological equipment is placed. Also, there is a building for processing of observation results and storage of equipment that is sensitive to cold temperatures. This weather station is located in a remote area without the possibility of connection to a centralized power supply. The weather station consists of: a set of meteorological and hydrological sensors; the central point which performs information processing from the sensors; storage for results before their transfer; the creation of the codes; radio transmitting apparatus etc.

In the figures below, the examples of typical meteorological stations in Russia are presented.

Figure 18 – Typical meteorological stations in Russia [49]

In this case, the considered meteorological station is autonomous designed station and considered as an additional source of weather data collection, which is necessary for the local meteorological station in the airport of the town Ulan-Ude to determine more accurate data. Moreover, several of these autonomous weather stations can be installed around the airport to obtain exact and correct data.

The objective of the case study is technical and economic evaluation of the construction of possible stand-alone energy systems in order to identify the optimum solution of power supply.

4.2. DETERMINATION OF OBJECT ELECTRICAL LOADS

The first step in designing a power supply system is to determine the energy consumed by the object. All electrical equipment of the object of investigation was mainly determined in accordance with the equipment installed in the meteorological station located in the airport of Ulan-Ude. Simple desired composition of the weather station is presented in Appendix 4. Since the parameters such as utilization factor of meteorological equipment, power mode and operating time are not available it was decided to accept the technical data from the data of the weather station located in the airport. Therefore, according to composition of the weather station, the maximum load of the object is 1.4 kW and the values of monthly energy consumption are presented in Table 5. All necessary data was provided by the technician engineer of the meteorological station in the airport [50]. A characteristic feature of weather stations is a constant load diagram during the day and the year. The calculated daily diagram is presented in Figure 19 [51]. The peaks are characterized by switching on of the cloud sensors.

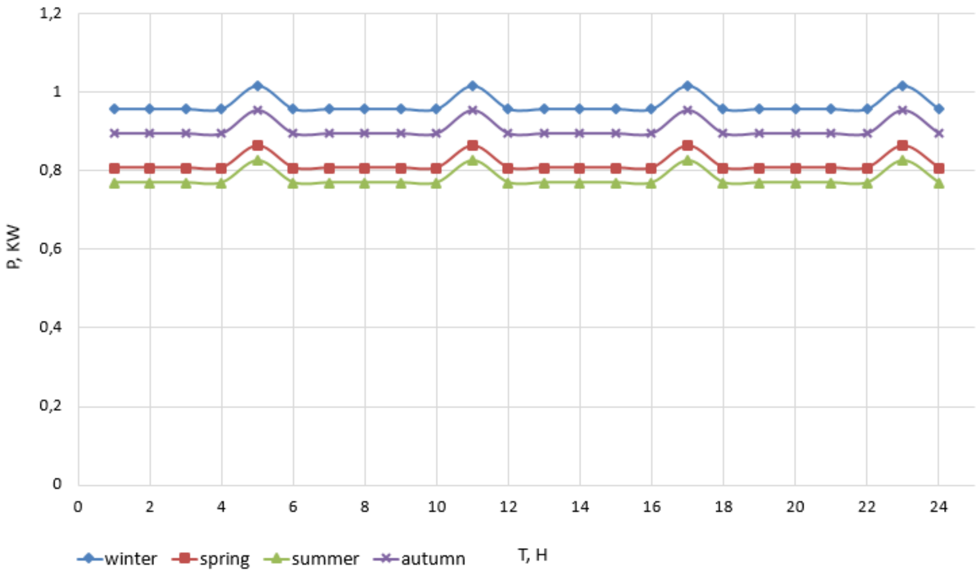

Figure 19 – Daily energy load diagram of weather station in different seasons

The annual energy consumption is equal to the sum of monthly energy consumption.

$$W_{total} = \sum_{i}^{12} W_{month} \qquad \text{Equation 1}$$

Table 5 – Monthly energy consumption of the object, kWh.

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total:
697	650	568	563	555	503	486	522	589	608	660	720	7120

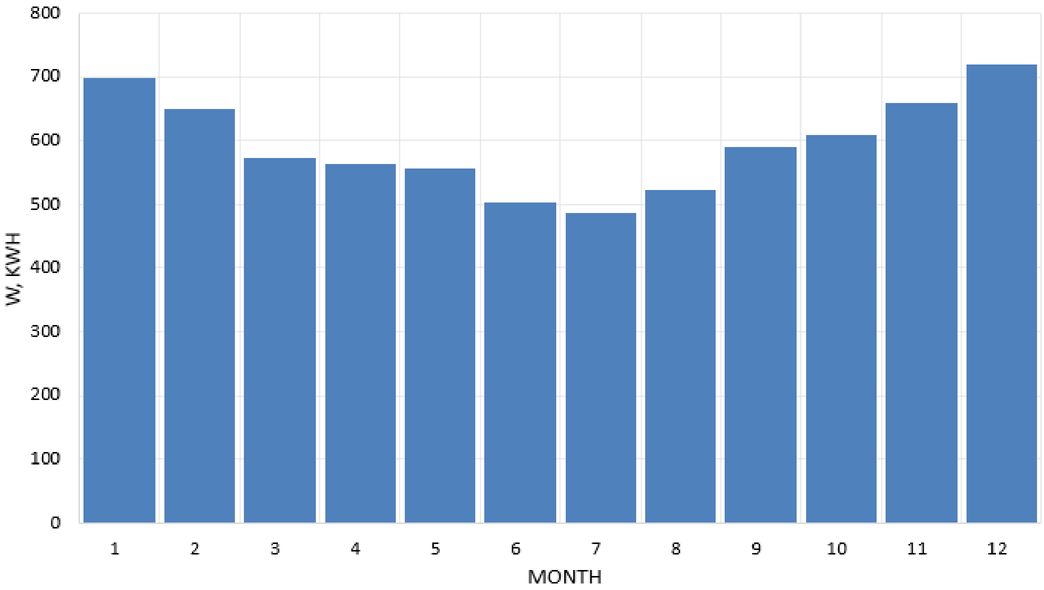

Figure 20 – The monthly energy consumption of the object

On the basis of the calculations the typical characteristic graph of energy consumption of the weather station was obtained. The annual energy consumption of the object is 7120 kWh per year. Consequently, the future proposed variants of power supply must provide this amount of energy.

4.3. THE PROPOSED TECHNICAL SOLUTIONS

Based on the discussion provided in the subchapters 1.3, 1.4, the possible technical solutions of power supply of the object are divided into supply systems based on fossil fuel (diesel/petroleum generator set) and based on photoelectric conversion of solar energy (PV system). Therefore, the technical evaluation of each power supply system will be performed.

4.4. VARIANT 1. ENERGY SUPPLY SYSTEM BASED ON GENERATOR SET

In this variant, the generator power plant is considered as the main source of power supply. In this case, the object is completely dependent on the generator, thus it is necessary to have an additional power supply source in order to provide reliable and uninterrupted power supply. Two identical generators are accepted. They must be connected in such a way that when one of the generators stops, – the other one must be started automatically, thereby excluding power outages. According to the calculation of annual energy consumption of the object which is equal to 7120 kWh, it is required that the annual energy output of the generator power plant must cover all energy consumption of the object during the operating period. Therefore, selection of the proper generator is important task.

Among a large number of completely different options of generator power plants, the following crucial parameters of generators should be taken into account when the generator is being chosen:

low price and relatively low weight; minimum maintenance requirements; the ability to use in severe conditions; type of fuel; the duration of autonomous supply. The selection of the power of generator should be carried out with the following requirements in order to supply the object in all situations [52]:

- The same size generators should be selected to enable the ease maintenance.
- A load of generators should be in the range of 25-80% relative to the nominal. If the generator load would be above these limits, the results would decrease the lifetime of the engine. If the generator operates at low loads, the specific fuel consumption is significantly increased.
- The number of units should be in excess to take the generator out of work for maintenance, minor, and capital repairs.
- Operating conditions should correspond to the climatic conditions of the region.

The selection is based on the maximum load of the object which is equal to 1.4 kW. Taking into account 80% of the maximum permissible load, the power of the generator is:

$$P_{gen} = \frac{P}{0,8} = \frac{1,4}{0,8} = 1,7\ \text{kW} \qquad \text{Equation 2}$$

In recent years, Chinese manufacturers have become quite popular in Russian market. Year by year the share of Chinese brands (YangDong, YTO) and their quality is constantly growing while the prices are 1.5 – 2 times lower than their European counterparts. According to the above-described requirements, the installation of the petroleum-based generator KIPOR KGE2500E with the nominal power of 1.7 kW as the main source of the object is accepted. The second generator is the same. Technical characteristics of the generator are presented in Appendix 5 [47]. The structural diagram of the generator power plant is presented in the figure below [53]. The petroleum generator is installed inside the building where the equipment is located. Therefore, the operating conditions of the generator set correspond to the requirements.

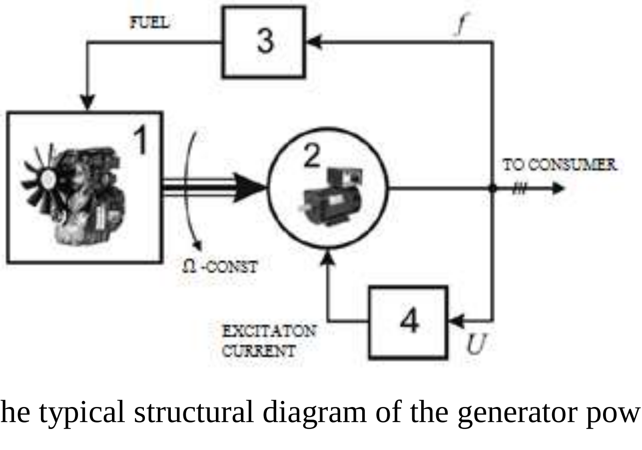

Figure 21 – The typical structural diagram of the generator power plant [27]

The fuel engine 1 rotates the rotor of the synchronous generator 2. The frequency of the voltage f at the output of the generator is proportional to the rotational speed of the rotor Ω, and the value of the voltage U is proportional to the excitation current of the generator. Speed controller 3 determines the frequency of the output voltage and maintains a constant speed of the engine shaft by acting on the controls of the diesel engine, thereby ensuring the stabilization of the frequency of the output voltage in all modes of operation. The voltage regulator 4, by influencing the excitation current of the generator, maintains the value of the output voltage close to the set value for all permissible loads. In the structural diagram, two automatic control systems are performed: an automatic control system of the engine speed (speed regulation) and automatic voltage control. The purpose of the first automatic system is frequency stabilization, the second is voltage stabilization.

Since the generator power plant has an additional source of energy represented by another petroleum based generator, the generator power plant should be equipped with an automatic transfer switching unit (ATS). An automatic transfer switching unit is an electrical switch that switches a load between two sources if the utility source fails. The next parameter of the power plant is the monitoring and remote control system. The generator power plant is located in a remote area where it is difficult to control the levels of operating fluids, to check the overall technical state of the generator power plant, to start/stop the generator, and to monitor its parameters. Therefore, the control system should be installed. Apart of that, the fuel tank designed for uninterrupted autonomous power supply and the long-term storage of fuel should be included also in the power plant.

To analyze the technical and economic performance of the petroleum-based generator power plant, the specific fuel consumption is taken into consideration. Thanks to the constant load diagram of the object, the generator can operate in the optimum mode, meaning that the specific fuel consumption of generator is optimal. Based on the linearization of discharged characteristics of the petroleum engine, the determination of specific fuel consumption for the generation of 1 kWh can be performed by using the following formula:

$$G_1 = K_{xx} \cdot G_n + (1 - K_{xx}) \cdot G_n \frac{P_1}{P_n} \qquad \text{Equation 3}$$

Where:

G_1 – actual fuel consumption, g/kWh;
G_n – nominal fuel consumption, g/kWh;
P_1 – actual power of generator, kW;
P_n – nominal power of generator, kW;
K_{xx} – coefficient characterizing the fuel consumption under no load operation and equals to $K_{xx} \sim 0.3$ [27];

Knowing the specific fuel consumption for the defined load conditions and the amount of generated (or consumed) energy it is possible to determine the amount of required fuel during the reporting period with the following formula:

$$Q_{fuel} = W \cdot G_1 \quad \text{Equation 4}$$

Where:

W – energy produced per day, month, and year, kWh;

When the specific fuel consumption is evaluated, it is necessary to take into account the density of fuel (0.78 g/sm^2) [54]. The technical parameters and fuel consumption of generator power plant are presented in the table below.

Table 6 – The technical parameters of the generator power plant

Installed power of the main generator, kW			1,7
Installed power of the second generator, kW			1,7
The specific fuel consumption G1, g/kWh			0,420
The specific fuel consumption G1, l/kWh			0,476
Month	Fuel consumption, l	Month	Fuel consumption, l
Jan	331	Jul	231
Feb	309	Aug	248
Mar	270	Sep	280
Apr	268	Oct	289
May	264	Nov	314
Jun	239	Dec	342
Total fuel consumption, l			3387

4.5. VARIANT 2. ENERGY SUPPLY BASED ON PV SYSTEMS

This stage of work will present power supply based on PV system. The PV system could be divided by the type of orientation of panels into following variants:

- PV system with manual changing of panel's position (later, optimally tilted PV system). This variant provides that the position of panels is inclined and fixed at the optimum angle.
- PV system with the dual-axis tracking system. The PV panels track the Sun's position using two coordinates.
- PV system with the single-axis tracking system. The PV panels track the Sun's position using only one coordinate.
- PV system with fixed position of panels. PV panels are fixed at the optimum angle during the whole operational period.

In order to determine the power output of PV systems, the technique which allows to calculate the hourly flow of the total solar radiation falling on a plane at any angle to the horizon and oriented in any direction on any given day will be presented. The calculations will be made in MathCad. The plane is considered as PV panel [55].

4.5.1. Solar radiation and calculation technique

It is known that the distance between the Sun and the Earth is about 150 million km. Since the longitudinal axis of the Earth moves around the sun by elliptical orbit, solar radiation which is incident on the Earth's surface varies according to the seasons of the year. The total solar radiation which falls on the surface area of 1m^2 (outside the Earth's atmosphere above 150 km) is called the solar constant which is equal to 1395 W/m^2. When solar radiation passes through the Earth's atmosphere, the intensity is reduced due to the follow actions: the absorption of molecules of oxygen, ozone, carbon dioxide, water vapor, dust and cloud layers; dry air and dust molecules scattering, etc. In general, the atmosphere is absorbed by 17...25% of the solar radiation. The radiation reaching the Earth's surface consists of direct and diffusion radiation. Direct radiation coming from the Sun is radiation that does not change its direction. Diffuse (or scattered) radiation is called radiation after changing its direction due to reflection and scattering. The figure below shows the diagram used for the calculation of incoming solar radiation.

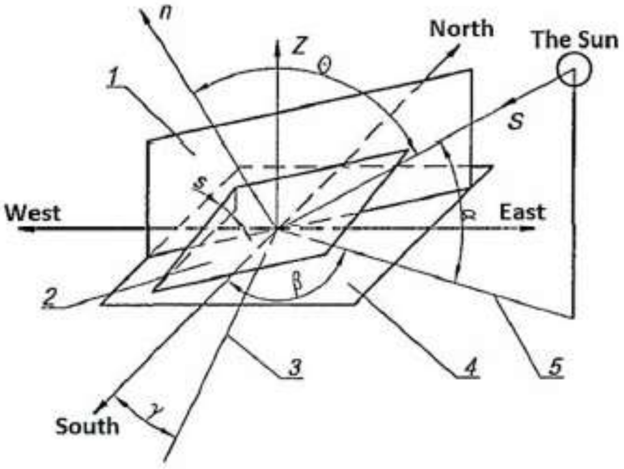

Figure 22 – Calculation scheme of incoming solar radiation at any oriented plane [27]

Where*: 1 – vertical plane; 2 – inclined plane; 3 – horizontal projection of a normal to an inclined plane; 4 – horizontal plane; 5 – horizontal projection of sunlight; Z – normal to a horizontal plane; n – normal to an inclined plane; S – direct sunlight to Earth's surface; α – solar altitude; β – solar azimuth angle; γ – plane azimuth angle; θ – angle of incidence of direct solar radiation; s – plane inclination angle (tilt angle).*

For the calculation it is necessary to introduce the following terms:

- Angle of incidence of direct solar radiation θ (rad) - the angle between the direction of radiation on any surface and the normal to the surface
- Declination δ (rad) – the angular position of the sun at solar noon relative to the plane of the equator (the value is positive in the northern hemisphere)
- Plane azimuth angle γ (rad) – deviation of the normal to the plane of the local meridian
- Solar altitude α (rad) – the angle between the direction of the direct solar radiation and the horizontal projection of the sun's ray
- Solar azimuth angle β (rad) – the angle between the horizontal projection of the sun's ray and the direction to the south
- Zenith angle θ_z (rad) – the angle between the vertical and the line of the sun's ray
- Hour angle ω (rad) – the angle that determines the angular displacement of the Sun during the day. One hour corresponds to π / 12 rad of angular displacement. At noon, the hour angle is equal to zero. The hours before noon angle are considered as positive values, in the afternoon – negative.

When the solar radiation coming on any inclined plane is calculated, the three components of radiation balance is taken into consideration:

$$\mathrm{Q}_{inc} = \mathrm{S}_{\mathrm{inc}} + \mathrm{D}_{inc} + \mathrm{R}_{inc} \qquad \text{Equation 5}$$

Where:

Q_{inc} – total solar radiation which is incident on the inclined surface, W/m^2;
$\mathrm{S}_{\mathrm{inc}}$ – direct solar radiation which is incident on the inclined surface, W/m^2;
D_{inc} – diffuse solar energy which is incident on the inclined surface;
R_{inc} – solar radiation reflected from the Earth's surface W/m^2.

$$\mathrm{S}_{\mathrm{inc}} = \mathrm{S}_{\mathrm{ort}} \cdot \cos\theta \qquad \text{Equation 6}$$

Where:

$\mathrm{S}_{\mathrm{ort}}$ – solar direct radiation which is incident on the orthogonally oriented plane to the Sun’s rays, W/m^2;

$$\mathrm{S}_{\mathrm{ort}} = \frac{\mathrm{S}_0 \cdot \sin\alpha}{\sin\alpha + c} \qquad \text{Equation 7}$$

Where:

S_0 – solar constant equals to 1395 W/m^2;
c – dimensionless coefficient characterizing the degree of transparency of the atmosphere.

Table 7 – The degree of transparency of the atmosphere

	The degree of transparency of the atmosphere						
	The highest	Very high	High	Normal	Low	Very low	The lowest
The value of coefficient	0,13	0,27	0,34	0,43	0,54	0,67	0,91

In this stage, the above-described ways of orientation of PV panels presented in 4.5 will be considered. The orientation is determined by the angle of incidence of solar radiation.

- Angle of incidence in case of the optimum tilted system. Angle of incidence of solar radiation on the plane at different angles to the horizontal plane is determined by formula below.

$$\cos\theta = \sin\delta\cdot\sin\varphi\cdot\cos s - \sin\delta\cdot\cos\varphi\cdot\sin s\cdot\cos\gamma + \cos\delta\cdot\cos\varphi\cdot\cos s\cdot\cos\omega + \cos\delta\cdot\sin\varphi\cdot\sin s\cdot\cos\gamma\cdot\cos\omega + \cos\delta\cdot\sin s\cdot\sin\gamma\cdot\sin\omega$$

Equation 8

Where:

φ – geographic latitude, rad;
δ – sun declination, rad;
γ – plane azimuth angle, rad;
ω – hour angle, rad;
s – plane inclination angle, rad.

The plane inclination angle *s* (tilt angle) varies from 0 to π/2, where the angle of 0 corresponds to a horizontal oriented plane, and π/2 – to vertical oriented plane. Plane azimuth angle γ ranges from - π to π, where the angle of 0 corresponds to plane oriented to the south, π/2 – the south-east, π/2 – the south-west.

- Angle of incidence in case of single-axis rotation. The calculation of the angle of incidence for the plane rotated about the vertical axis with a fixed tilted angle is performed by the formula below. The tracking is performed from East to West. The tilt angle *s* is fixed. The solar azimuth angle β is equal to plane azimuth angle γ. The plane's inclination angle s is fixed and equals to the optimum angle.

$$\cos\theta = \cos\theta z\cdot\cos\beta + \sin\theta z\cdot\sin\beta$$

Equation 9

Where:

θ_z – zenith angle θz, rad.

Zenith angle can be found according to formula below:

$$\cos\theta_z = \cos\delta \cdot \cos\varphi \cdot \cos\omega + \sin\varphi \cdot \sin\delta \qquad \text{Equation 10}$$

- Angle of incidence in the case of dual-axis rotation. The calculation of the amount of incoming solar radiation is performed at the angle which is perpendicular to the flow of falling solar radiation, consequently the angle of incidence of solar radiation θ is equal to 0. The plane's inclination angle s is equal to the zenith angle θ_z . The solar azimuth angle β is equal to plane azimuth angle γ.

$$\cos\theta = 1 \qquad \text{Equation 11}$$

- Angle of incidence in the case of fixed position of panels. Equation 14 allows to calculate this case, where the plane's azimuth angle γ and angle of incidence θ are fixed at the optimum angle.

Estimation of the value of the Sun declination can be determined by the formula of Cooper:

$$\delta = \delta_0 \cdot \sin\left(2 \cdot \pi \cdot \frac{284+N}{365}\right) \qquad \text{Equation 12}$$

Where:

$\delta_0 = 23.49$ - sun declination for the northern hemisphere, ℃;
N – serial number of day in a year, counted from January 1;

Determination of the length of sun day by using the following formula:

$$T_\mathrm{d} = \frac{2}{15} \cdot \arccos(-\mathrm{tg}\,\varphi \cdot \mathrm{tg}\,\delta) \qquad \text{Equation 13}$$

Time of sunrise t_{sr}:

$$t_{sr} = 13 - \frac{T_\mathrm{d}}{2} \qquad \text{Equation 14}$$

Time of sunset t_{ss}:

$$t_{ss} = 13 + \frac{T_\mathrm{d}}{2} \qquad \text{Equation 15}$$

Sun altitude is determined by the formula:

$$\sin\alpha = \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos\omega \qquad \text{Equation 16}$$

Solar azimuth angle is determined by the formula:

$$\cos\beta = \frac{\sin\alpha \cdot \sin\varphi - \sin\delta}{\cos\alpha \cdot \cos\varphi} \cdot \sin\varphi \qquad \text{Equation 17}$$

Diffuse solar radiation coming on the plane is determined by the formula:

$$\mathrm{D_{inc}} = \mathrm{D_{hor}} \cdot (0{,}55 + 0{,}434 \cdot \cos\theta + 0{,}313 \cdot (\cos\theta)^2) \qquad \text{Equation 18}$$

Where:

D_{hor} – flow of diffuse solar radiation which is incident on a horizontal surface, W/m^2;

$$\mathrm{D_{hor}} = \frac{1}{3} \cdot (S_0 - S_{\mathrm{ort}}) \cdot \sin\alpha \qquad \text{Equation 19}$$

Reflected solar radiation falling on the inclined plane from the Earth's surface R_{inc} is negligible. Therefore it does not have a significant effect on the total incident energy.

Thus, using the formula given above, the total solar radiation which is incident on the plane in clear weather conditions at different angles of inclination to the horizon can be calculated by this formula:

$$\mathrm{Q_{inc}}(\varphi, \omega, \gamma, \mathrm{s}, \mathrm{N}) = \mathrm{S_{inc}}(\varphi, \omega, \gamma, \mathrm{s}, \mathrm{N}) + \mathrm{D_{inc}}(\varphi, \omega, \mathrm{s}, \mathrm{N}) \qquad \text{Equation 20}$$

$$\mathrm{k} = 1 - (\mathrm{a} + 0.38 \cdot \mathrm{n}) \cdot \mathrm{n}) \qquad \text{Equation 21}$$

Where:

a – empirical coefficient depending on the environment (land or sea) and on the latitude of the object;

n – the number of clouds as a decimal (n = 0 - cloudless sky, n = 1 cloudiness). This number can be found on the basis of meteorological observations database.

Thus, the total solar radiation falling on the plane inclined to the horizon at an optimum angle in case of cloudy weather conditions can be calculated by using the following formula:

$$\mathrm{Q}_{cloud}(\varphi, \omega, \gamma, \mathrm{s}, \mathrm{N}) = (\mathrm{S_{inc}}(\varphi, \omega, \gamma, \mathrm{s}, \mathrm{N}) + \mathrm{D_{inc}}(\varphi, \omega, \mathrm{s}, \mathrm{N})) \cdot \mathrm{k} \qquad \text{Equation 22}$$

It can be concluded that by setting the angles of incidence of solar radiation, the amount of incident radiation for any given location and for any day and time of the year can be determined. Thus by using the above described technique, it is possible to calculate the level of specific insolation for the typical day (it is recommended to take a day in the middle of the month) of each month at different weather conditions (cloudy or partly cloudy) for the analyzed month. By multiplying the daily specific radiation by the number of days in the month it is possible to obtain the specific monthly energy of solar radiation at a place where the photovoltaic system is located.

4.5.2. Optimally tilted PV system

In this case, the PV system has a structure that allows manual changing of position of the panels when it is required. The variant provides that the position of panels is fixed and inclined at the optimum angle. Such changing of position helps to compensate for the ecliptic changes that occur in the winter, spring, summer and autumn seasons. [27] Further, the example of solar radiation calculation for May 15th will be presented.

- $\varphi = 51.07$ – geographic latitude of the object, deg;
- $S_0 = 1395$ – the solar constant, W/m^2;
- $N = 135$ – serial number of days in a year, counted from the 1st January;
- $c = 0{,}43$ – dimensionless coefficient characterizing the degree of transparency of the atmosphere for the current region;
- $\gamma = 0$ – plane azimuth angle is oriented to the south (corresponds to the longest duration of irradiation), rad;
- $\alpha = 0{,}383$ – for the current region (land);
- $n = 0{,}4$ – the number of clouds as a decimal for the current region. For the analysis of actual cloudiness, meteorological data from the weather archive at the meteorological station of the Ulan-Ude airport were used. The data stored with a time interval of 0.5 to 3 hours. In total 34.478 observations for 2012-2016 were used. [18]

Determination of the length of sunlight in a day, time of sunrise and time of sunset were calculated according to Equation 12, 13, 14 respectively. The results are presented in the Appendix 6. This period of time corresponds to the changing of the hour angle:

$$\omega = (\frac{\pi}{2}, \frac{5\pi}{12}, \frac{\pi}{3} \dots - \frac{7\pi}{12})$$

The angles of inclination of the plane to the horizon are:

$$s = \frac{\pi}{12}, s = \frac{\pi}{6}, s = \frac{\pi}{4}, s = \frac{\pi}{3}, s = \frac{5\pi}{12}$$

The calculation includes the following order:

- Finding the value of the sun declination by using the formula of Cooper (Equation 12).
- Determining of the Sun altitude (Equation 16) and the angle of incidence of solar radiation on the plane at different angles to the horizontal plane by using Equation 8.
- The total solar radiation which is incident on the plane in clear weather conditions at different angles of inclination to the horizon is defined by using Equation 20.

- The optimal angle of inclined plane in case of the total solar radiation which falls on the surface in clear weather conditions is being chosen according to the obtained graphs.
- Determining of the total solar radiation falling on a plane inclined to the horizon at the optimum angle in partly cloudy weather (Equation 22).

The figure below shows the graph of the daily total solar radiation coming on the inclined plane at different angles to the horizon on the clear day, May 15th.

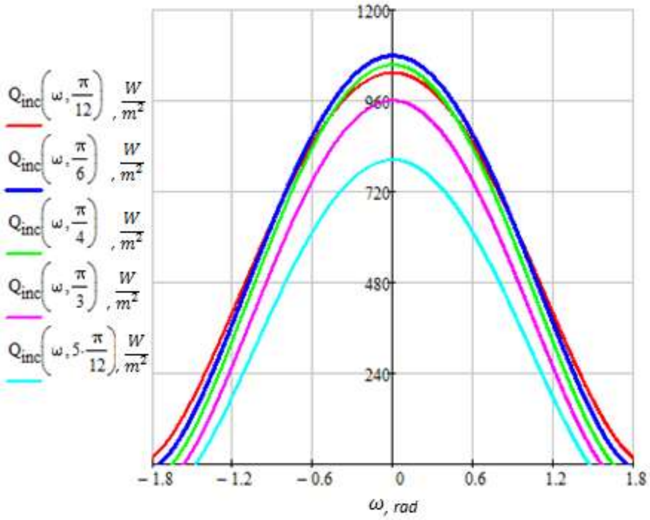

Figure 23 – The solar radiation falling on the plane which is inclined at different angles on clear day

According to the graph presented above, it can be seen that the maximum amount of solar radiation is gained at the angle π/6 (30°), which is the optimum angle of the inclined plane to the horizon. The calculation of the total specific energy falling on the plane area of 1 m^2 at the angle π/6 on May 15, it is necessary to integrate:

$$\int_{\omega 1}^{\omega 2} Q_{inc}(\omega) \cdot \frac{24}{2\cdot\pi} \cdot d\omega = 8490\ \frac{Wh}{m^2}$$

Equation 23

Where:

$\omega 1, \omega 2$ – hour angles related to the moment of the beginning and end of the radiation process, respectively, rad;

Q_{inc} – total solar radiation which is incident on the inclined surface in clear weather conditions, W/m^2;

The calculation of total specific energy falling on the plane area of 1 m^2 at the angle π/6 in case of partly cloudy day:

$$\int_{\omega 1}^{\omega 2} Q_{cloud}(\omega) \cdot \frac{24}{2\cdot\pi} \cdot d\omega = 6519\ \frac{Wh}{m^2}$$

Equation 24

Where:

Q_{cloud} – total solar radiation which is incident on the inclined surface in cloudy weather conditions, W/m^2;

The graph of the total solar radiation falling on a plane inclined to the horizon at an angle of π/6 on a partly cloudy day is presented below.

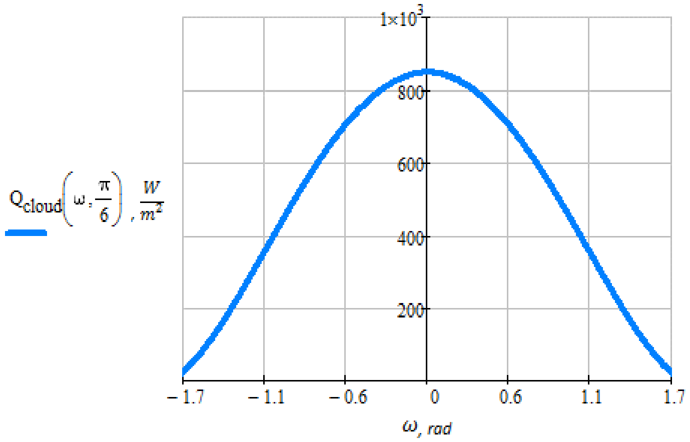

Figure 24 – The solar radiation on a plane which is inclined at the angle of π / 6 on a partly cloudy day

The level of specific total energy for a typical day (May 15) of the month was calculated. The values of total solar radiation which falls on the plane for the rest of months are determined similarly and presented in the Appendix 6.

4.5.3. Dual-axis tracking system

This variant includes a sun tracking system that allows tracking the Sun in both coordinates (tilt and azimuth). In this case, the angle of incidence is calculated according to Equation 11. The figure below shows the graph of the total solar radiation falling on a plane in case of dual-axis tracking on the clear day, 15th May.

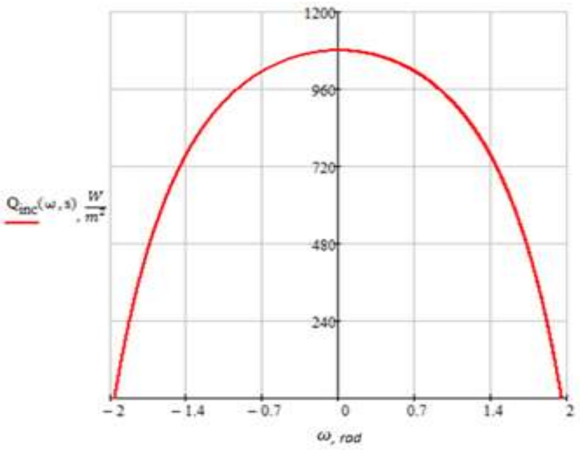

Figure 25 – The solar radiation falling on a plane on clear day (dual-axis tracking)

The total specific energy falling on the plane area of 1 m^2 on clear day:

$$\int_{\omega 1}^{\omega 2} Q_{\text{inc}}\,(\omega)\cdot\frac{24}{2\cdot\pi}\cdot d\omega = 12458\ \frac{\text{Wh}}{\text{m}^2}$$

The total specific energy falling on the plane area of 1 m^2 in case of partly cloudy day:

$$\int_{\omega 1}^{\omega 2} Q_{\text{cloud}}\,(\omega)\cdot\frac{24}{2\cdot\pi}\cdot d\omega = 9364\ \frac{\text{Wh}}{\text{m}^2}$$

The figure below shows the graph of the total solar radiation which falls on a plane in case of dual-axis tracking on a partly cloudy day May 15th. The table with results of calculation are performed in the Appendix 6.

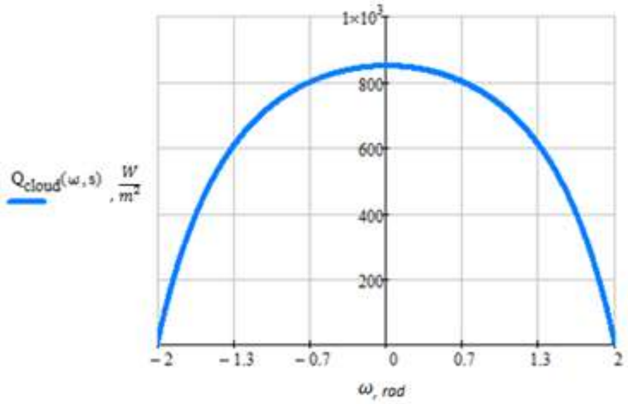

Figure 26 – The solar radiation falling on a plane on a partly cloudy day (dual-axis tracking)

4.5.4. Single-axis tracking system

This variant considers that the plane track the sun's position only using one coordinate (azimuth movement). In this case, the angle of incidence is calculated according to Equation 9. Figure 27 shows the graph of the daily total solar radiation falling on the plane on the clear day, May 15th.

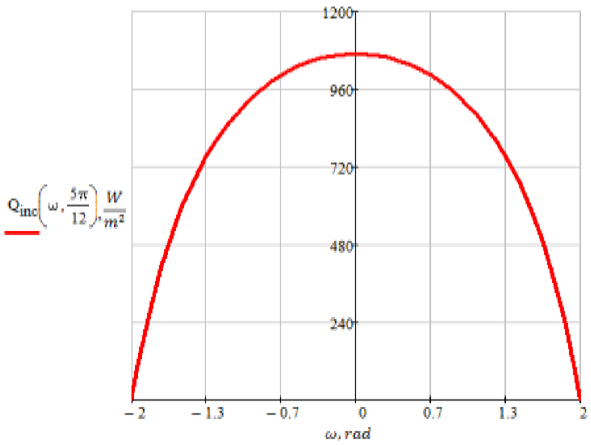

Figure 27 – The solar radiation falling on a plane on sunny day (single-axis tracking)

The total specific energy falling on the plane area of 1 m^2:

$$\int_{\omega 1}^{\omega 2} Q_{inc}(\omega) \cdot \frac{24}{2 \cdot \pi} \cdot d\omega = 10829 \ \frac{Wh}{m^2}$$

The total specific energy falling on the plane area of 1 m^2 in case of partly cloudy day:

$$\int_{\omega 1}^{\omega 2} Q_{cloud}(\omega) \cdot \frac{24}{2 \cdot \pi} \cdot d\omega = 8845 \ \frac{Wh}{m^2}$$

The figure below shows the graph of the total solar radiation which falls on a plane on a partly cloudy day May 15. The table with results of calculation is performed in Appendix 6.

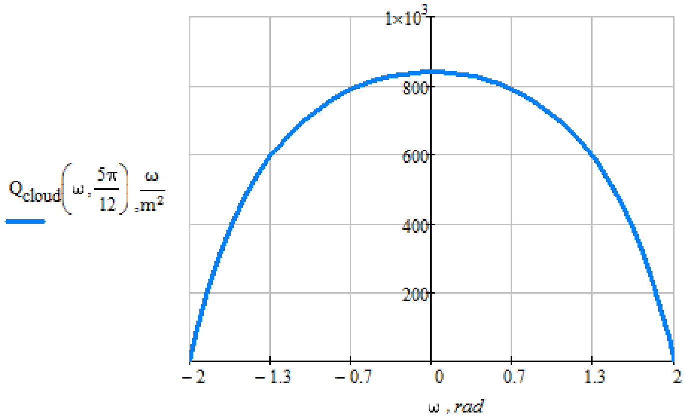

Figure 28 – The solar radiation falling on a plane on a partly cloudy day (single-axis tracking)

4.5.5. Fixed position of panels

This system is described by a fixed position of solar panels for the entire period of operation. The calculation will be performed at the optimum tilt angle for the region which is defined at 45 degrees. In this case, the angle of incidence is calculated according to Equation 8. The plane azimuth angle is oriented to the south. The figure below shows the graph of the daily total solar radiation falling on the inclined plane at the optimum tilt angle to the horizon on clear day.

The total specific energy falling on the plane area of 1 m^2 on clear day:

$$\int_{\omega 1}^{\omega 2} Q_{inc}(\omega, s) \cdot \frac{24}{2 \cdot \pi} \cdot d\omega = 8134 \ \frac{Wh}{m^2}$$

The total specific energy falling on the plane area of 1 m^2 in case of partly cloudy day:

$$\int_{\omega 1}^{\omega 2} Q_{cloud}(\omega, s) \cdot \frac{24}{2 \cdot \pi} \cdot d\omega = 6007 \ \frac{Wh}{m^2}$$

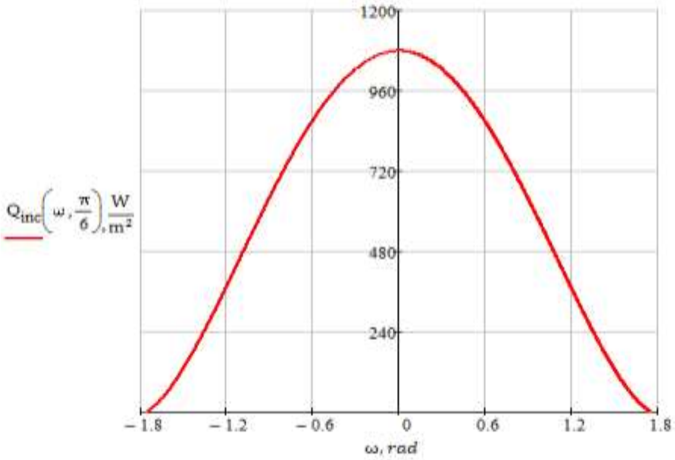

Figure 29 – The solar radiation falling on a plane inclined at 45 deg. on sunny spring day

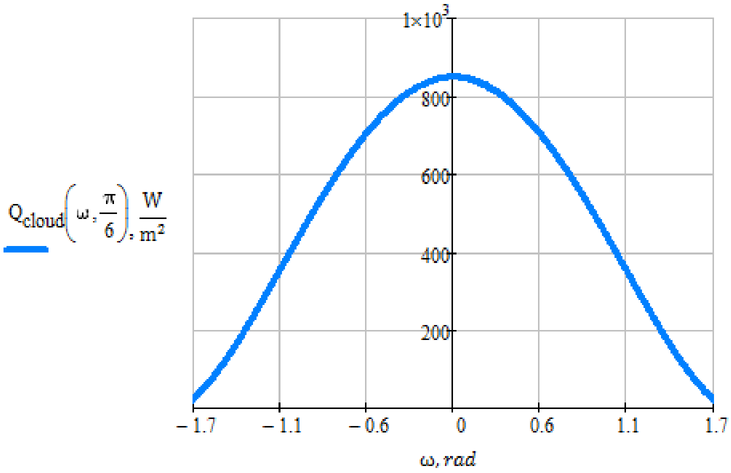

Figure 30 – The solar radiation falling on a plane inclined at 45 deg. on a partly cloudy day

4.6. RESULTS OF SOLAR RADIATION CALCULATION

According to above-described technique, the amount of incident solar radiation energy falling on the plane area of 1 m^2 was identified for all variants of orientation of PV panels. The results of the calculations are presented in Appendix 6.

Table 8 – Calculated annual solar radiation falling on the plane area of 1 m^2

	Annual average solar radiation (clear day), Wh/m^2	Annual average solar radiation (cloudy day), Wh/m^2
Fixed position	5792	4568
Monthly changing	6253	4854
Single-axis	7353	6007
Dual-axis	8453	6505

Table 9 – Comparative view of the performance of variants

Month	December	April	June	October
1	124%	100%	113%	113%
2	103%	131%	136%	105%
3	118%	144%	148%	117%
4	114%	113%	109%	113%

Where: 1 – optimum tilted system is compared with fixed position of panels; 2 – single-axis tracking is compared with optimum tilted; 3 – dual-axis tracking is compared with optimum tilted; 4 – dual-axis tracking is compared with single-axis tracking. Table 9 presents a comparative view of the performance of variants for December, April, June, and October are presented. Comparison of other months is presented in Appendix 8. Optimum tilted variant has significantly higher performance comparing with fixed position of panels (24% and 13% in December and October periods, respectively). Consider April, the optimum angle is the same in both variants. In the winter period, the performance of the single-axis tracking variant is substantially low when compare with the optimum tilted variant (only by 3% higher). In the case of the dual-axis tracking, the performance is higher by 18% in the same period. In the summer period, the performance of the single-axis tracking variant is increased and equals to almost 36% to compare with optimum tilted variant, as for the dual-axis tracking, it is increased by 48% in the same period. The performance both single-axis and dual-axis tracking variants are quite significant in the spring and summer periods to compare with the autumn period (October) where the performance is almost the same as in the winter period (December). Comparing both performance of the single-axis and the dual-axis tracking variants with the optimum tilted variant, the dual-axis is a more attractive variant since it is the most efficient. Under dual-axis tracking, the system receives more solar radiation, especially, in the winter and autumn periods which are vital for stand-alone energy system in severe conditions. Solar radiation is substantially lower in the variant with the fixed position of panels than in the optimum tilted variant. In the result, the following variants are chosen for further investigation:

Variant 2. Optimally tilted PV system

Variant 3. PV with the dual-axis tracking system (later, solar tracker)

4.7. SOLAR RADIATION BY USING ONLINE CALCULATORS

In this step of work, the level of solar radiation in the region of the object will be analyzed by using methods listed below. The results of all methods will be compared with the results obtained by using the calculation technique.

- The first method: the online calculator of Atmospheric Science Data Center was used. Accordingly, the monthly averaged insolation on a horizontal surface is defined [56].
- The second method: the online calculator of Photovoltaic Geographical Information System (PVGIS) was used [57].
- The third method is based on statistical data. There are tables with values of solar radiation for different regions of Russia [58].
- Provided calculation technique.

The results of defined solar radiation falling on horizontal surface are presented in Appendix 7.To summarize, the level of solar radiation slightly differ when using the above mathematical technique and the above described methods. The small imperfections of presented technique can be the first reason of the difference. The second factor is statistical data used for determining the cloudiness and the degree of transparency.

4.8. STRUCTURAL DIAGRAM OF PHOTOVOLTAIC SYSTEMS

In this subchapter, the structural diagram of PV systems will be considered. When an autonomous power supply system based on photoelectric converters is designed, it must be mentioned that the level of energy coming from the Sun is unstable. First of all, it is related to the fact that photovoltaic system is capable of producing energy only in daytime. Additional factors that influence the production of solar panels are cloudiness, precipitation, etc. In the winter period, when the daytime is short the total amount of produced energy is less than in the summer period.

Based on above description and taking into account the location and weather conditions (especially, winter period) of the meteorological station, the petroleum-based generator (KIPOR KGE2500E) will be considered as an additional source of power supply in the energy balance of the photoelectric system. Photovoltaic panels provide large part of produced energy and subsequent amount of energy is covered by the generator. In this case, the combined electrical complex will be efficient. The construction scheme of PV system is provided in Figure 31.

The construction uses (Ph) - set of photovoltaic modules to cover the (L) - load, and (G) – an additional source of the power supply (petroleum generator) which is designed for periods when the total value of the solar insolation is not sufficient to provide the required amount of energy. Automatically adjustable ballast load (BL) is also the part of the system's composition which is designed to redirect the excess of power from the solar panels. A battery (AB) is intended to ensure a no-break operation of the electrical complex (for example, in the case of an accident on the source

(G), or in the period when the source (Ph) does not produce the desired power, or when switching between sources occurs). At this moment the (AB) is discharging to cover the required load. The batteries recover its capacity when there is an excess of energy coming from (Ph); if necessary, the charge of the battery can be carried out from the source (G) therefore it helping to increase the capacity utilization factor of the source (G).

Converting from DC to AC is the task of the inverter (I). The switching element (K) is also provided in the system. When intensive panel work occurs, the switch (K) is needed in order to save electricity coming from an additional source. For example, switch (K) turns off the source (G) in periods of an excess of solar radiation and connects back to it when the generated energy of the panels is insufficient to cover the load. In this case, the compensation of electricity coming from different sources in order to provide the optimal power supply occurs automatically. Distribution device (D) provides the transfer of energy from the generating sources. To avoid the recharge of the batteries, the system includes a charge controller (CPh) of the photovoltaic system (or it can be embedded in (I)) and charge the controller of the power source (CG) to provide an optimum battery charging process to increase service life and its efficiency.

It should be noted that the capacity of the battery (AB) in different cases of the application can vary significantly. If the source (G) is the main source, the designation of source (Ph) – is supporting a stable level of power supply and saving of fuel, but the battery (AB) operates in a buffer mode with a small depth of discharge so the total capacity of the battery (AB) may be relatively small. If the source (Ph) is the main source, and the source (G) is auxiliary, the battery (AB) is often operated in a cyclic mode so the battery capacity should be increased. One important fact is that the total cost of the battery (AB) can vary significantly and consequently affects the cost of the whole photovoltaic system. In addition what is described, the system includes devices which are needed for protection from interference and other external influences and a microprocessor based controller unit to monitor and manage the system automatically.

The reasonably selected construction scheme of the system makes it easier to design and scale the energy complexes, it also permits the use of the system equipment efficiently and provides an effective component interaction of autonomous power sources. The only difference between two considered PV systems is the presence of solar tracker which is installed as a part of the PV panels.

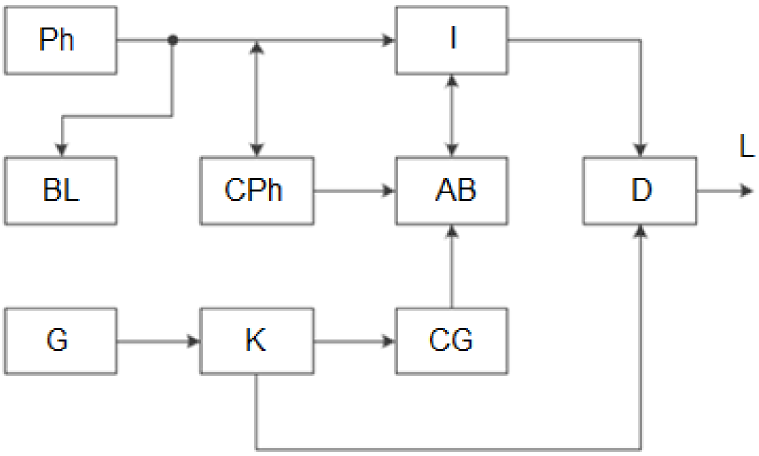

Figure 31 – The structural scheme of the photovoltaic system

The design concept of these PV systems is the ability of the full autonomous supply of the object in the spring, summer and earlier autumn periods (from March to September). Accordingly, in the variant with manual changing of panel's position, it is accepted to change the position only twice: from March to October the panels will be at the optimum fixed angle of 45 degrees, from November to February the panels will be set at the optimum angle of 75 degrees for the winter period in order to maximize the contribution of PV panels. Therefore, the position of panels will be changed two times per year. Such seasonal changing of panels' position is found reasonable since there is enough amount of incoming solar radiation and also it allows to decrease overproduction of panels in the summer period. It should be noted that the effectiveness of the PV system will be mainly determined by the composition and characteristics of the equipment used. Based on that, the photovoltaic systems require specialized energy equipment, thus the selection of main required devices and equipment for PV system will be considered further.

4.8.1. Selection of PV panel's type and number

The tabular characteristic of solar panels which allow to select reasonable types were identified. In the table below the most important parameters of different types of solar cells are performed.

Table 10 – Characteristics of different types of solar cells [59]

Type	I_{sc} (mA/sm^2)	U_{oc} (V)	I_{opt}(mA/sm^2)	U_{opt} (V)	P_{max} (W)	E	n (%)
C-Si	42,2	0,67	40,4	0,59	23,85	0,842	24
AsGa	28,2	1,03	27,42	0,942	25,82	0,886	26
poly-Si	38,1	0,64	36,40	0,564	20,54	0,83	20,5
a-Si	19,4	0,72	18,61	0,64	11,91	0,85	11,9
CuInGaSe2	35,7	0,66	34,12	0,58	19,79	0,84	19
CdTe	25,9	0,72	24,28	0,643	15,99	0,85	16

Where: I_{sc} – specific short-circuit current, U_{oc} – open-circuit voltage, I_{opt} - specific optimal current, U_{opt} – specific optimal voltage, P_{max} - specific maximum capacity, E – fill factor, n - efficiency at the point of maximum power.

When the efficiency of solar cells is being evaluated, a fill factor plays a crucial role in the decision making. It is one of the key parameters. Fill factor is the ratio of maximum power to the product of the short-circuit current and the open-circuit voltage of the solar cell. A solar panel with a high fill factor has fewer losses due to the serial and parallel resistors. Another key parameter is the efficiency factor of the panel. The efficiency factor is determined as the ratio of power generated by the solar cell to the incident solar radiation power. Therefore, according to above described reasons and on the basis of previously presented information in 2.4.1, the best choice of the type of solar panel is C-Si. The following criteria highlights the most suitable type of solar panel needed for weather station conditions: cost, operating life, and availability. Based on research of the Russian market the most popular, reliable and recommended monocrystalline solar modules is FSM-250. The power of the panel is 250 W. The voltage is 24 V. The efficiency is 15.4 %. The area of the panel is 1.632 m^2. The full technical characteristics are presented in Appendix 11 [60].

Energy generation by panel

The technical characteristics of the selected solar panel such as the efficiency factor and the working area are required for the calculation of generated energy. The actual solar radiation falling on the plane area of 1 m^2 is found by using the following formula [27]:

$$Q_{act} = Q_{cloud} \cdot \eta \qquad \text{Equation 25}$$

Where:

Q_{cloud} – the daily average amount of solar radiation in the case of partly cloudy conditions, Wh/m^2;

η – the efficiency factor of PV panel, %;

The calculation of the energy which is generated by solar panel:

$$W_{panel} = Q_{act} \cdot S_{panel} \qquad \text{Equation 26}$$

Where

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

It is necessary to mention about the connection of solar panels in PV systems. In this work, a series and parallel connection is used in order to achieve the optimum characteristics of the output voltage. The solar panels will be connected as such: 2 panels have a serial connection in order to create voltage value of 48 V, and the rest of panels have a parallel connection. Since that the design concept of PV supply system is to supply the object from March to September, from the technical point of view the optimum number of panels for both variants is determined and shown in the table below.

Table 11 – Number of PV panels

Optimally tilted PV system	16
PV with dual-axis tracking	12

4.8.2. Selection of battery type and its number

According to the tabular characteristics of batteries which allow reasonably to select the types of batteries provided in [28], it can be concluded that AGM (Absorbent Glass Mat) and GEL lead-acid batteries are the most commonly used types for PV systems among the known types of batteries. In this case study, GEL lead-acid batteries are chosen due to the unique characteristics such as: high indicators in case of deep discharge, big number of charge-discharge cycles, the acceptability of long standing in a discharged state, almost no maintenance, low unit cost (cost / number of cycles), protected from spills and leaks, does not corrode, no outgassing and can stand the severe conditions of the winter period. GEL lead-acid batteries require only protection against overcharging, and they should have a voltage limiter when the battery is in charge. When batteries are chosen, it is necessary to take into account the depth of discharge. In this case study, the required energy of a battery is determined by using the following formulas:

$$W_{AB} = W_{sh} \cdot d \qquad \text{Equation 27}$$

Where:

W_{sh} – the energy required to accumulate, kWh;

d – the coefficient that characterizes by how much the capacity of the battery should be increased. For example, in the long term of operation, the battery should always have at least 30% of the charge for a long operation life. This means that required battery capacity is increased by 30% meaning that coefficient d is equal to 1.3. In other words, it represents the depth of discharge of batteries. See Table 12.

Determination of number of batteries that is needed to install to create voltage value of 48 V:

$$N_{row} = \frac{U_s}{U_{AB}} \qquad \text{Equation 28}$$

Where:

U_s – voltage of system, V;

U_{AB} – voltage of battery, V;

The necessary capacity of all batteries:

$$C = \frac{W_{AB}}{U_{AB}} \qquad \text{Equation 29}$$

The capacity of batteries in one row:

$$C' = \frac{C}{N_{row}} \quad \text{Equation 30}$$

The capacity of one battery:

$$C_1 = \frac{C\prime}{n_{par}} \quad \text{Equation 31}$$

Where:

n_{par} – number of parallel rows consisting of series connected batteries;

In this work, based on discussion provided above, the batteries DELTA GX-200 are installed in both PV systems. The voltage of AB is 12 V. The capacity of AB is 200 Ah. Other technical characteristics are presented in Appendix 12. The number of cycles strongly depends on the depth of discharge of the batteries. According to [61], when the battery is discharged to 30% the number of cycles is equal to 1400. Therefore 30%, 50%, 70% of depth of discharge is considered. Based on the calculations, the required energy of the batteries is identified. The results are presented in Table 12 [62].

Table 12 – Number of batteries with different deep of discharge

Number of cycles	Lifetime of battery, years	Depth of dischage	d
1400	6,6	30%	1,7
800	3,8	50%	1,5
500	2,3	70%	1,3

After calculation of each variant of the depth of discharge, a 30% depth of discharge was accepted in order to extend the lifetime of the batteries. Therefore, Table 13 and Table 14 present the number of batteries for each month. The required number of batteries was calculated according to the shortage of energy that are not covered by PV panels. The available number of batteries was calculated according to the excess of energy generated by PV panels using the same Equation 29 (instead of shortage of energy, the excess of energy produced by PV panels is used). It can concluded that the number of batteries for the winter and summer periods is unreasonable. In the winter period, the level of solar radiation is very low, therefore it does not allow to accumulate enough energy. In the summer period, some of batteries would just stand idle if to install available number of the batteries. In the result, according to the March and September, the eight batteries (30% DOD) are installed in order to provide autonomous supply while four of them has a serial connection to create the voltage value of 48 V.

Table 13 – Number of batteries in optimally tilted PV system

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Required number	11,5	10,1	**7,6**	6,7	5,5	4,6	4,5	5,8	**7,7**	8,8	11,1	12,4
Available number	3,00	5,27	**7,6**	9,1	10,6	11,6	11,7	10,1	**8**	6,4	3,2	2,0

Table 14 – Number of batteries in PV system with the tracker

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Required number	11,7	10,3	**7,6**	6,6	5,4	4,5	4,5	5,7	**7,7**	8,8	11,2	12,5
Available number	2,4	4,3	**7,7**	10,9	12,5	14,2	14,1	11,6	**8**	5,6	2,6	1,5

4.8.3. Selection of controller

It is necessary to pay attention to parameters such as the input voltage of the solar panels, specifically, the open-circuit voltage when the controller is being selected. The first factor of selecting the controller is voltage. The maximum voltage of a controller that can be found in a manufacturer's specification should be 20 percent higher than the open-circuit voltage of photovoltaic panels. This is necessary in order to ensure the system’s operability when the operating conditions are different from the conditions of passport measurements. In the result, to protect the controller from breaking. The second factor is the power. The production of the output current of the controller and the voltage of the system when the batteries are in a discharged state must be equal to or more than the total power of the connected solar panels, where the total power of the panels is taken with 20 percent more for reserve. Based on above-mentioned requirements and the connection of solar panels, the controller DOMINATOR MPPT 200/100 is chosen for both PV systems. Technical characteristics of the controller are presented in Appendix 13 [63].

4.8.4. Selection of inverter

The nominal power of the inverter should be equal to or more than the total power of loads of the object. It should be noted that some devices have a start current which might be higher by 2-3 times and selection of the inverter must be based on this current. In the result, the inverter is taken with a 30 percent of power reserve. Based on requirements, MAP-SIN-PRO 48-3 inverter is installed for both PV systems. Rated power of inverter is 2 kW. The rated voltage of the inverter is 48 V. All technical characteristics of the inverter are presented in Appendix 14 [63].

4.8.5. Selection of solar tracker

The Russian solar tracker market is completely undeveloped. The research shows that, at present, there is only one company “EDS Group” that manufactures and distributes solar trackers in the

Russian market. Therefore, for further economic evaluation of PV systems, the ED-2000 Dual solar tracker from this company is chosen. The sensitivity analysis on the cost of dual-axis solar tracker of foreign manufacturers will be provided in the 5.4.4. The permissible number of PV panels for the solar tracker ED-2000 Dual is 12. The recommended modules for this tracker are panels with power of 210-250 W and with dimensions of 1650x990. This corresponds to already chosen PV modules. The energy consumption of the tracker is 0.015 kWh per day. This amount of energy is taken into account in the energy balance of the system. The other technical characteristics are presented in Appendix 15[64].

4.9. ENERGY BALANCE OF PV SYSTEMS AND RESULTS

To create an energy balance of the system, it is necessary to refer to the graph of monthly energy consumption of the object in Figure 19. The energy balance of both photovoltaic systems, including both produced energy and consumed energy, is composed and presented in the tables below. In accordance with the energy balance of both PV systems, a large part of produced electricity is provided by PV panels with the batteries. The PV panels satisfy the required energy amount during the considered period from March to September. It can be seen from Table 15 that there is a lack of energy generation in January, February, October, November, December. This needed amount of energy is covered by the combination of PV panels and the petroleum-based generator. The difference between the variant with optimally tilted PV system and PV with solar tracker in the energy consumption column in Table 16 is explained by the energy consumption of the tracker. In order to provide the full yearly autonomous power supply based on only PV system, it is necessary to install 42 PV panels in case of optimally tilted PV system and 37 PV panels in case of PV system with solar tracker.

Table 15 – The energy balance of optimally tilted PV system

Variant 2. Optimally tilted PV system + generator				
Month	Energy consumption, kWh	Energy production by panels Q_{act}, kWh	Energy production by generator, kWh	Fuel consumption, l
Jan	697	336	360	171
Feb	650	426	224	107
Mar	568	568	0	0
Apr	563	660	0	0
May	555	706	0	0
Jun	503	716	0	0
Jul	486	733	0	0
Aug	522	711	0	0
Sep	589	602	0	0
Oct	608	467	141	67
Nov	660	341	319	152
Dec	720	280	440	209
Total:	7120	6546	1484	706

Table 16 – The energy balance of PV system with solar tracker

Variant 2. PV system with tracker + generator				
Month	Energy consumption, kWh	Energy production by panels Q_{act}, kWh	Energy production by generator, kWh	Fuel consumption, l
Jan	701	284	418	199
Feb	654	385	269	128
Mar	573	590	0	0
Apr	568	758	0	0
May	560	882	0	0
Jun	507	926	0	0
Jul	491	922	0	0
Aug	527	809	0	0
Sep	593	635	0	0
Oct	613	482	131	62
Nov	665	295	369	176
Dec	724	236	489	232
Total:	7175	7204	1676	797

Application of trackers allows to install fewer PV panels (12 panels) and keep the appropriate level of required energy coverage. The difference is only 2.6% (Table 17). This 2.6% can be interpreted as 91 liters of fuel consumption (Table 16). The significant role in the energy balance plays the winter period. It can be seen that in winter period, the production of energy by 12 installed panels that track the sun is not efficient as 16 PV panels of optimally tilted PV system, but in the autumn, spring and summer periods the situation is changed in favor of 12 panels. The other parameter is the overproduction of solar panels during the spring and, especially, the summer period (presented in Table 17). In this case, the excess of energy production goes to the ballast load of the system.

Both variants significantly reduce the fuel consumption of the generator: the PV system without tracker reduces consumption by 2681 liters; the system with the solar tracker reduces by 2590 liters. Moreover, the introduction of PV systems reduces the number of operating hours of the generator and therefore its maintenance, which significantly influences on the economic evaluation of the systems.

Table 17 – The technical data of considered variants

	Generator	PV system + generator	PV system with tracker + generator
Number of panels FSM-250	-	16	12
Solar tracker ED-2000 DUAL	-	-	1
Number of batteries GEL GX-200 (with 30% of DOD)	-	8	8
Installed capacity of the system, kW	1.7	4	3
Energy production by solar panels, kWh/year	-	6546	7204
Coverage of required energy of PV system	-	79.2 %	76.6 %
Overproduction of solar panels, kWh/year	-	910	1704
Produced energy by generator, kWh/year	7120	1484	1676
Number of operating hours of generator per year	8760	2032	2286
Fuel consumption of generator, l/year	3389	706	797

5. ECONOMIC EVALUATION

5.1. METHODOLOGY

In order to verify the viability of the proposed technical solutions of power supply to meet the requirements of the meteorological station at reasonable costs, the net present value technique is undertaken. The NPV is the standard method to evaluate the effectiveness of investment projects. It compares the amount which has been invested today with the future discounted returns. In this case study, the calculation of NPV is made with the help of Microsoft Excel. The values of the minimum price will be compared to each other.

The NPV can be defined by using the following formula:

$$NPV = \sum_{t=1}^{T} CF_t \cdot (1 + r_d)^{-t} - I_0 \qquad \text{Equation 32}$$

Where:

T – lifetime of the project, year;
t – considered year of the project, year
CF_t – cash flow of the project during the period t, RUB;
r_d – discount rate, %;
I_0 – total investment costs, RUB;

This project is considered from the point of view of the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet state non-profit organization). Therefore, this project does not consider the revenues over the whole operational period. The total initial investment costs in the beginning of the project and the operating costs in the following years will be implemented into the economic model.

The minimum price per 1 kWh can be easily derived from the condition that the NPV indicator is equal to zero. To achieve this, the fictive revenues from the sale of produced electricity are implemented into the economic model.

In this case study, the lifetime of the project is 25 years, although the system’s lifetime could be reasonably expanded. The whole generated electricity of the power systems supplies the object itself. The land size is not considered since there is no limitations of space on the territory of the object. Therefore, this does not affect the decision.

5.1.1. Discount rate

The most important factor which has the greatest impact on results is discount rate. The discount rate is the rate that takes into account the time value of money, the risks and uncertainty of the future cash flows. Consequently, the determination of discount rate must be done appropriately and correctly in order to avoid overestimated values, or vise-verse underestimated values. Therefore, according to the type of above-described investor (nonprofit state organization Roshydromet) and discussion with supervisor, the nominal discount rate of the project is determined as the nominal discount rate of the Russian government bond with the same time of maturity as the project and equals to 9.02 % [65].

5.1.2. Inflation rate

According to statistical data of the Federal Service of State Statistics, the inflation level was 5.4% in the year of 2016, against 12.9% in 2015. In 2014 the inflation level was 11.4%. Such big difference can be explained by a devaluation of the Russian ruble. However, today the ruble has become more stable and more independent, which has a positive effect on the economy of the country. The ruble is appreciating. In 2017 the situation in the economy will be completely stabilized. According to the Central Bank of Russia in moderate and strict conditions of the monetary policy, the targeted level of inflation of 4% will be reached by the end of 2017 and will be at the same position during following two-three years [66]. But at the same time, inflation risks are still remained. Therefore, based on the long-term predictions of the Economic Development Ministry, the inflation rate of the project is determined as 5.3 % [67].

5.1.3. Fuel price growth rate

The prices of fuel have a tendency of constant growth. According to the report “Dynamics of prices for fuel” of the Russian goverment, in 2011-2015, the retail prices of fuels - petroleum and diesel – grew by one-third approximately corresponding to the inflation rate of the economy for the same period. The Russian analysts for oil and gas predict the petroleum prices to grow in 2017-2020. Prices will increase by the average of 6 – 7%, or 2 - 4 RUB per liter for petroleum. The growth of prices is inevitable. Accordingly, the annual growth of fuel prices of the project is estimated as 6.5% [68].

5.2. INPUT DATA

5.2.1. Investment costs

First of all, it is necessary to note that the total initial investment costs of PV systems strongly depend on the conditions of the individual countries, for example, the maturity and size of the market as well as the renewable energy policy. Therefore, in this case study, the investment costs were identified based on the statistical analysis of current prices of equipment on the Russian market for the year 2017. All system equipment is produced by domestic manufacturers. The prices are found on the manufacturer’s web-site [53], [60], [62]–[64], [69]. The initial total investment costs of generator set variant, the optimally tilted PV system and the PV with solar tracker are presented in Table 18, Table 19, and Table 20, respectively.

Table 18 – Investment costs of generator set variant

Component	Brand	Units	The price, RUB
Variant 1. Generator set variant			
Generator including ATS	KIPOR KGE2500E	1	65 000
Backup generator	KIPOR KGE2500E	1	35 000
Other equipment	Include: protection and measurement devices, monitoring system		21 750
Fuel tank	3500 l	1	45 000
Total system price			166 750
Installation & shipping			33 350
Project documentation			21 750
Total investment costs			**210 250**

Table 19 – Investment costs of optimally tilted PV system

Variant 2. Based on optimally tilted PV system			
Solar panel	FSM-250	16	240 000
Inverter	MAP-SIN-PRO-48-3	1	45 000
Controller	MPPT DOMINATOR 200/100	1	35 000
Battery	GEL DELTA GX 12-200	8	256 000
Generator	KIPOR KGE2500E	1	65 000
Other equipment: PV + generator	Includes: protection and measurement devices, cables, monitoring system, constructions		86 400 + 11 500
Fuel tank	1000 l	1	10 000
Total price: PV system + generator set			662 400 + 85 400
Installation & shipping			157 700
Project documentation			37 500
Total investment costs			**943 000**

Since the object is located in the remote area, geographical conditions and transportation issues are taken into account. Therefore, the site preparation, installation and shipping costs of power supply systems to the region of the object is estimated as 20% of the total investment costs. The other equipment including protection and measurement devices, cables, supporting structures and monitoring systems of all variants is estimated as 15% of the total price of the main equipment. The project documentation is estimated as 5% of the total investment costs. The above-described estimations for PV systems were determined according to the commercial proposal of the “UNISOLEX”, “EDS Group”, “Akvaliya”, and “Generacom” companies. [64], [70]–[72]

Table 20 – Investment costs of PV system with tracker

Variant 3. Based on PV system with dual-axis tracking			
Solar panel	FSM-250	12	180 000
Solar tracker	ED-2500 DUAL	1	280 000
Inverter	MAP-SIN-PRO-48-3	1	45 000
Controller	MPPT DOMINATOR 200/100	1	35 000
Battery	GEL DELTA GX 12-200	8	256 000
Generator	KIPOR KGE2500E	1	65 000
Other equipment: PV + generator	Includes: protection and measurement devices, cables, monitoring system, constructions		119 250 + 11 500
Fuel tank	1000 l	1	10 000
Total price: PV system + generator set			915 400 + 87 000
Installation & shipping			213 000
Project documentation			63 500
Total investment costs			**1 279 000**

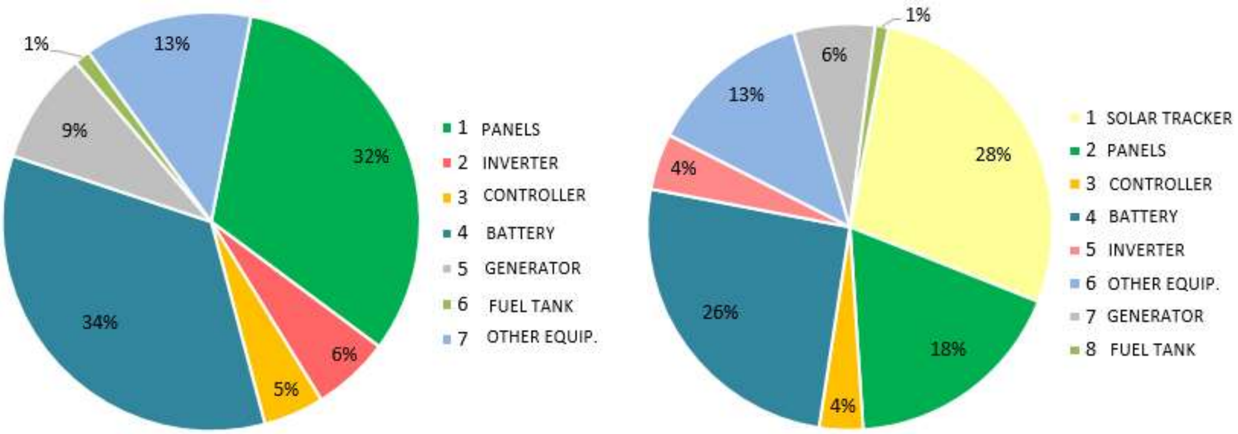

Figure 32 – Share of system costs: optimally tilted PV system (left), PV with solar tracker (right)

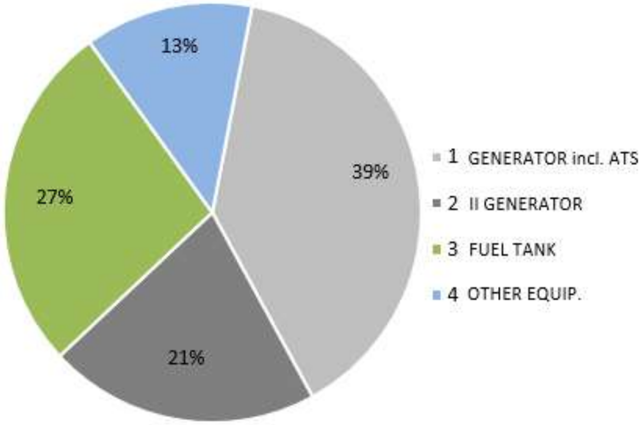

Figure 33 – Share of system costs: generator set

5.2.2. Operating costs

Operating costs are the annual costs incurred by a continuous process. In this project, the operating costs are expenses associated with the maintenance of generator, maintenance of PV systems, fuel consumption and its transportation, an insurance of the systems. These costs are taken into account every year from the beginning of the operation process. The important economic parameters concerning to the operating costs are presented in the Table 21.

Fuel and transportation costs

In this work, the fuel costs are calculated with the help of the fuel consumption of generator, the current price of fuel in the region and the predicted growth of fuel prices in the future.

$$C_{fuel} = \mathrm{Q_g} \cdot \mathrm{P_f} \cdot \sum_{\mathrm{t=1}}^{\mathrm{T}} (1 + \mathrm{r_{fuel}})^{\mathrm{t}} \qquad \text{Equation 33}$$

Where:

C_{fuel} – fuel costs, RUB;

$\mathrm{Q_g}$ – the amount of liters consumed per year, l;

$\mathrm{P_f}$ – current price of fuel in the region, RUB;

$\mathrm{r_{fuel}}$ – rate of fuel prices growth, %;

Taking into account the location of the object, the fuel transportation costs are calculated according to: required volume of fuel (depends on the variant of the power supply system); travelling costs - 500 RUB/hour, where the distance to the object from the center of Ulan-Ude town is equal to 115 km. The cost of fuel transportation per liter is defined as 2 RUB/l according to the online calculator of “Magnum oil” company which allows to calculate the cost of fuel transportation for every distance in Russia. [73] The current price of fuel in the region is 36.5 RUB/l [74].

Maintenance costs

Generator variant

Maintenance is one of the important factors in analyzing the technical as well as the economic performance of generator power plant. The maintenance is the basis of efficient operation of a generator power plant and reliable prevention of severe damage and breaking. Moreover, serious attention must be paid to the scheduled maintenance of generator because the proper maintenance is the reason behind the long duration of work. In this case study, all the functions of the generator controlling and managing are automated, and the constant presence of personnel is required only during the maintenance cycle. For generators with power less than 10 kW, the regular maintenance should be provided each 500 - 800 operating hours depending on the type of maintenance [52]. In this case, it was accepted to provide the maintenance after each 800 operating hours (about 11 events per year). Such maintenance includes the following services: oil change, replacing oil and fuel filter elements, engine coolant replacement, test run with diagnostics of parameters, cleaning the cylinder head, nozzles, gaskets. The cost of maintenance for less than 10 kW generator is estimated at 8000 rubles per event including the following components: the cost of travel to the place, service, and time spent for the service [70].

Both PV system variants

PV systems are reliable, low-maintenance power sources. Nonetheless, they require some annual maintenance in order to identify problems before they even arise and to ensure the high performance of systems. In this case study, maintenance of optimally tilted PV system is equal to 1.50 % of the total system costs. Such costs include inverter and controller maintenance, cleaning of panels, general overhead and field repairs. Apart from that, the PV system without tracker requires to adjustment of the panel's position during the operational period (two times per year). Accordingly, this work takes into account the work which provides such service. According to the company "UNISOLEX", the service is estimated at 3000 RUB per event. In the case of PV system with dual-axis tracking, the maintenance is equal to 1.50 % of the total system costs as well. The maintenance of such systems increases by 28% comparing with optimum tilted PV system's maintenance costs. Estimations of maintenance costs are based on the discussion with representatives of the companies "UNISOLEX", "EDS Group", and "Generacom" [75]–[77].

5.2.3. Insurance

Insurance is necessary in order to cover the losses of external (e.g. wind and storm) and internal causes (e.g. material and construction defects) as well as losses due to short-circuits, human factors and data losses. Therefore, it was decided to consider the insurance of each variant as 1% of total investment costs.

5.2.4. Reinvestment of equipment

Every device and equipment has its own lifetime or a limited number of operating hours, thus, this important factor will be taken into consideration.

- Batteries. According to the calculations in the subchapter 4.8.2, the lifetime of GEL GX batteries is defined and equals to approximately seven years once DOD is equal to 30%.
- Generator. The service lifetime of the generator set is estimated 40000 operating hours according to [52]. In this case study, the lifetime substantially depends on the variant of power supply system. In the case of generator set variant, the calculations define this lifetime equals to five years for the first generator and nine years for the second generator. As for the variant with optimally tilted PV system, the lifetime of generator is 20 years. The PV system with tracker has the generator lifetime equals to 17 years.
- Inverter and controller. According to the manufacturers, the average lifetime of devices is ten years. Thus, ten years is considered as the lifetime of these devices.

- PV panels, solar tracker, and fuel tank. These elements has longer lifetime than lifetime of the project. Solar trackers has lifetime more than 25 years. Fuel tank's lifetime is considered as 45 years. PV panels has no less than 30 years. The degradation rate of solar panels is estimated as 0.73%. [78] To the end of the project lifetime, the performance of PV panels is expected to be 80.2%. Despite fact that PV panels are losing their performance (efficiency), the additional PV panels can be bought after the lifetime of the project in order to satisfy energy requirements.

All above described input economic parameters are concluded in Table 21.

Table 21 – Input economic parameters

Parameter	**Value**
Lifetime of project	25 years
Price of fuel	36.5 RUB/l
Price of fuel transportation	2.00 RUB/l
Fuel price growth rate	6.50 %
Maintenance of generator	8000 RUB/event
Adjusting panel (Service)	3000 RUB/event
Maintenance of PV	1.50 % (from total system cost)
Maintenance of PV + tracker	1.50 % (from total system cost)
Degradation rate	0.73 %
Insurance	1.00 % from total investment costs
Inflation	5.30 %
Real discount rate	3.53 %
Discount rate	9.02 %

5.3. ECONOMIC RESULTS

For every technical solution of energy supply the economic model is created. The cash flow of each variant is presented in Figure 34, Figure 35. Based on the presented methodology, the results of the NPV and the minimum price are obtained and presented in the table below.

Table 22 – Economic results

	Variant 1	Variant 2	Variant 3
Minimum price, RUB/kWh	37.18	25.55	29.68
Net Present Value, mil. RUB	- 4.13	- 2.84	- 3.3

According to the table, the highest NPV relates to optimally tilted PV system variant. The NPV of PV system with solar tracker differs from the optimally tilted PV system by 459 thou. RUB. Comparing two variants based on PV systems, there are a number of powerful factors that have an influence on the presented economic results. The first factor is the cost of the solar tracker which plays a fundamental role in decision making. It’s clear that the price of 280 thou. RUB for solar tracker makes this variant unfeasible. Therefore, a sensitivity analysis of NPV on the cost of solar tracker is conducted in order to identify the price that would be acceptable for construction of PV system using solar tracking (5.4.4). The second factor which has an impact on the final NPV is that the solar tracker requires a more maintenance costs due to its complex technology, control system, and moving parts. According to the discussion provided in the 4.9, the third factor is the performance of sun tracking in the conditions of the winter period when there is a substantial need for energy.

However, comparing with the generator set variant that has the worst value of NPV, both PV systems show better results. The difference between the NPV of generator set variant and optimally tilted PV system is 1 290 thou. RUB. PV with the tracker has higher value of NPV by 831 thou. RUB. There are some solid reasons for the significantly high difference. According to the results of the technical evaluation presented in 4.9, implementation of PV panels in the energy balance of supply system makes an enormous contribution to reducing the operating hours of the generator (optimally tilted PV system – 6728 hours, in the case of PV with tracker – 6474 hours) and extending its lifetime. Thereby PV systems reduce the consumption of fuel (2681 l for optimally tilted PV system and 2590 l for PV system with tracker) and, especially, the maintenance costs (number of events is reduced to three times for both optimally tilted PV system and PV system with the solar tracker).

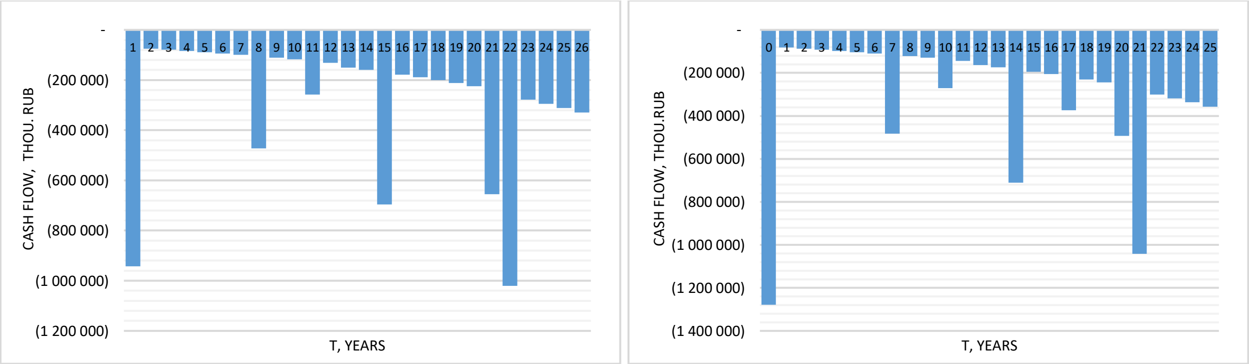

Figure 34 – Cash flow: Optimally tilted PV system (left), PV system with tracker (right)

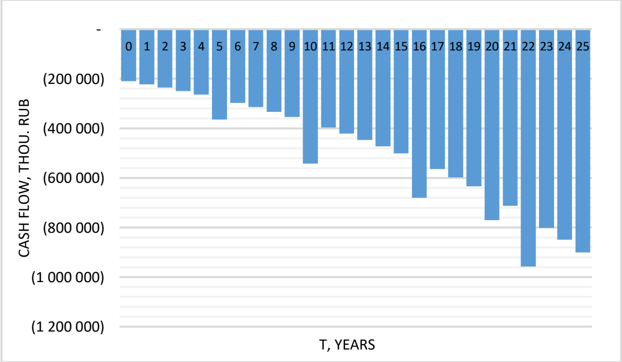

Figure 35 – Cash flow: generator set

5.4. SENSITIVITY ANALYSIS

The economic evaluation includes a number of input parameters the value of which is quite difficult to predict over a long period. Specialists of the US National Renewable Energy Laboratory recommend to use a sensitivity analysis for these purposes. The sensitivity analysis is applied to define the impact of different factors on system performance indicators. The idea behind the sensitivity analysis is quite simple: changing factors one by one and identifying the changes in the performance indicator - the Net Present Value, in this case. This subchapter will analyze the influence of the change of the following central factors on the performance of the power supply systems.

5.4.1. Sensitivity on fuel price

Since each variant has the generator in its composition, the essential factor that influences the economic results is fuel price. In this case study, the fuel price was accepted to equal 36.5 RUB/l, and the fuel price growth rate was estimated at 6.5%. As it was discussed at the beginning of the chapter 0, the fuel costs will only grow in the future. Accordingly, the dependence of NPV on the future possible growth of prices is presented for every variant in the figure below. It can be seen that this parameter mainly influences the generator set variant. The great contribution (76.6% with the solar tracker and 79.2% without) in the energy balance of the overall supply system explains the weak influence of the variants based on PV panels. As the result, the future growth of fuel prices has a significant impact on the generator set variant, and it does not change the decision, the optimally tilted PV system still has the highest NPV.

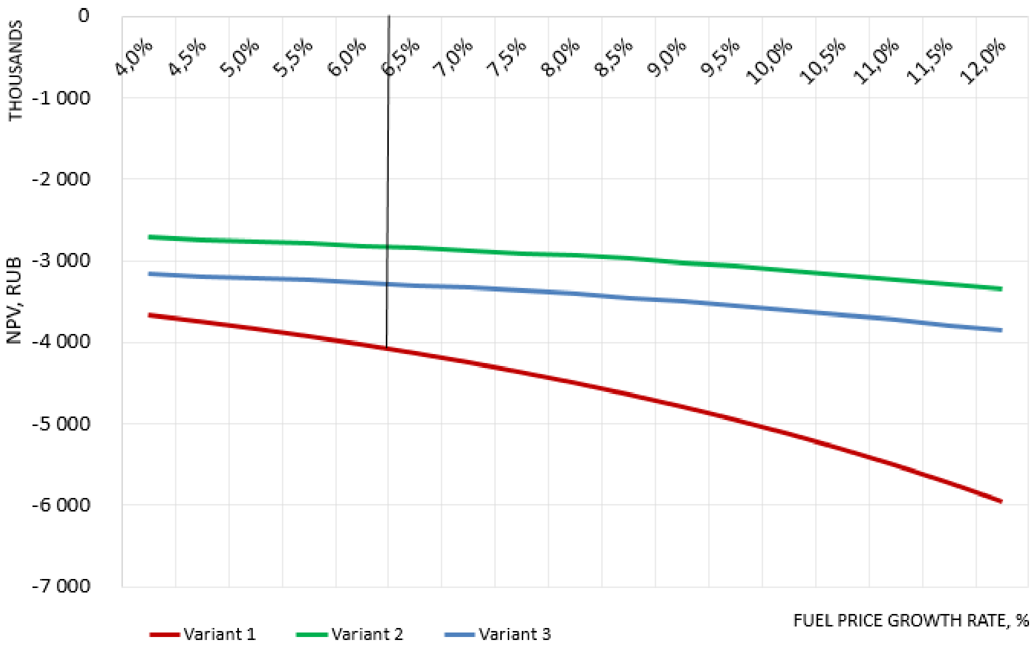

Figure 36 – Dependence NPV on fuel price

5.4.2. Sensitivity on discount rate

Discount rate is a substantial factor that automatically requires a sensitivity analysis. The black thin line indicates the nominal discount rate of the project. There is a high dependence of NPV of generator set variant on discount rate. Both PV systems have less dependence of NPV the behavior of which is identically changing. It can be noticed from Figure 37, that the change of discount rate influence the decision. The decision is changed in favor of the generator set variant when the level of nominal discount rate equals to 16.6 %.

The nominal discount rate depends on a macroeconomic indicator – inflation which has variable character. For instance, inflation has varied significantly for the last seven years in Russia. Therefore, a high level of nominal discount rate can be easily distinguished. But according to the discussion in the subchapter 5.1.2, the inflation forecasting shows that the level of inflation higher than 6% has a substantially low chances in Russia.

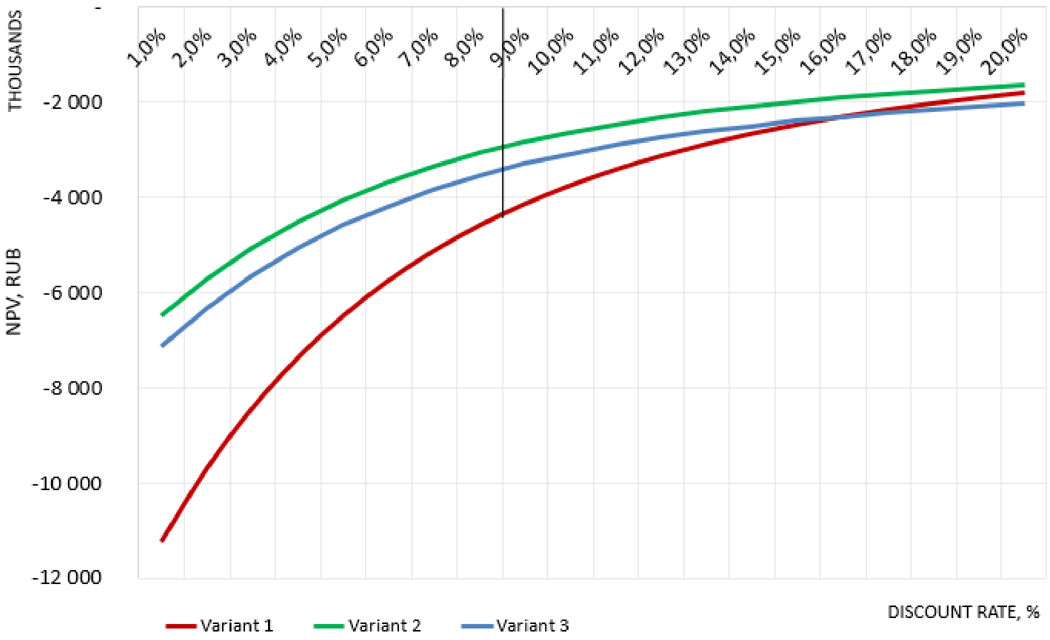

Figure 37 – Dependence NPV on discount rate

5.4.3. Sensitivity on initial investment costs of the system

Total initial investment is a crucial factor for every variant which significantly influences the performance of the NPV. In this analysis, 0% corresponds to the current investment costs of the system, 50% (- 50%) means that the investment costs are increased or decreased by half. The presented dependence of NPV on investment costs of the first variant is characterized by a weak influence in comparison with the other two variants. It can be explained that the major part of the NPV value contains the operating and maintenance costs of the generator, but the initial investment costs are low. As for variants based on PV systems, the situation is changed vice-versa since PV systems require high initial investments costs, but low maintenance and operating costs.

The analysis considers the future relatively low prices of the components of PV systems. As it was discussed in 2.4.1, a reduction of the cost of solar cells will lead to a decrease in the cost of PV panels, as well as in the cost of all PV system's components such as a controller, supporting structure. According to the extensive analysis of future investment costs conducted by "Fraunhofer-Institute for Solar Energy Systems", solar power will hold a leading position as the cheapest form of electricity. Taking into account their ambitious assumptions, the cost of PV will be decreased by almost 50% by the end of the year 2050 [32]. Therefore there is a high potential for future low investment costs for PV systems.

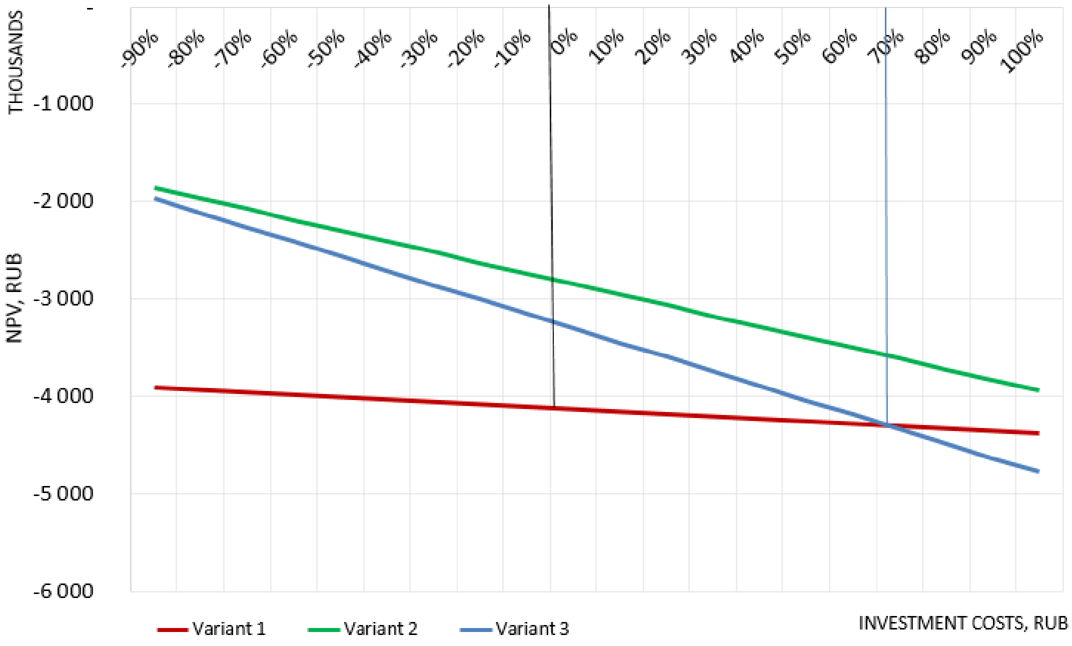

Figure 38 – Dependence NPV on initial investment costs

If the investment costs of PV system with solar tracker is increased by 72%, the variant with generator set is becoming a more attractive decision, but still, the variant with the optimally tilted PV system has higher value of NPV. The NPV of PV system with the tracker is more sensitive to the investment costs in comparison with the other variants. Accordingly, the sensitivity of NPV on the cost of solar tracker will be examined.

5.4.4. Sensitivity on cost of solar tracker

Referring to the discussion in the subchapter 5.3, the main factor which strongly influences the economic performance and the decision of PV with solar tracker is the current cost of solar tracker. Therefore, the analysis shows how much the solar tracker should cost today, in this particular case, in order to guarantee the viability of usage of solar trackers in PV systems. As Figure 39 indicates, the cost of solar tracker must be less or equals to 35 thou. RUB. It is about eight times lower than the original price. Surely, the development of such scenario is quite difficult to imagine. However, at the moment, the "Global Solar Tracker Market 2015 – 2019" report provides a comprehensive analysis of the global solar tracker market, identifies the economic drivers for tracking systems and forecasts the price. According to the report, the global market for solar tracking systems is expected to grow at a CAGR of 17.2% from 2016 to 2025. The majority of cost reduction will be impacted by the wider economics of the PV sector and will come from the minimization of electrical elements and lower structural elements within the composition of tracking systems. As the result, taking into account such a high annual growth rate and development of the PV sector, the cost reduction of solar trackers have a chance in the near future.

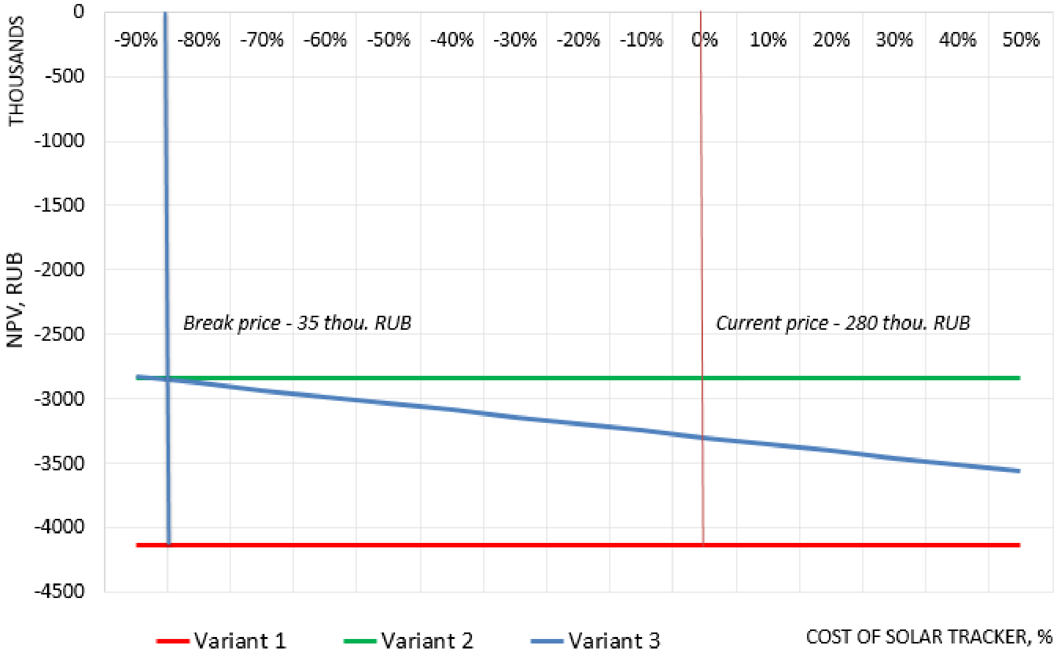

Figure 39 – Dependence NPV on cost of solar tracker

In this case study, the cost of the solar tracker is taken from the Russian company "EDS Group" (4.8.5). However, there is a number of companies dealing with the manufacture of trackers. Therefore, the possible range of the cost of dual-axis solar tracker is analyzed and provided in the above sensitivity analysis. The possible range is based on the current prices of dual-axis solar trackers according to the following companies: "Rentechno" (Ukraine), "Array Technologies" (Spain), "Convert" (Italy), "Traxle" (Czech Republic), Soltec (USA), Nextracker (USA), Arctech Solar (China).

5.4.5. Sensitivity on number of panels

One of the important sensitivity analyses is the dependence of NPV on a number of installed PV panels. The number of panels have a substantial influence the final decision. The analysis is conducted in order to determine the optimum number of panels from the economic point of view. In Figure 40, the dependence NPV on the number of PV panels in the case of the optimally tilted PV system is presented.

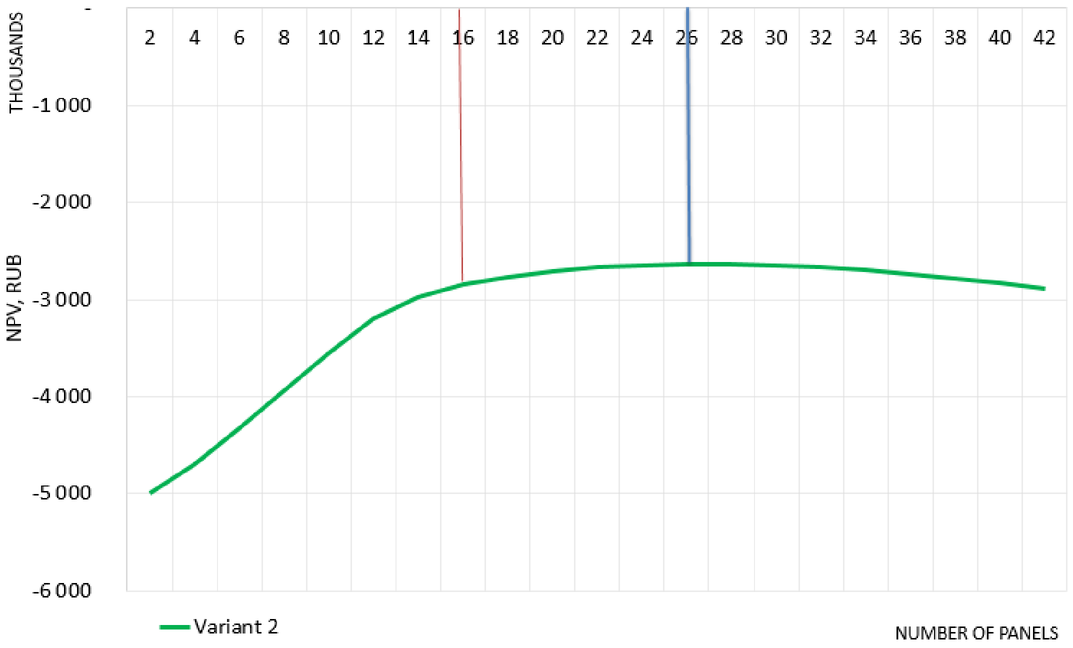

Figure 40 – Dependence NPV on number of panels in optimally tilted PV system

According to the chapter of technical evaluation of the variants, the number of installed PV panels for optimally tilted PV system is 16 from the technical point of view. Based on the presented graph, it can be seen that from the 16th panel the influence of the NPV is becoming weaker to compare with the first part of graph (number of panels less than 16). But the NPV is slowly increasing with increase of installed number of PV panels. The dependence is explained by the relatively low performance of panels in November, February and the overall winter period. Therefore, the number of operating hours of the generator, consequently, the fuel consumption is slowly and gradually decreases step by step. Such increasing behavior of the NPV is keep going till the moment when the number of installed panels reaches 26. After that, the NPV is slowly decreasing. The reason of that is the increase of the investment costs: PV panels and its wires, a new controller since that the short-circuit current of additional PV panel is increasing as well as the value of open-circuit voltage. At the same time, the maintenance costs are increasing. From one side the fuel consumption and operating hours of generator are reducing, from another side, the investment costs are increasing. The NPV of 26th installed panels has the highest value, therefore, it can be concluded that the optimum number of PV panels is 26 from economic point of view. Since there is no space limitations on the territory of the object, such extension (scale of the system) of the PV system is acceptable. The additional factor in favor of extension PV system is development and modernization of the meteorological station (for instance, additional equipment).

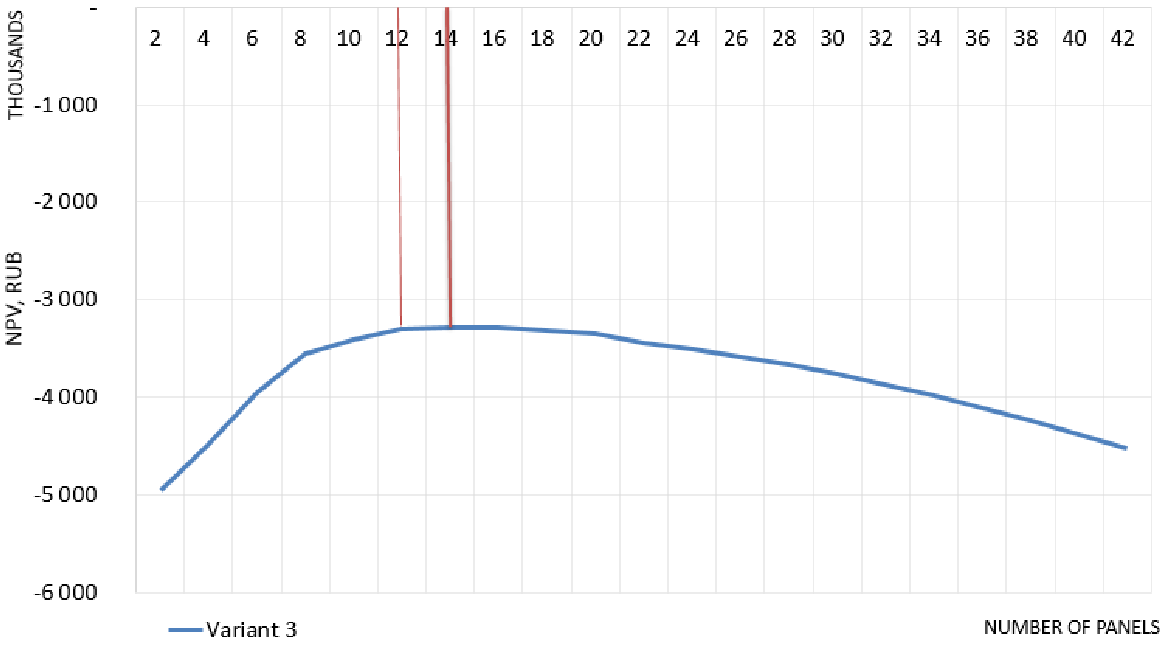

Figure 41 – Dependence NPV on number of panels in PV system with solar tracker

The same scenario applies to the PV system with the solar tracker, but the only the difference is a number of installed panels. Since the performance of one additional PV panel which tracks the Sun's position is relatively higher in comparison with fixed PV panel, there is a quite sharp change in the behavior of NPV when the number of panels is increasing. The significant cost of the solar tracker, consequently, the significant total investments costs explains the extreme falling of the NPV value. Therefore, it can be seen from the dependence that the optimum number of PV panels in the system with the solar tracker is equal to 14. Based on the discussion provided above, the economic results for both new PV systems with optimum number of PV panels are presented in Table 23.

Table 23 – New economic results

	Optimally tilted PV system	PV with tracker
NPV (old system), thou. RUB	- 2 839	- 3 298
Minimum price, RUB/kWh	25.55	29.68
NPV (new system), thou. RUB	- 2 637	- 3 239
Minimum price, RUB/kWh	23.75	29.52

CONCLUSION

The most relevant and economically viable way of utilization of PV systems is an energy supply of decentralized consumers in remote areas. Therefore, in the beginning of the work, I have analyzed the problem associated with the decentralized energy supply in the world and in Russia. The utilization of stand-alone energy systems either based on fossil fuels and RES was found as the effective solution of such problems. Therefore, according to the object of investigation presented in the case study, the key parameters of stand-alone systems were analyzed and identified. The analysis has shown that the decentralized consumer (object of investigation) of the south-east part of Russia is a great platform for implementation of PV stand-alone systems. The further work was dedicated to the detailed investigation of stand-alone PV systems.

The main components, parameters and advantages of PV stand-alone systems were described. Since the stand-alone PV systems possess a number of serious constraint factors such as low efficiency and high investment costs of solar cells, I have identified and described the ways to improve the efficiency of PV systems. The provided results of the analysis have shown that the implementation of the maximum power take-off mode and the usage of solar trackers are the most efficient solutions to improve the energy output. Thus, according to the objective of the thesis, I have investigated solar trackers in more details. The major elements and types, methods of control and classification of tracking systems were identified. As the result, taking into account the severe conditions with significant annual and daytime temperature changes in large part of Russia, the solar trackers on the basis of programming controllers is the reasonable choice for Russia.

For the application of solar trackers, the case study of the thesis provides a meteorological station as the object of investigation. The station is located in the remote area of the Republic of Buryatia without possibility of connection to the centralized power. According to the analysis, the following technical solutions (variants) to power-up the object were determined: petroleum generator power plant; PV system with manual changing of panel's position (optimally tilted PV system tilted system); PV system with dual-axis solar tracker. The petroleum generator is considered as an additional power source in both PV systems according to their design concept (full autonomous supply from March to September). The structural diagram, number of PV panels (16 for optimally tilted PV system and 12 for PV with tracker) and batteries, inverter and controller of the system were calculated based on the concept of PV systems. The results of the calculation of the PV system's power output have demonstrated that the dual-axis tracking incredibly increases the power output (performance is higher by 47% in the summer period, and by 17% - in the winter period) in comparison with the optimally tilted PV system.

As the result of the technical evaluation, it can be concluded that the implementation of PV systems in the energy balance of the generator set can essentially reduce the consumption of fuel: the PV system without the tracker reduces fuel by 2681 liters/year; the PV system with the solar tracker reduces fuel by 2590 liters/year; the fuel consumption of the generator set is 3387 liters/year.

Therefore, such combination of systems has reduced the number of operating hours of the generator (optimally tilted PV system decreases by 6728 hours; in the case of the PV system with the tracker – by 6474 hours) and, consequently, its maintenance costs that play a crucial role in the economic evaluation.

The economic evaluation of the considered technical solutions have shown that the highest NPV value (- 2.84 mil. RUB) is attributed to the optimally tilted PV system. The NPV value of the system with tracker is - 3.3 mil. RUB. The first powerful factor that had influenced the presented economic results is the significant cost of the solar tracker (280 thou. RUB). The second factor that had the impact is that the solar tracker amount to higher maintenance costs. The third factor is the relatively low performance of sun tracking in the conditions of the winter period. To compare the results with the generator set variant that has the NPV value equals to – 4.13 mil. RUB, both PV systems have better results. Despite the fact that the usage of solar trackers substantially increases the power output of PV systems, and taking into consideration the economic evaluation I have concluded that the application of solar trackers, in this particular case, is not feasible. However, the utilization of PV systems with panels that are set at the optimum angle is the primary way of developing energy supply for consumers in decentralized areas.

The sensitivity analysis on the cost of solar tracker has demonstrated that the cost, in this particular case, should be equal to or less than 35 thou. RUB in order to guarantee the viability of the utilization of solar tracker. At the moment, the global market for solar tracking systems is expected to grow at an annual growth rate of 17.2% from 2016 to 2025. The majority of cost reduction will be impacted by the wider economics of the PV sector and will come from the minimization of electrical elements and lower structural elements within the composition of tracking systems. As the result, taking into account such a high annual growth rate and development of PV sector, a significant cost reduction of solar trackers might be possible in the near future.

The sensitivity analysis on a number of installed panels has shown that the optimum number of panels in the case of the optimally tilted PV system is equal to 26. Since there are no limitations from technical point of view, for instance, the territory of the object has enough space, such extension of PV system is acceptable and reasonable. The additional factor in favor of PV system extension is the development and modernization of the meteorological station. As for PV system with the solar tracker, the optimum number of PV panels is equal to 14. Therefore, the installation of 26 and 14 PV panels can be limited only by investment costs. The project was considered from point of view of the non-profit state organization “Roshydromet”. Since this organization relates to the state customer, the initial necessary investments in the project are considered as the state order meaning that the money for any state project are received from the federal budget.

In conclusion, after technical and economic evaluation of the different variants of power supply systems, the final recommendation is the utilization of the PV system with 26 PV panels installed at the optimum angle.

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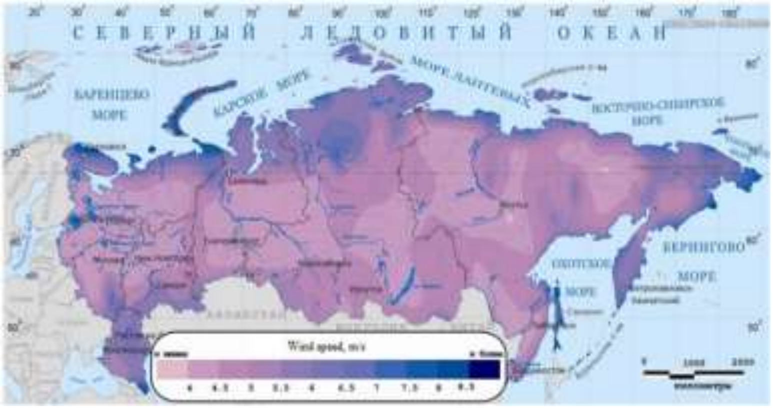
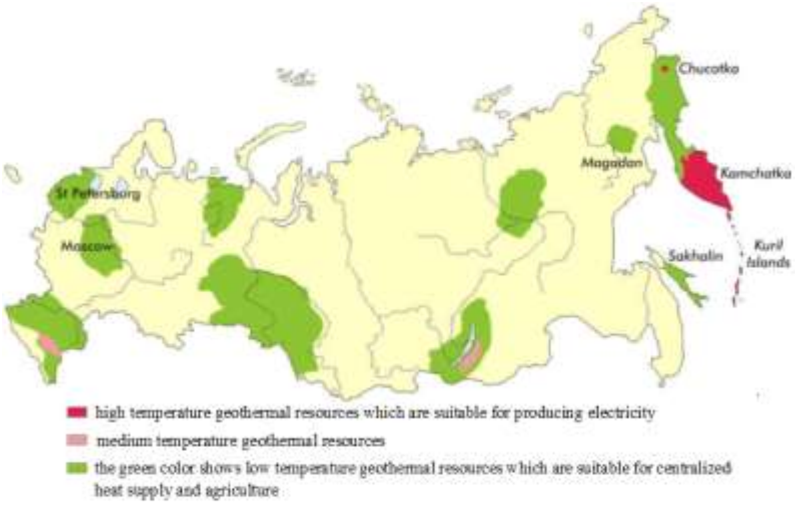
APPENDICES

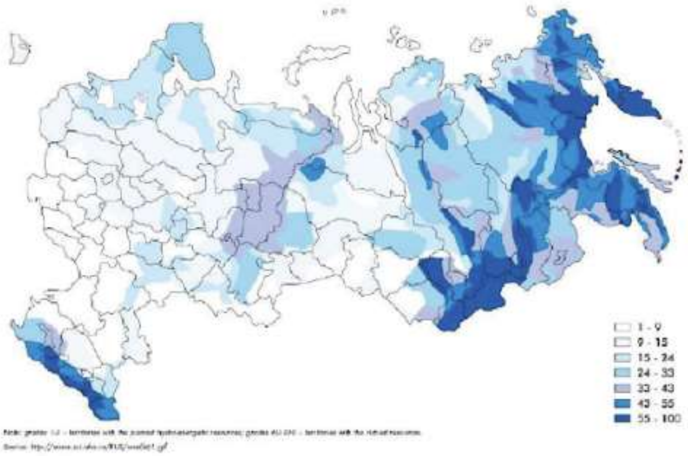
Appendix 1 – Annual wind speeds on the territory of Russia (height is 50 meters) [8]



Appendix 2 – Map of geothermal resources of the Russian Federation [8]



Appendix 3 – Hydro resources in Russia



Appendix 4 – Equipment of the meteorological station

Equipment of station	P_{nom}	Additional equipment	P_{nom}
	W		W
Sensor-barometer	3	Lightning	50
Psychrometer	30	Display board	250
Anemorumbometer	40	Computer	400
Thermo-anemometer	40	Survelliance	50
Cloud sensor	57	Heating system	600
Pluviograph	5	*TOTAL(additional equipment)*	1350
Device Peleng	35		
Measuring Cloud Boundaries	150		
Meteorological distances device	150	TOTAL	1925
Electro-pneumatic command device	35		
Piranometer Peleng SF-06	15		
Balance meter Peleng SF-08	15		
TOTAL (equipment of station)	*575*		

Appendix 5 – Technical characteristics of generator KIPOR KGE2500

Rated power (kW)	1,7
Max. power (kW)	2
Volume (sm^3)	418
Trigger mode	electric
Cooling	Air
Oil level sensor	Yes
Output voltage, V	230/12
Frequency (H)	50
Fuel reservoir (l)	15
Speed , rpm	3000
Weight (kg)	43
Fuel consumption, g/kWh	0,420
Type of fuel	Petroleum
ATS	Incl.

Appendix 6 – results of the daily incident solar radiation calculation

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Middle of month	15 jan	14 feb	15 mar	15 apr	15 may	15 june	15 july	15 aug	15 sep	15 oct	15 nov	15 dec
middle days	15	45	74	105	135	166	196	227	258	288	319	349
δt,	30	29	31	30	31	30	31	31	30	31	30	31
δ, °	-21,26	-13,62	-2,81	9,41	18,79	23,31	21,51	13,78	2,21	-9,59	-19,14	-23,33
Tc, h	8,16	9,67	11,53	13,58	15,32	16,30	15,90	14,36	12,37	10,39	8,61	7,7
tsr, h	8,9	8,2	7,2	6,2	5,3	4,9	5	5,8	6,8	7,8	8,7	9,2
tss, h	17,1	17,8	18,8	19,8	20,7	21,2	21	20,2	19,2	18,2	17,3	16,8
Fixed position of plane (PV panel) for whole operation period (Pi/4)												
Qinc, Wh/m2/day	2964	4767	5874	7389	8134	8437	8141	7375	6806	5162	2903	2184
Qcloud, Wh/m2/day	2176	3417	4839	5807	6007	6197	6131	5849	5297	3919	2418	1818
Monthly changing of plane's (PV panel) position or optimally tilted PV system												
Optimum angles	5Pi/12	5Pi/12	Pi/3	Pi/4	Pi/6	Pi/6	Pi/6	Pi/6	Pi/4	Pi/3	5Pi/12	5Pi/12
Qinc, Wh/m2/day	3566	4775	6217	7389	8490	9034	8586	7896	6806	5283	3848	3146
Qcloud, Wh/m2/day	2677	3755	4887	5807	6519	6929	6784	6207	5297	4355	2801	2230
Single-axis tracking												
Qinc, Wh/m2/day	3614	5087	7257	9543	10829	11365	10964	10004	8120	5555	3318	2585
Qcloud, Wh/m2/day	2759	4029	5731	7653	8845	9546	9231	8123	6345	4593	2911	2313
Dual-axis tracking												
Qinc, Wh/m2/day	3959	5762	8099	10579	12458	13402	12322	11469	8898	6617	4434	3439
Qcloud, Wh/m2/day	3112	4529	6262	8315	9364	10156	9781	8588	6739	5116	3236	2601

Appendix 7 – Monthly averaged insolation incident on a horizontal surface, Wh/m^2/day

Online calculator of Atmospheric Science Data Center

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
H_h	1280	2361	3863	4934	5785	5722	5153	4441	3466	2257	1398	978

Online calculator of Photovoltaic Geographical Information System

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
H_h	1170	1940	3470	4600	5930	6090	5610	4720	3710	2270	1420	1000

Tables with statistical data of solar radiation

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
H_h	1042	1641	3393	4033	5261	5375	5158	4323	3117	2075	1100	809

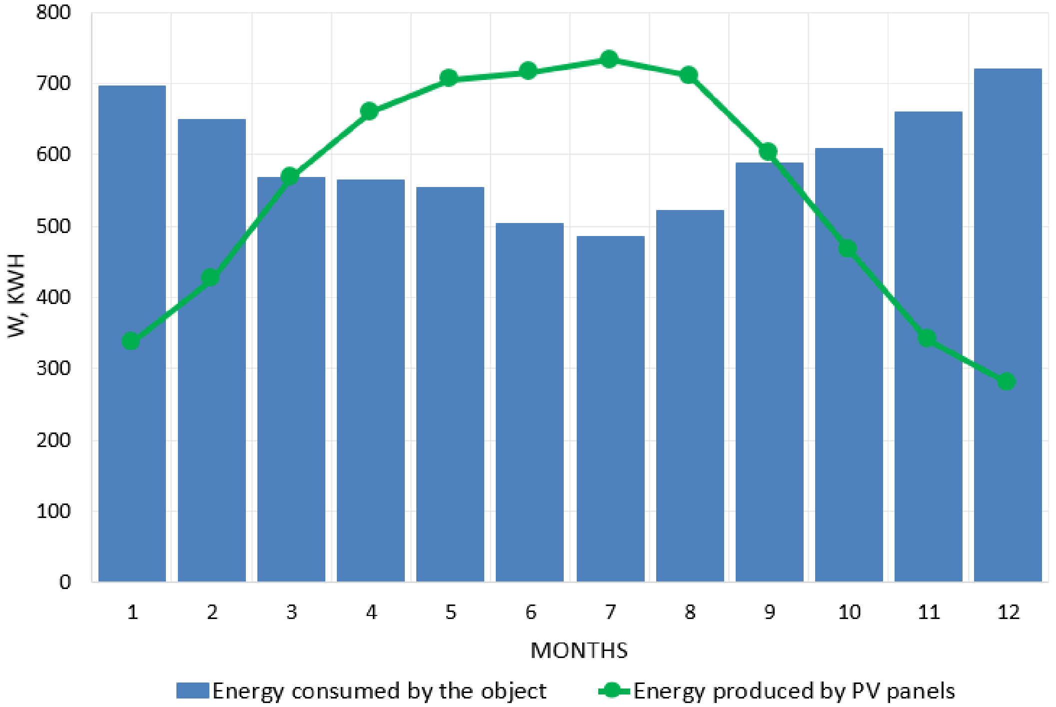
Calculation technique

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
H_h	825	1608	2961	4713	6057	6686	6421	5347	3638	2061	1023	678

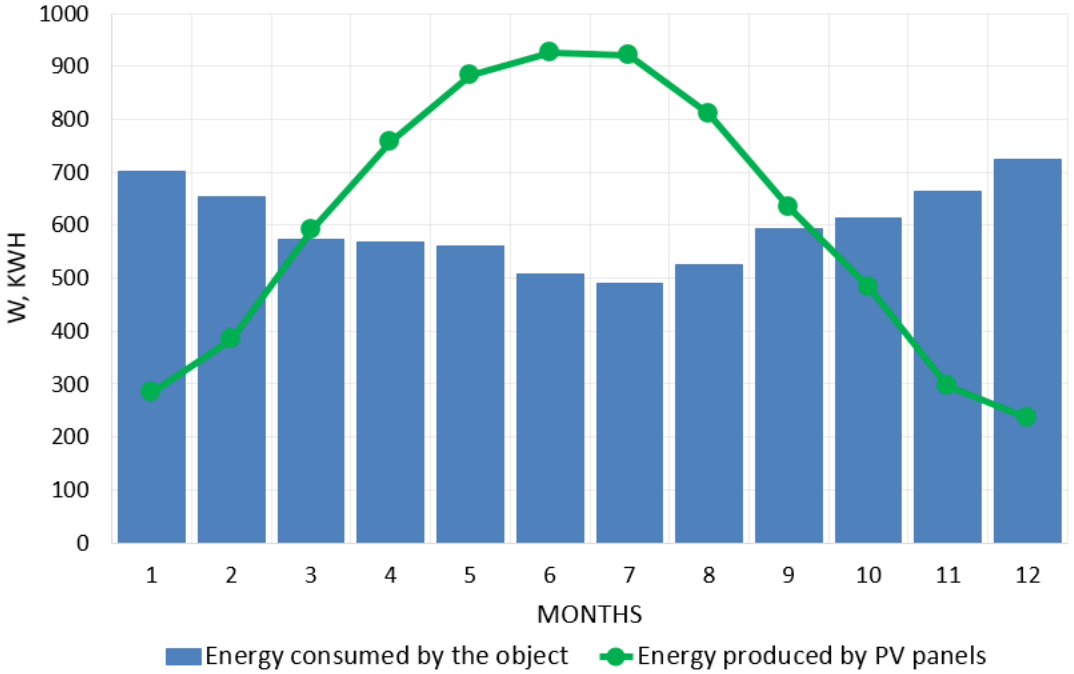
Appendix 8 – Comparative view of the performance of variants

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	123%	110%	101%	100%	109%	112%	111%	106%	100%	109%	116%	123%
1	103%	107%	117%	132%	136%	138%	136%	131%	120%	105%	104%	104%
2	116%	121%	128%	143%	144%	147%	144%	138%	131%	117%	117%	117%
3	113%	112%	109%	109%	106%	106%	106%	106%	110%	111%	113%	112%

Appendix 9 – Energy balance of PV optimally tilted PV system



Appendix 10 – Energy balance of PV system with solar tracker



Appendix 11 – Technical characteristics of solar panel FSM-250

Rated power (W):	250
Nominal voltage DC (V):	24
Open circuit voltage (V):	37,7
The voltage under the load (V):	30,9
The current under the load (A):	8,09
Efficiency of solar element (%):	17,3
Efficiency of solar panel (%):	15,4
Type of solar panel:	Grade A, monocrystalline
Quantity of diodes (unit):	3
Connectors:	MC4
Protection index:	IP 65
Overall dimensions LxWxH (mm):	1640x992x45

Appendix 12 Technical characteristics of the battery GEL GX-200

	Parameters
Type of battery	Gel
Rated voltage, V:	12
Rated capacity, A·h:	200
Lifetime, years:	10 - 12
Number of cycles at 30% discharge:	1400
Number of cycles at 100% discharge:	330
Internal resistance, mOhm	3,6
Self-discharge:	3% per month
The maximum charge current, A:	60
The maximum discharge current, A:	1000
Operating temperature range, ^{o}C:	-20..+60
Overall dimensions (l x w x h), mm:	522 x 238 x 218
Weight, kg:	65

Appendix 13 – Technical characteristics of controller MPPT DOMINATOR 200/100

Technical characteristics of the controller	
Technique	MPPT
Maximum voltage from solar panels, V	200
Max. current to AB (40°C)	185
Accumulators voltage, V	12 / 24 / 36 / 48 / 96V
Type of accumulators	AB: GEL, AGM, closed, open
Temperature sensor	External
Temperature compensation (by default)	-3mV / °C per 2V battery cell
Efficiency with full load	24V: 96,5% / 36V: 97% / 48V: 98%
Energy consumption in the idle mode	1,9 W
Body material	Aluminum/steel
Size, mm	350x120x210
Weight, kg	5

Appendix 14 – Technical characteristics of inverter MAP-SIN-PRO 48-3

Technical characteristics of the inverter	
Rated power, kW	2
Maximum power, kW (10-20 minutes)	3
Output voltage, V (50 H)	220
Input voltage, V	48
Operating temperature range, C	25-35
Efficiency	96%
Energy consumption in idle mode, W	24
Dimensions [HxDxW], cm	180x510x370
Weight, kg	19

Appendix 15 – Technical characteristics of tracker ED-2500 DUAL

Technical characteristics of the tracker	
Reccomended panels	1640x992x45
Number of panels	12
Power of motor	5 W x 2
Consumption per day	≤0,015 kWh
Rotating angles	-10° до 75°, -120° до 120°
Wind resistance	170 km/h
Lifetime	≥25