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Department of Economics, Management and Humanities

Hybrid electric supply system for Baikalskoe village

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Field of study: Economics and management of power engineering

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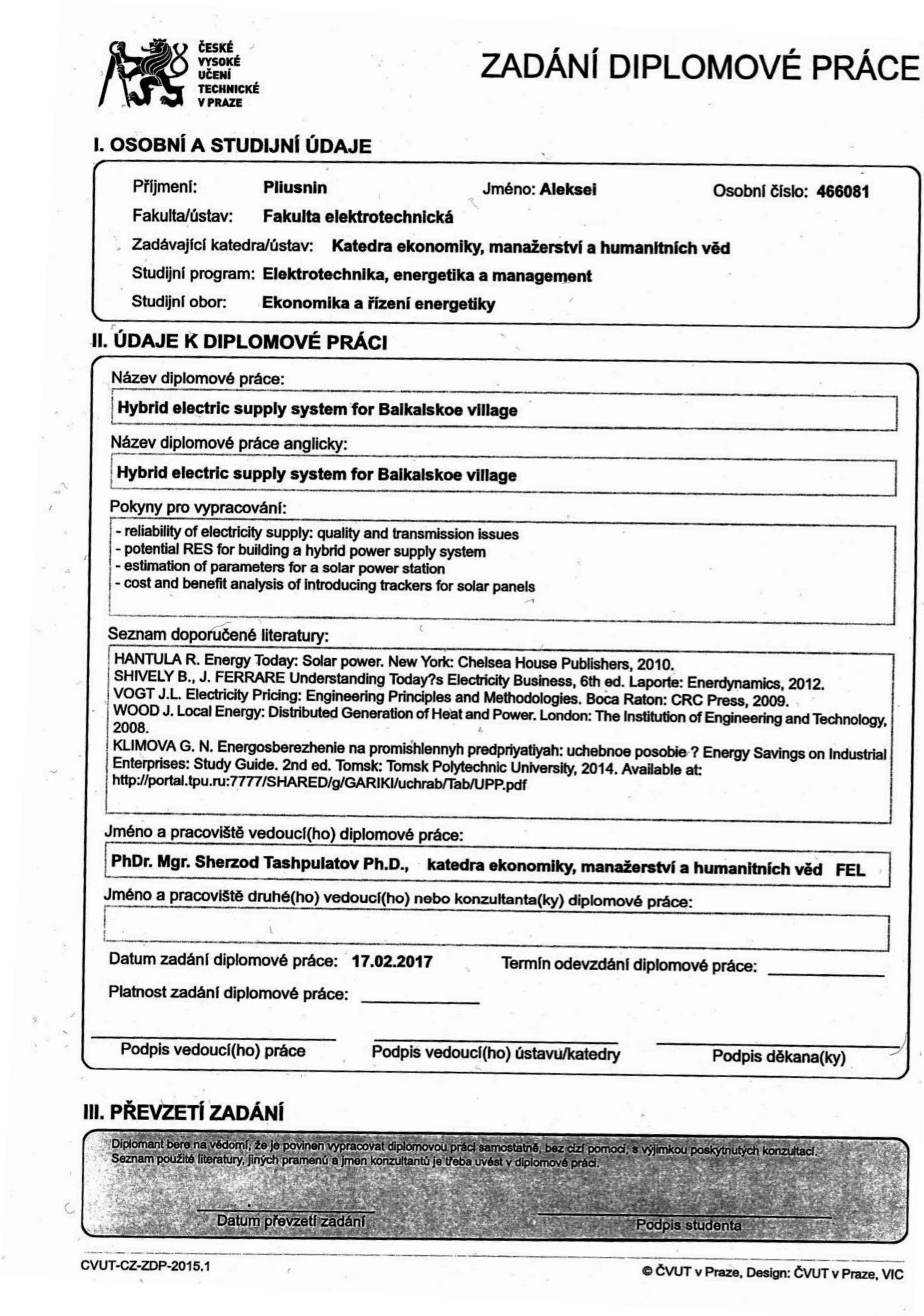

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Hybrid electric supply system for Baikalskoe village

Pokyny pro vypracování:

- reliability of electricity supply: quality and transmission issues
- potential RES for building a hybrid power supply system
- estimation of parameters for a solar power station
- cost and benefit analysis of introducing trackers for solar panels

Seznam doporučené literatury:

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Datum převzetí zadání Podpis studenta

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Declaration:

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

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Abstract

At present time a conventional solution for electricity supply is to set up an overhead transmission line from the nearest substation. Baikalskoe village is connected to centralized electricity grid via single-circuit transmission line with length of more than 35 km and nominal voltage of 10 kV. However, in order to avoid high power and voltage losses which do affect quality of electricity supplied, recommended voltage class for such a length should be at least 35 kV. To follow the conventional solution it is necessary to switch to a higher voltage power line. Considering the fact that there are two main types of line supports, it falls into alternatives with application of either steel or reinforced concrete poles. There are some exceptions which require nonconventional solutions like a construction of a hybrid electric power supply system which. In this particular case such a system should combine centralized power supply with local generation based on renewables. In this work, the conventional and nonconventional solutions for electricity supply in Baikalskoe village are compared.

In Statement of the problem section, quality and transmission issues of Russia's rural areas in general and Baikalskoe village in particular are described. Then, in Chapter 1, renewable energy sources are discussed in global and local scales. Potential of renewables available in the region are estimated there. Based on these estimations, the type of power plant is proposed. In Chapter 2, parameters of power plant are estimated. The relationship between generation and weather conditions are discussed. The necessary number of power plant equipment is calculated. Finally, in Chapter 3, conventional and nonconventional solutions are compared in terms of economic efficiency. Cost and benefit analysis of different alternatives is performed. Based on it, the optimal solution is recommended.

Keywords

Hybrid electric power supply, solar power plant, solar tracking system, rural grid.

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List of abbreviations

AADAT – Azimuth-Altitude Dual Axis Tracker

AC – Alternating Current

ALT – Automatic Load Transfer

CAPEX – Capital Expenditures

CTL – Cable Transmission Line

CV – Coefficient of Variation

DAT – Dual Axis Tracker

DC – Direct Current

DG – Distributed Generation

FSM – Fotoelektricheskiy Solnechnyy Modul – Photovoltaic Solar Module

HAVT – Horizontal Axis Wind Turbine

HSAT – Horisontal Single Axis Tracker

OECD – Organisation for Economic Co-operation and Development

OTL – Overhead Transmission Line

PASAT – Polar Aligned Single Axis Tracker

PV – Photovoltaic

RES – Renewable Energy Sources

SAT – Single Axis Tracker

SPP – Solar Power Plant

TSAT – Tilted Single Axis Tracker

TTDAT – Tip-Tilt Dual Axis Tracker

UPS – Uninterruptible Power Supply

VAWT – Vertical Axis Wind Turbine

VSAT – Vertical Single Axis Tracker

W_G – Energy generated by PV panels

Introduction

Over the humankind history energy obtained from various resources was used to create proper environment for people's life. The form of energy utilized was changing over the centuries. The level of energy consumption positively affects the economy of society [1]. Hundreds of thousands years ago energy consumption started with usage of fire for heating, cooking and lighting purposes. It was the beginning of the organic economy in humanity history. Usage of fire resulted in the start of crafting. Afterwards society found its ways to use water and wind energy for agricultural and other purposes [2].

Favorable environment leads to an increase in population meaning a decrease in commodities per capita available to population. The growing demand for commodities resulted in the so-called "The Industrial Revolution" – a new turn in technological development and energy consumption. At that point the transition to the fossil fuel economy took place. Since then, an especially notable increase in energy consumption was observed [3]. With new volumes of energy utilized the level of economic development increases. A modern person consumes 100 times more energy, than primitive one and lives 4 times longer [3].

Nowadays the most widely spread form of energy is electricity. It is caused by many reasons:

- weightless;
- suitable for various transformations, transmission and distribution;
- the highest efficiency in terms of consuming energy, and others.

The process of replacing other forms of energy by electricity or introduction of electricity in new areas is called electrification. Electrification plays a significant role in country's economic development and population welfare.

Electrical energy generated by power plants is transmitted over long distances to end-consumers using an electrical grid – an interconnected network for energy transportation. Basically, there are two main elements of an electrical grid: substation and power line. Substations are used to receive, transform, and distribute electricity. Power lines are used for electricity transmission.

Depending on transmission distance and amount of energy to be transmitted, a voltage class of a power line is chosen. For instance, in Russia the maximum length for the maximum load of 10 kV OTL is 5 km [4] and the length for 10 kV OTL of lower loads should not exceed 15 km. Initially, however, requirements for the energy quality there were less strict. It is explained by the strategy of the first step of electrification there: the strategy of the widespread implementation of centralizing electricity supply which is considered to be completed. Due to enhanced requirements, rural grids (particularly 0.4–10 kV) fail to meet them. The current tasks of rural engineering and conditions of rural grids in Russia are described in section of statement of the problem. In that section the issue of centralized electricity supply system of Baikalskoe village is described, too.

A centralized electrical grid can be away from the rural area or it is not reliable or connection to the grid is expensive. In these cases the usage of renewable energy sources (RES) for hybrid electric supply system can be an economically attractive solution for the electrification problem.

Baikalskoe village has an advantageous location at the coast of Lake Baikal. Firstly, coastal wind near waterbody is stronger than boreal forest wind. So, such a place is supposed to have wind potential. Secondly, there is also quite high atmospheric transmittance and sunshine duration exceeding 2000 hours (≈0.23%) per year. Consequently the village has solar power potential, too. So, in the first chapter the available RES for a new plant are described. These sources are reviewed in the world scale and estimated for Baikalskoe village. An evaluation of wind and solar power potentials is performed.

In the second chapter daily and monthly demands for electricity of the village are calculated. The estimation of the necessary number of different equipment for a power plant is performed.

In the last chapter an economic comparison of possible alternatives is made. Conventional solution to the problem there is switching to a higher voltage power line. There are two types of poles considered: steel and reinforced concrete poles. These scenarios are evaluated using consolidated indices of construction cost. Nonconventional solution is to build a power plant based on RES and combine it with existing power supply system in order to provide a customer with AC electricity of stable, constrained parameters. Finally, in order to decide which one is the most optimal solution to our problem, advantages and disadvantages of proposed scenarios are summarized.

Statement of the problem: quality and transmission issues in electricity supply

Despite the fact that power production in industrial scales commonly happens only nearby large conventional sources of energy, generated power can be delivered over a very long distances to the end-consumers thanks to interconnected network for delivering electricity from producers to consumers which is called electrical grid. There are two main elements of electrical grid: substation and power (transmission) line. Substations are used to receive, transform and distribute electricity. For electricity transmission power lines are used. There are two types of power lines: cable transmission lines (CTL) and overhead transmission lines (OTL). By virtue of Russia's tremendous area, the most common way of power transmission there is OTL. There, total length of all OTL is more than 152 thousands km [5].

The maximum length of OTL is limited for each voltage class. For example, the maximum length for the maximum load of 10 kV OTL is 5 km [4] and the length for 10 kV OTL of other loads should not exceed 15 km. But in the very beginning of Russia's electrification this rule was not so strict in order to penetrate rural areas. The first stage of rural electrification in Russia is considered to be done. The next step now is to implement electricity in agricultural industry more effectively as a result of the following measures:

- comprehensive mechanization and automatization of stationary processes;
- increase of the electrification level for residential usage;
- improvement of reliability and quality of electricity supply.

For the sake of clarity we introduce the following definitions.

Reliability is the ability to consistently maintain required functions keeping the performance within the range of values which are specified in norms and standards [41].

Quality is the degree of conformity of electricity parameters in the particular grid node to the set of specified quality rates [6]. Voltage changes in the particular node of the consumer connection, which are related to frequency of the current, to values and shape of the voltage, to the voltage symmetry in three-phase networks, fall into two categories: long-term changes of voltage parameters and random changes.

Long-term changes of the voltage power supply parameters are long time deviations of the voltage from nominal values and are resulted by load changes or due to nonlinear load. They fall into the following types:

- frequency variations;
- long-term voltage changes;
- voltage fluctuations and flicker;
- Waveform distortion;
- non-symmetry of the voltage in three-phase systems.

Random changes are sudden significant changes of the voltage shape that result in deviation of the voltage parameters from nominal values. Usually, such changes of the voltage are caused by random events (for instance, consumer's equipment damages) or external factors (for instance, weather conditions or actions of the third party which is not the consumer of electricity). Random changes fall into the following types:

- voltage interruptions;
- undervoltages and overvoltages;
- surge voltages.

At the first steps of rural electrification, when electricity was used mainly for lighting and some secondary processes, rural consumers were basically referred to third category of safety (and reliability) requirements. These requirements have been increased during rural electrification. In 2003–2011 the consumers' welfare and their interests were coming into focus of electricity supply industry. By 1st of January, 2011 the electricity market liberalization in Russia has been completed. At present, by safety requirements all rural consumers fall into the following three reliability categories [7].

The first category, when an interruption of power supply leads to significant financial damage due to damage of goods or serious break-down of a production process. For especially important consumers of this category an automatic load transfer (ALT) should be provided. For other consumers of the category the maximum duration of power supply interruption should be no longer than 30 minutes.

The second category, when an interruption of power supply can cause break-downs of a production process, reduction in production, partial damage of goods. Outages for these consumers should be no longer than 3.5 hours.

All the other consumers are considered as the consumers of the third category. For this category an interruption of power supply should be no longer than 24 hours.

By virtue of increase in requirements, rural grids (particularly 0.4–10 kV) fail to meet them in terms of reliability. General condition of rural grids is described by Table 1.

Table 1. – Technical conditions of rural grids [7]

The grid element	Condition of grid elements, %		
	Good, acceptable	poor	Not usable
OTL 0.4 kV	81.6	12.9	5.5
OTL 6–20 kV	85.8	10.7	4.5
Substations 6–35/0.4 kV	87.1	10	2.9

The level of power losses in rural grids of the voltage less or equal to 35 kV is about 12% which is two times higher than in industrial or urban grids of the same voltage [7]. Composition of these losses for recent years is reflected in Table 2.

Table 2. – Composition of power losses in rural grids [7]

Name of the grid element	Portion of power loss, %
OTL 0.4 kV	34
Transformer substations 10/0.4 kV	26
OTL 6–10 kV	25
Substations 35–110 kV	6
OTL 35–110 kV	9
Total	100

So, the main task of rural power engineering is the containment of those "bottlenecks". It falls into such subtasks as increase in transmission capacity of the grid and improvement in its reliability. They are implemented through introduction of the following measures:

- disaggregating of substations 110/35/10 and 110(35)/10 kV for reduction of lengths of operating OTL 10 kV;
- increase in the number of two-transformer substations 110(35)/10 kV;
- increase in the number of substations with duplicate electric power supply;
- gradation to 110/10 kV system.

Unfortunately, for the scale of Russia these measures are not enough and many of rural “bottlenecks” cannot be solved in traditional ways. Lots’ of OTL 10 kV lie over a very long distances and its replacement by OTL of the higher voltage class is not an economically attractive solution due to relatively low power consumption by the end-consumers.

One of such OTL 10 kV supplies Baikalskoe village in Republic of Buryatia, Russia. The length of this OTL 10 kV is 35.5 km, which is more than twice longer than it should be according to the current requirements. For such a length of OTL the recommended voltage class is 35 kV [7]. The replacement of the existing line by a higher voltage class OTL is not attractive solution due to the low load. In the beginning of the line there is another village. Most likely that during peak loads there is a voltage drop in the beginning of the line which is also affects Baikalskoe village power supply. The quality of electricity supply of the end-consumers there is in bad conditions. And this is far from being an isolated case.

Because of the strategy of centralizing electricity supply there are more than 80% of consumers (about 120 million consumers) connected to the central grid which covers 1/3 of the country’s area. However, the remaining 20% (about 25 million consumers) have decentralized or stand-alone power supply and these consumers are spread over 2/3 square of the country. It can be concluded that the strategy of centralizing of electricity supply is not applicable for such a large territory.

Another way of rural electrification was demonstrated by China. In the 1990s the countryside there was suffering from energy poverty: less than 60% of rural population had access to electricity. One by one China launched two of the world’s largest rural electrification programs using renewable energy sources (RES) – China Township Electrification Program and China Village Electrification Program. Now, 100% of people there have access to electric power.

In China, instead of centralizing rural electricity supply, the concept of distributed generation (DG) was introduced. The concept of DG means that low-power generators are installed nearby the local consumer and cover its power demand. DG reduces transmission and distribution losses and improves reliability of electricity supply at an end-use consumer side [8].

This concept can be adopted in decentralized areas of Russia as a tool of reliability and quality improvements. In this case existing low-voltage OTL of rural areas are usable.

Chapter I: Wind and solar energy sources for hybrid power supply system

At present time a standard solution for electricity supply task is to set up an overhead transmission line from the nearest substation. Local power grid is obliged to supply a customer with alternating current electricity with stable constrained parameters. The realities of Russia's circumstances show that reliability of electricity supply and quality of electrical energy beyond the cities very often leave a lot to be desired. Moreover, electricity is generated mainly by large power stations located near large customers (i.e. cities, enterprises) and is transmitted via high- and low-voltage OTL to consumers in remote and rural areas.

If centralized electrical grid is away from the rural area or it is not reliable or connection to the grid is expensive then the usage of renewable energy sources (RES) for hybrid electric supply system is an economically attractive solution for the electrification problem.

Renewable power has two main advantages: many technologies have no fuel expenses and generally they are environmentally friendly. On the other side, many RES are variable and can be not available for some time [8].

In the next three sections I perform a review of two potential and dominant RES that can be used for hybrid power supply system.

1.1 Renewable energy sources: wind versus solar

Development of wind and solar power plants grows rapidly around the world. There are a number of factors boosting this process: growth of demand for energy, deterioration of conventional recourses, uncertainties over future environmental mitigation costs for coal, considerable reduction in the capital costs of wind-turbine and photovoltaic (PV) projects, usage of renewables is becoming compulsory, green programs [8].

While prices for conventional resources were falling during the last years, RES have been thriving. Investment in renewables has achieved new records in 2015. In Figure 1 we can see that RES are beating fossil fuels two to one.

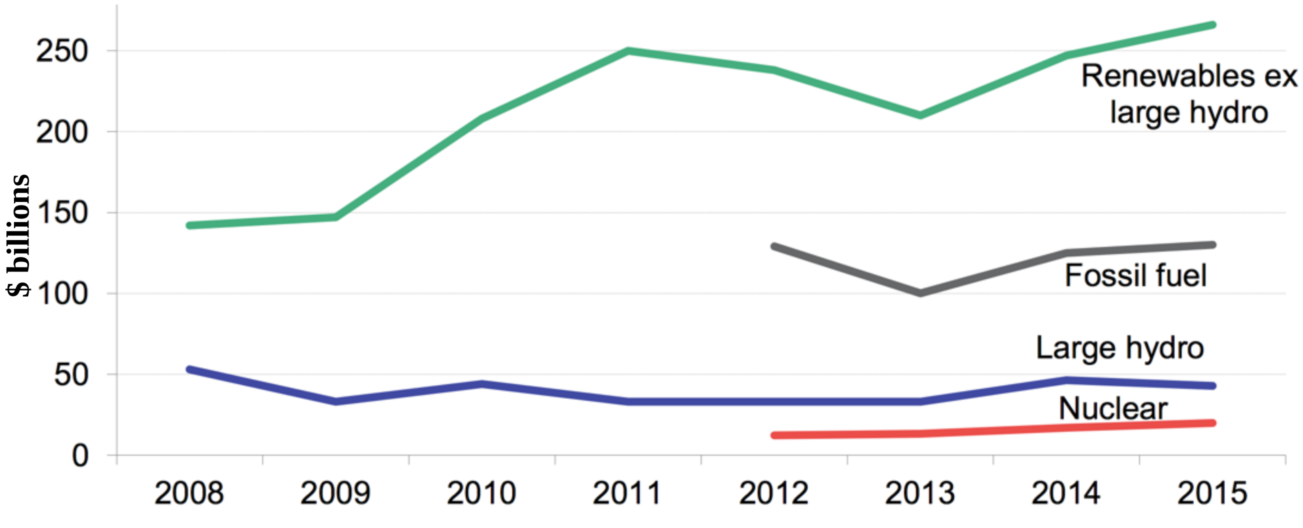


Figure 1. – World investment in power capacity [9]

From Figure 2 we see how investment in solar and wind energy technologies and renewables in total have been changing through the last 10 years. It is obvious that solar power and wind power technologies together became absolutely dominant among other RES considering amount of investment.

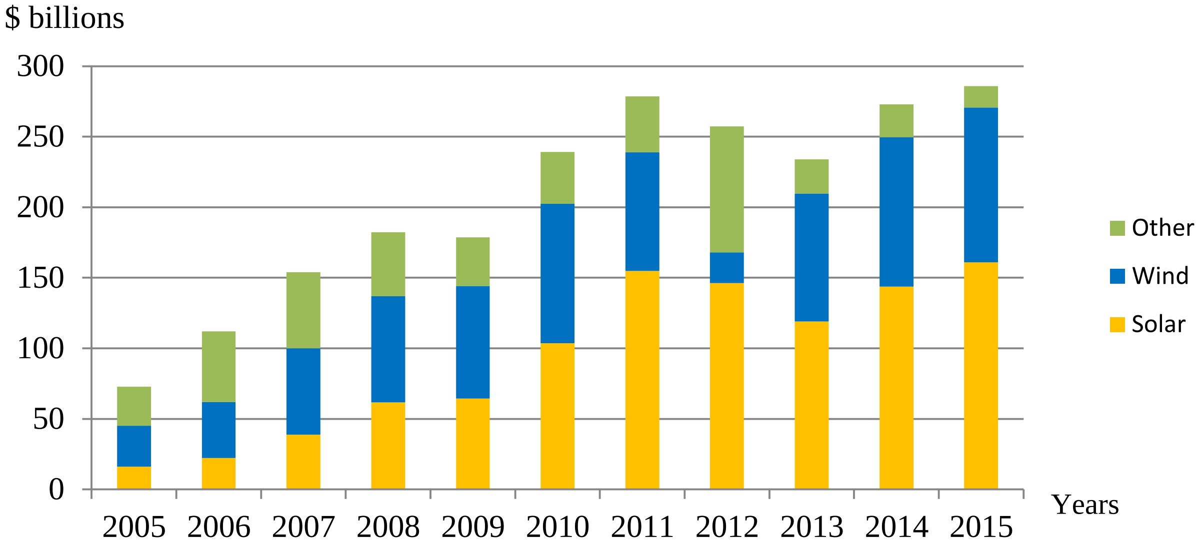


Figure 2. – Global trends in renewable energy investment [10]

We can also observe a steady average decline in prices of renewables. This is particularly true for solar PV technology. According to recent figures, in non-member countries of Organisation for Economic Co-operation and Development (OECD) capital expenses (CAPEX) for PV projects fall below wind [11].

Figure 3 shows changes in average cost of new wind and solar projects from 58 non-OECD countries through the last seven years. From this chart we can see that prices of solar plants fell down more than three times during last seven years and fell even below prices of wind plants. The reason of such a fast fall in solar project prices is that solar energy production is based on a technology, not on a fuel. Efficiency of this technology increases while prices go down over time. On top of that, as we saw in Figure 2, investments in solar energy in the last years were the largest in comparison with any other technology. Therefore the capacity of installed PV panels grows rapidly. In Figure 4 a steady doubling trend in solar and wind power generation is shown.

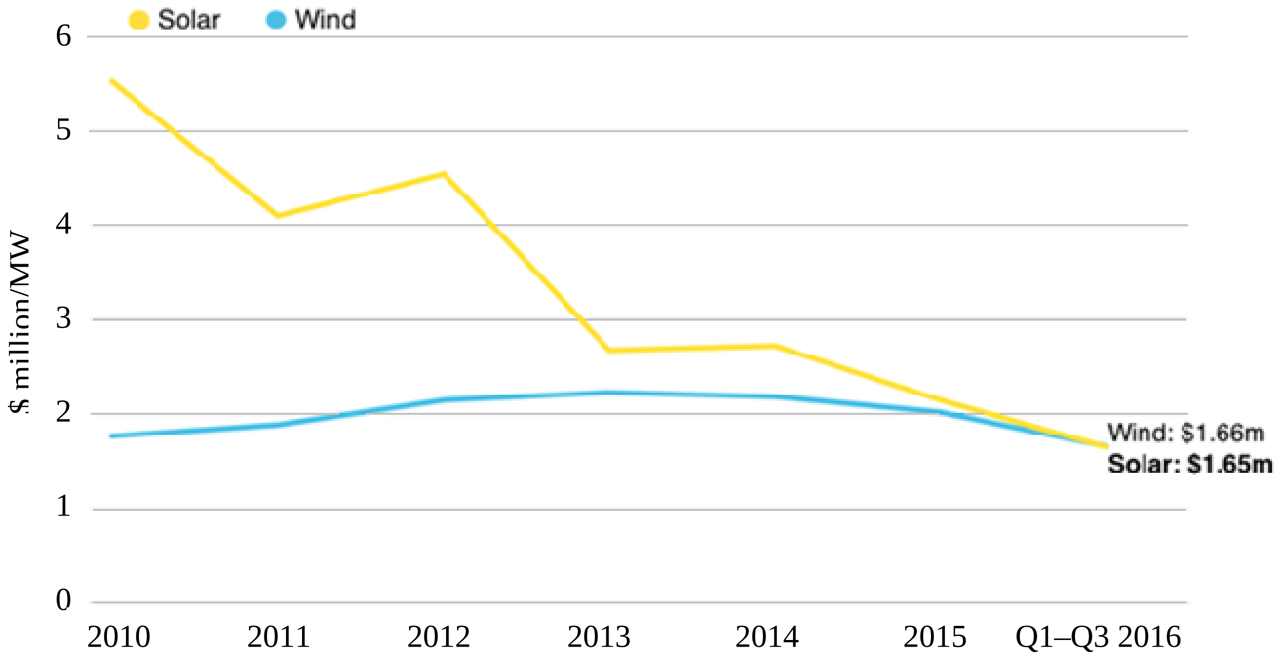


Figure 3. – Disclosed CAPEX for onshore wind and PV projects in 58 non-OECD countries [11]

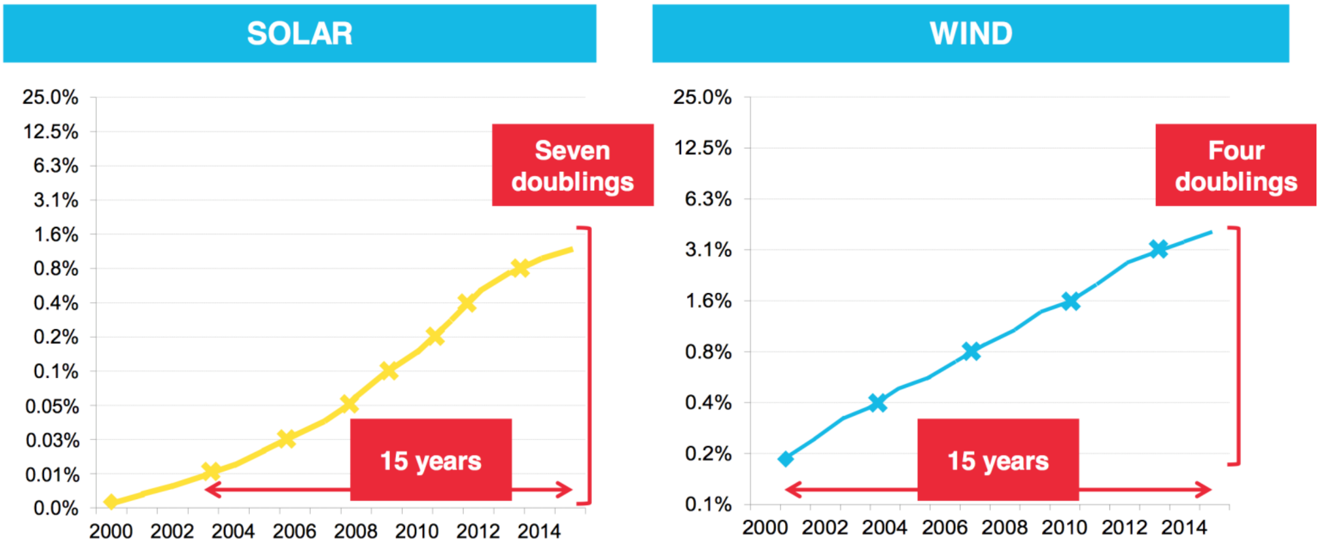


Figure 4. – Solar and wind share of power generation [9]

Wind and solar generation significantly contributed to RES generation of the European Union (EU) and I think it is a very good example that shows an importance of those two sources. In 2014 more than 27% of the demand on electricity in the EU was covered by renewables and more than one third of it was generated from solar and wind energies (see Figure 5). But it is taking into account hydropower. Excluding it, two thirds of the consumed energy was produced from wind and solar (approximately 15% of the EU consumption).

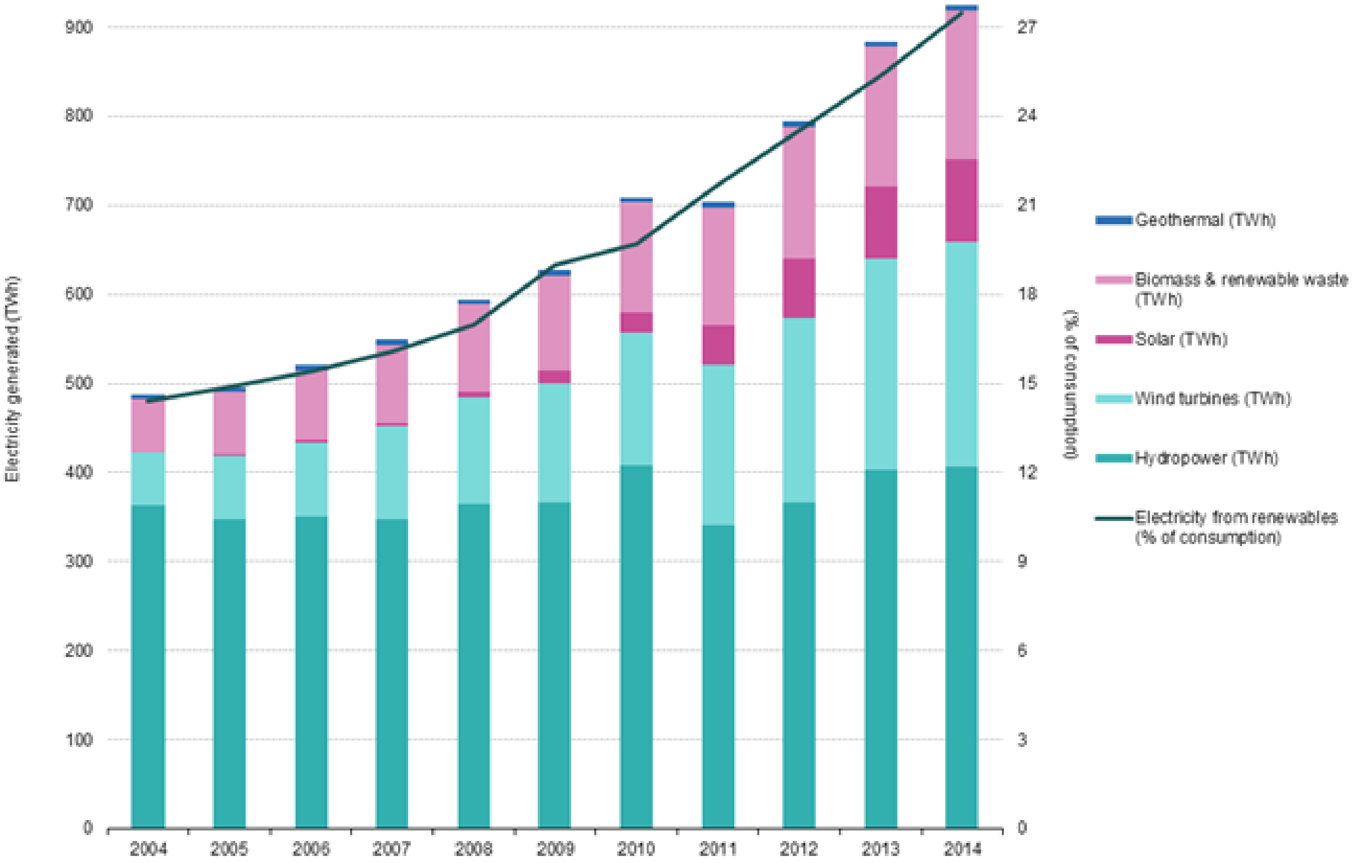


Figure 5. – RES electricity generated in the EU 2004–2014 [12]

Yet the EU is not going to stop on achieved results. By the 2020 the EU intends to reach 20% consumption from RES. To achieve it, all the EU countries are developing energy infrastructure in accordance with so-called national renewable energy action plans. National action plans regard to goals in energy, changes in policy, enhancing of energy mix and cooperation mechanisms [12].

Wind and solar have been underestimated for years. Long-term forecasts of the International Energy Agency for solar and wind have been raised 14 and 5 times, respectively. Every time global solar and wind double, there are 24 and 19 percent drop in cost [9]. But even modest expectations have a positive forecast for those energy technologies.

1.1.1 Wind energy

Working principle of all wind turbines is the same as of windmills: kinetic energy of wind stream is converted into mechanical energy of rotation which is then converted into electricity via generator. There are two main types of turbines in the wind business: vertical and horizontal axis wind turbines, which are denoted by VAWT and HAWT, respectively.

The rotational axis of VAWT stands vertically to the ground. This turbine is able to work well under tumultuous wind steams because it is powered by wind blowing from all sides and even for some models from top to bottom. That is why those turbines are used in places with inconsistent wind or when HAWT turbines cannot be installed at the necessary height due to social discontent.

HAWT are dominant type of turbines in the world wind industry. Those turbines are places at the height of several tens of meters where wind stream is stronger and more stable. HAWT produces more electricity from a given amount of wind. This is the main reason of its widespread adoption.

Wind capacity has contributed a lot to European electricity generation. Most intensively it has been used in Denmark. In 2015 wind energy has covered 23% of demand on electricity in the west and 55% in the east of the country. Overall Danish electricity production from wind turbines was 42% [13]. The Figure below shows how wind generation has been changing over 2005–2015.

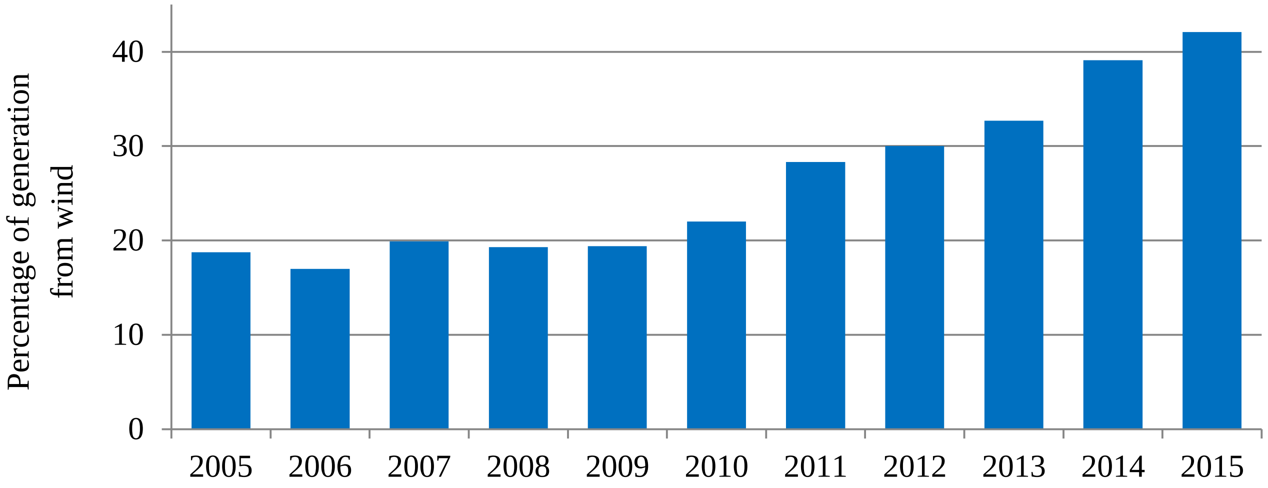


Figure 6. – Wind power share in Denmark [13]

In such countries as Spain, Portugal, Ireland and Lithuania this source of energy provides 15% of total electricity production or even more. The largest wind power producer in Europe is Germany. In 2015 this country has generated about 14% of its consumption by wind energy [14]. Table 3 shows global wind power capacity and added new capacity in 2015 year for top 10 countries.

Table 3. – Top 10 countries by total wind capacity [10]

Country	Total end–2014	Added 2015	Total end–2015
	GW		
China	114.6	30.8	145.4
United States	65.4	8.6	74
Germany	39.2	6	45
India	22.5	2.6	25.1
Spain	23	0	23
United Kingdom	12.6	1	13.6
Canada	9.7	1.5	11.2
France	9.3	1.1	10.4
Italy	8.7	0.3	9
Brazil	6	2.8	8.7
World Total	**370**	**63**	**433**

Notes: Some capacity in Germany was decommissioned in 2015. Additions refer to gross capacity.

A much smaller share has the United States – there wind contributed 4.5% of generation [14]. Nevertheless, the United States is the second country in the world in terms of installed wind capacity – 74 GW at end–2015. Wind provides just 3.2% of the power consumed in China [14]. But China has one third of the world installed wind capacities (145.4 GW at end–2015) and, taking into consideration this fact, takes the first place in the world.

1.1.2 Solar PV energy

Not so long time ago solar panels have been associated with spaceships, satellite stations and Moon rovers. But now we can find a device generating electricity from sunlight even in calculators.

Moreover, in countries of high solar radiation (such as Italy, Spain, Portugal, the Southern states and others) solar installations save money on electricity and heat delivery. The phenomenon initiated by both population and government of those counties.

The conversion of sunlight into electricity in PV panel happens because of photoelectric effect: additional energy of photons excites the electrons in a panel, the ordered motion of which is called electric current.

From one side, as we saw in Figure 4, the contribution of solar power into overall electricity production is still low. But from the other side it is already noticeable and grows very fast (see Figure 7). Global solar power capacity and added new capacity in 2015 year for top 10 countries are shown in Table 4.

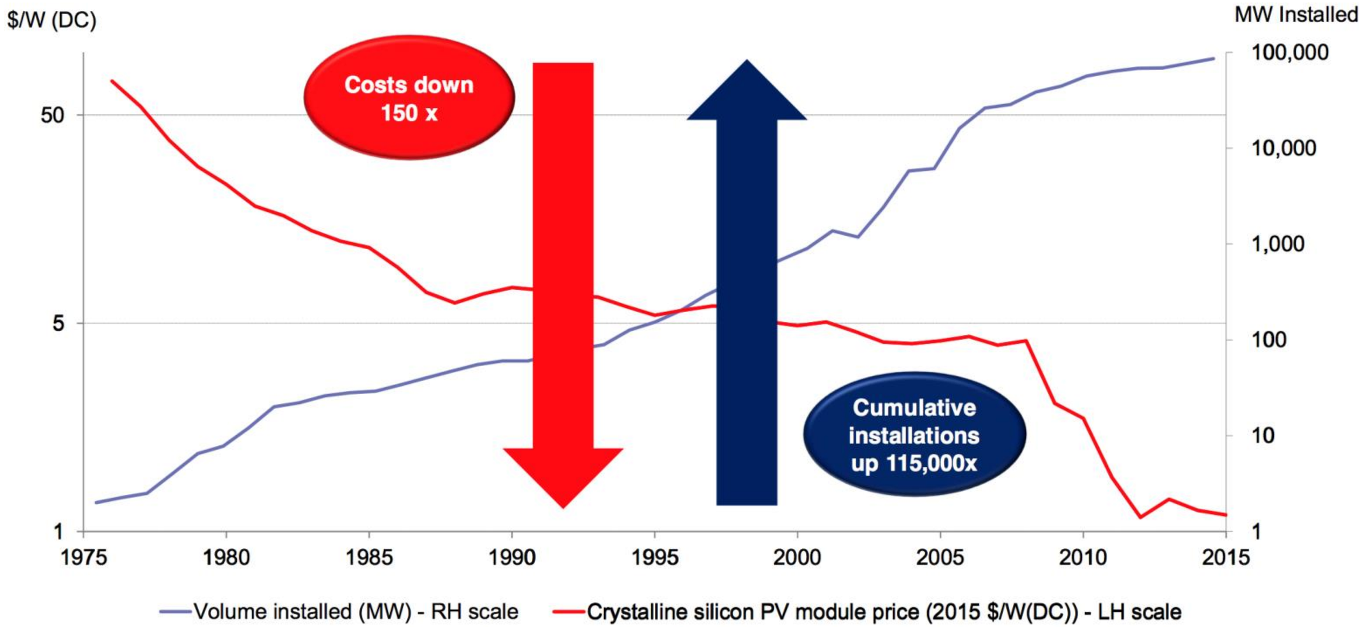


Figure 7. – Changes in cost of PV panels and PV capacity installed over 40 years [9]

Table 4. – Top 10 countries by total PV capacity [10]

Country	Total end–2014	Added 2015	Total end–2015
	GW		
China	28.3	15.2	43.5
Germany	38.2	1.5	39.7
Japan	23.4	11	34.4
United States	18.3	7.3	25.6
Italy	18.6	0.3	18.9
United Kingdom	5.4	3.7	9.1
France	5.6	0.9	6.6
Spain	5.4	0.1	5.4
India	3.2	2	5.2
Australia	4.1	0.9	5.1
World Total	**177**	**50**	**227**

Notes: Table includes all countries with operating commercial solar plant capacity at end–2015. A few countries with commercial solar plants also have test or demonstration plants that were not included in the table. They are: Italy and Oman (both 7 MW), Israel (6 MW), China and Turkey (both 5 MW), France (1.6 MW), Germany (1.5 MW) and Canada (1.1 MW).

This technology has a price falling trend. During the last 40 years, price of PV panels has fallen by 150 times. PV projects have become attractive to investors as never before. That is why the largest share of investment in renewables is in solar power.

1.2 Estimation of regional potential for using wind and solar energy resources

Russia intends to keep pace with countries introducing RES. It is reflected in Energy Strategy of Russia for the period up to 2030, according to which the strategic objectives of using RES and local energy resources are [15]:

- reduction in growth rates of anthropogenic load onto the environment and resistance to climate changes under the condition of necessity to satisfy growing energy consumption;
- rational use and reduction in growth rates of existing fossil fuels consumption under the condition of inevitable exhaustion of its reserves;
- preservation of health and quality of life of the population by means of slowdown in growth rates of environmental pollution from fossil fuel use; reduction in the state expenditures on health protection;
- reduction in growth rates of expenses for distribution and transportation of electricity and fuels and in the resulting losses;
- involvement of additional fuel and energy resources into the fuel and energy balance;
- enhancement of energy security and reliability of energy supply at the expense of its increasing decentralization.

Additionally, 2017 year is declared as Year of the Environment in Russia. The main purpose of this decree is to draw the society’s attention to existing challenges in ecological sphere and to help improve environmental security in Russia. Numerous changes in field of environmental legislation (which had been considered in past years) will enter into force in 2017.

According to last estimations, Russia’s renewable energy capacity equals at least 4.5 billion tons of coal equivalent per year. It is four times more than the country actually needs. RES potential of Russia’s territories mainly consists of solar and wind energy. Economic capacity of renewables depends on a number of factors such as cost, quality and availability of conventional sources, current economic conditions and regional characteristics. It changes over time and must be estimated in advance in order to implement renewable energy projects [15].

In light of the above, first of all I need to estimate RES potential of the region. But before that I would like to introduce the area of interest, that is Baikalskoe village.

Baikalskoe is an old fishing village which has an advantageous location near the coast of Lake Baikal. Map of the area is shown in Appendix 2. The village is 41 km away from Severobaikalsk city and is surrounded by mountain ridges and the Cape of Ludar. This cape has an archeological value as a center of the early man living. There are a post office, hospital, shops and cellular retranslator in the village. Population is 660 people.

The area of interest has both wind and solar power potentials. In the next section I evaluate the use of available RES.

1.2.1 Wind power potential of the region

In order to estimate the potential of wind power in Baikalskoe village I use local weather archives [16] with the necessary changes to the average wind speed.

It is common knowledge that with distance from the underlying ground the wind speed increases and wind stream becomes more stable. The wind speed on the height *h* can be evaluated by the following formula [17]:

$$V_h = V_V \left(\frac{h}{h_V} \right)^{\alpha}, \tag{1}$$

where V_h – the wind speed on height h, m/s;
h_V – the height of weather vane, m;
V_V – wind speed on the height of weather vane, standard value 10 m;
α – coefficient which depends on average wind speed on the height of weather vane.

To calculate monthly average speed of the wind I use average wind speeds:

$$\bar{V}_h = \bar{V}_V \left(\frac{h}{h_V} \right)^{\alpha}, \tag{2}$$

where $\bar{V}_h$ – monthly average speed of the wind on height h, m/s;
$\bar{V}_V$ – monthly average wind speed on the height of weather vane, standard value 10 m.

It is necessary to use bulk of measurement during quite a long period of time in order to obtain reliable figures of average wind speeds. But because of the lack of wind speed data in the village I would use 2015–2016 year statistics reported in [16].

In general, average wind speed is defined as arithmetic mean value obtained by measuring the wind speed at regular intervals within specified time period [18]:

$$\bar{V}_V = \frac{1}{n}\sum_{i=1}^{n} V_i . \tag{3}$$

Calculation of the monthly average of wind speed in February 2015 is given below.

$$\bar{V}_V = \frac{1}{n}\sum_{i=1}^{n} V_i = \frac{1}{31}\left(2+4+\cdots+7\right) = 2.32 \ {}^{m}\!/_{s} .$$

According to [17] for $V_V \leq 3$ m/s we use coefficient $\alpha = 0.2$. Calculation example of average wind speed on height of 20 m in February 2015 is shown below. My computation results for other months are presented in Table 5.

$$\bar{V}_{h=20} = \bar{V}_V \left(\frac{h}{h_V}\right)^{\alpha} = 2.32\left(\frac{20}{10}\right)^{0.2} = 2.66 \ {}^{m}\!/_{s} .$$

Table 5. – Computation results of monthly average wind speed for each month during February 2015 – January 2016

Month	$\bar{V}_V, \ m/s$	$\bar{V}_{h=20}, \ m/s$
February	2.32	2.66
March	2.83	3.25
April	2.94	3.38
May	2.70	3.10
June	2.00	2.30
July	2.06	2.37
August	2.53	2.91
September	2.65	3.04
October	2.53	2.91
November	1.81	2.08
December	1.74	2.00
January	1.71	1.96
Annual average		2.66

Thus, annual average wind speed on height of 20 m:

$$\bar{V}_{ann,\ h=20} = \frac{1}{n}\sum_{i=1}^{n} \bar{V}_i = \frac{2.66+3.25+...+1.96}{12} = 2.66 \ {}^{m}\!/_{s} .$$

The most common recommendation for application of low and medium-sized wind turbines is that annual average wind speed should be at least 4 m/s [19]. Therefore, installation of wind turbines in Baikalskoe village is not recommended.

1.2.2 Solar power potential of the region

Solar radiation is an inexhaustible, powerful and environmentally-friendly source of energy. But in spite of the fact that solar radiation seems to be an advantageous source of energy its usage in much of Russia's area is limited by individual climatic characteristics of particular territories and absence of estimation of valid methods.

First facts about atmospheric transmittance on Lake Baikal, Irkutsk and other regions were obtained by V. Bufal in the 1960s. Solar radiation near Lake Baikal is 13% higher than in Irkutsk city which is placed 68 km away from the lake. Integral atmospheric transmittance of Lake Baikal basin is noticeable due to its high degree [20]. Furthermore, sunshine duration there exceeds 2000 hours per year [22].

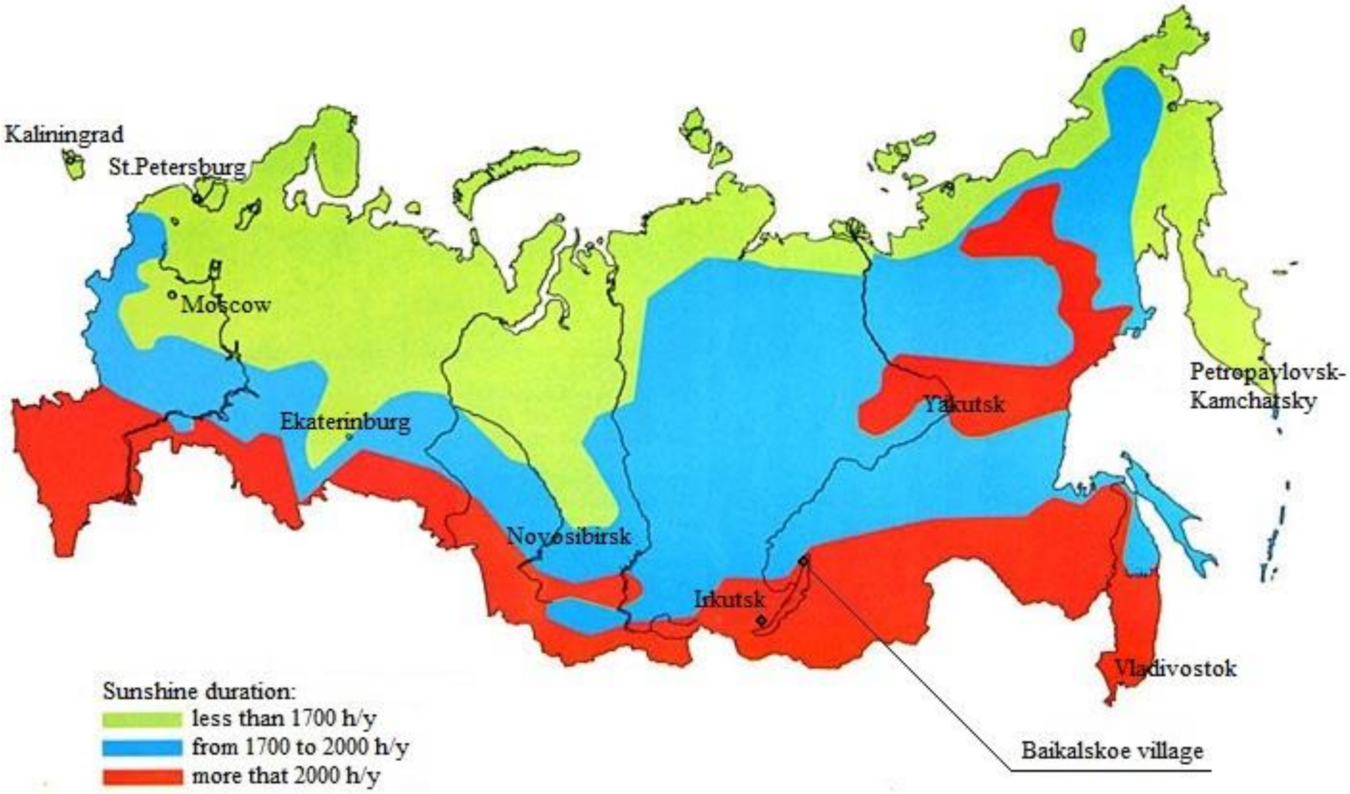


Figure 8. – Russia's solar energy resources [21]

All these facts are advantage factors for using solar potential for electricity generation. In order to compute radiation during spring season in 2015 year I consider three components of radiative balance [22]:

$$Q_{inc} = S_{inc} + D_{inc} + R_{inc}, \tag{4}$$

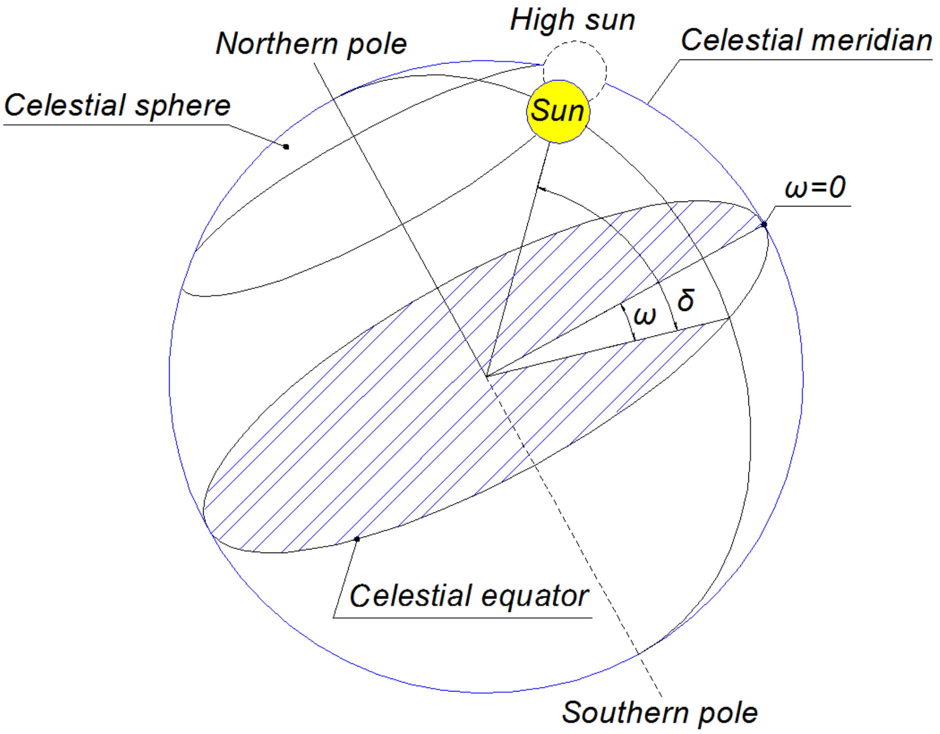
where Q_{inc} – total solar radiation on inclined surface, W/m^2;
S_{inc} – direct solar radiation on inclined surface, W/m^2;
D_{inc} – scattered solar radiation on inclined surface, W/m^2;
R_{inc} – radiation of ground reflection, W/m^2.

Then I estimate the height of the Sun and incidence angle of solar radiation on the inclined surface at its different angles to the horizon using the following equation [22]:

$$\begin{gathered}\cos\theta = \sin\delta\cdot\sin\varphi\cdot\cos s - \sin\delta\cdot\cos\varphi\cdot\sin s\cdot\cos\gamma + \cos\delta\cdot\cos\varphi\cdot\cos s\cdot\cos\omega + \\ + \cos\delta\cdot\sin\varphi\cdot\sin s\cdot\cos\gamma\cdot\cos\omega + \cos\delta\cdot\sin s\cdot\sin\gamma\cdot\sin\omega\end{gathered} \tag{5}$$

where φ – geographic latitude of the area, rad;
δ – solar declination, rad;
s – incline angle of the surface to the horizon, rad;
γ – azimuth angle of the surface, rad;
ω – hour angle, rad.

To clarify I illustrate δ and ω parameters in Figure 9.



Source: Author's illustration.

Figure 9. – Solar declination δ and hour angle ω

Considering R_{inc} negligible low during the summer, flux density of total solar radiation which falls on inclined surface at different angles to the horizon in fine weather [22]:

$$Q_{inc}\left(\varphi,\omega,\gamma,\mathrm{s},\mathrm{N}\right) = S_{inc}\left(\varphi,\omega,\gamma,\mathrm{s},\mathrm{N}\right) + D_{inc}\left(\varphi,\omega,\gamma,\mathrm{s},\mathrm{N}\right). \tag{6}$$

Incoming solar radiation on a surface of size S m^2 during time period T h is called solar insolation. Solar insolation calculated for a spring day of clear sky is shown in Figure 10. Data of monthly average cloudiness in the village I found in weather statistics base [23].

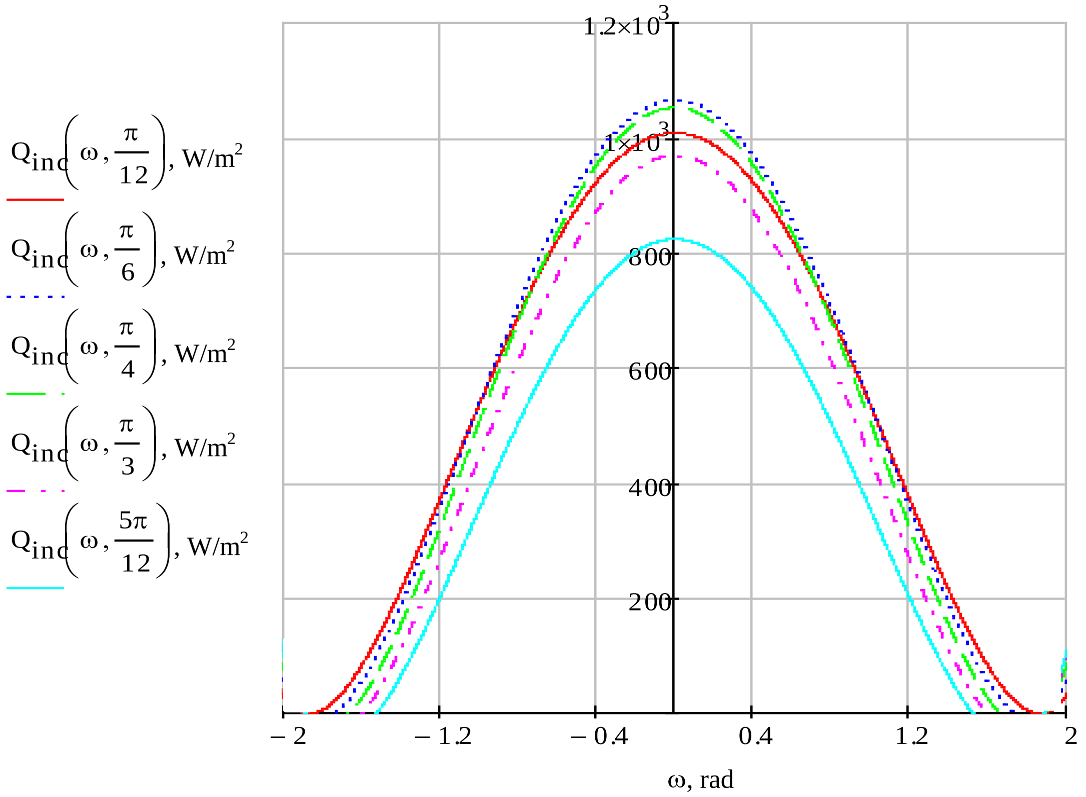


Figure 10. – Solar insolation on the surface inclined at different angels during spring day of clear sky

It is not clear from the graph what is the optimum tilt to the horizon. But using the following integral function in Mathcad Software I have calculated squares under these curves and have obtained values of daily solar insolation on the surface inclined at different angels [22]. Obtained values are shown in Table 6. From this Table it is obvious that the optimum tilt to the horizon is π/6.

$$\int_{-\omega_i}^{\omega_i} Q_{inc}(\omega, s_i)\cdot\frac{24}{2\pi}\cdot d\omega \tag{7}$$

Table 6. – Solar insolation on the surface inclined at different angels *s* during spring day of clear sky

s, rad	π/12	π/6	π/4	π/3	5π/12
s, ^{O}	15	30	45	60	75
Q_{inc}, kWh/m^2	7.85	8.02	7.68	6.88	5.66

Source: Author's calculations.

Further I estimate solar insolation on the surface inclined at different angels during day of cloudy sky using the following equation [22]. Incoming solar insolation calculated for a spring day of cloudy sky is shown in Figure 11.

$$Q_{cloud}(\varphi,\omega,\gamma,\mathrm{s},\mathrm{N}) = \left(S_{inc}(\varphi,\omega,\gamma,\mathrm{s},\mathrm{N}) + D_{inc}(\varphi,\omega,\gamma,\mathrm{s},\mathrm{N})\right)\cdot\left(1-(a+b\cdot n)n\right), \tag{8}$$

where *n* – cloud quantity (*n* = 0 for clear sky, *n* = 1 for overcast sky);
b – constant coefficient which equals 0.38 [22];
a – coefficient which depends on environment (land or sea) and on latitude of the place.

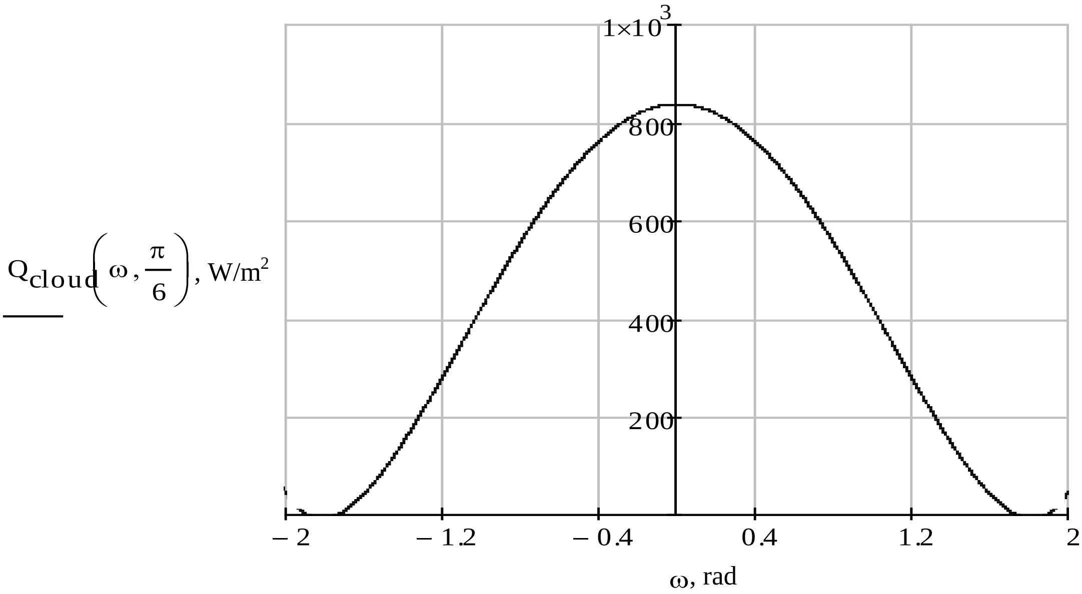


Figure 11. – Solar insolation on the surface inclined at π/6 angel during spring day of cloudy sky

Values of solar insolation for characteristic summer, autumn and winter days I have estimated the same way. Corresponding graphs are shown in Figures 12–17.

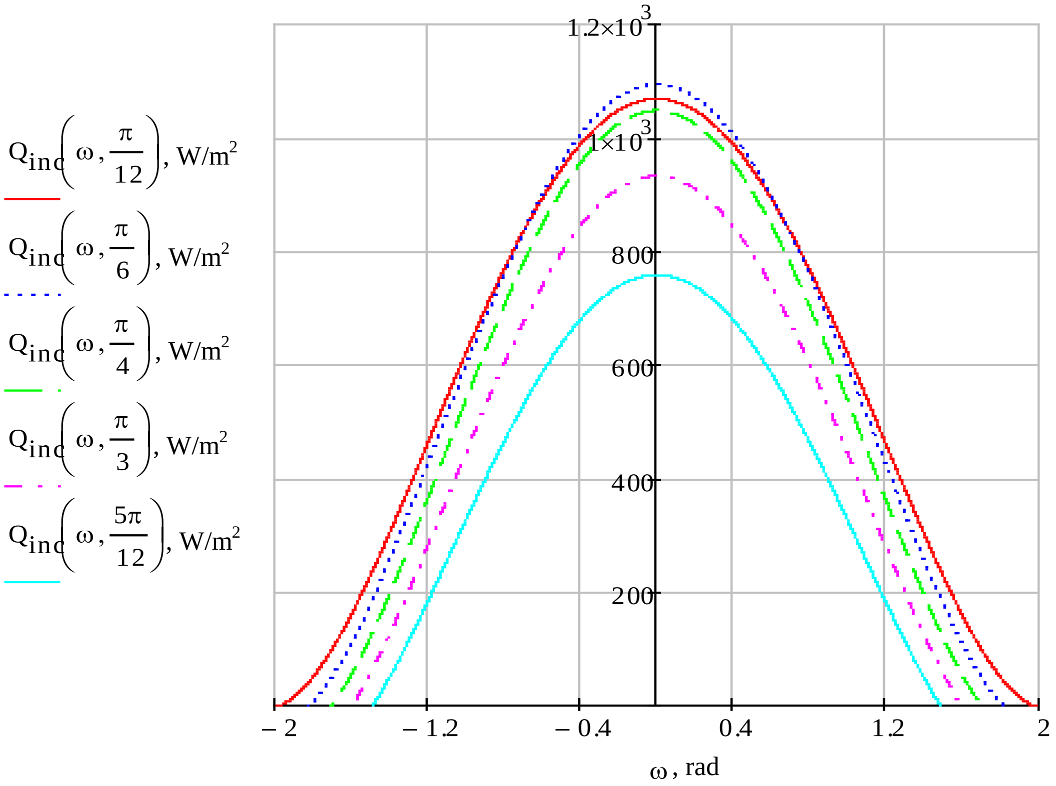


Figure 12. – Solar insolation on the surface inclined at different angels during summer day of clear sky

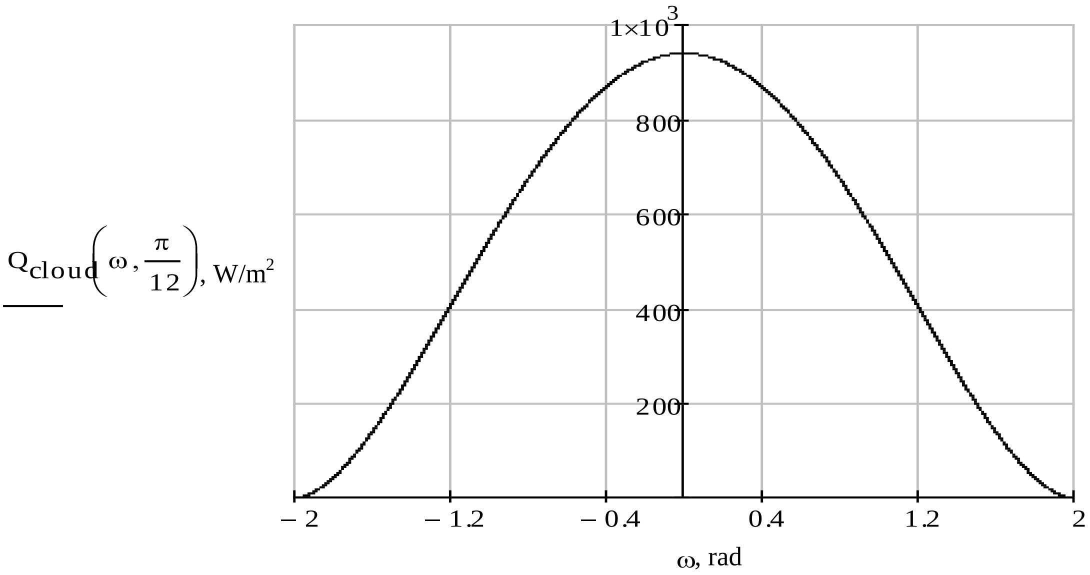


Figure 13. – Solar insolation on the surface inclined at π/12 angel during summer day of cloudy sky

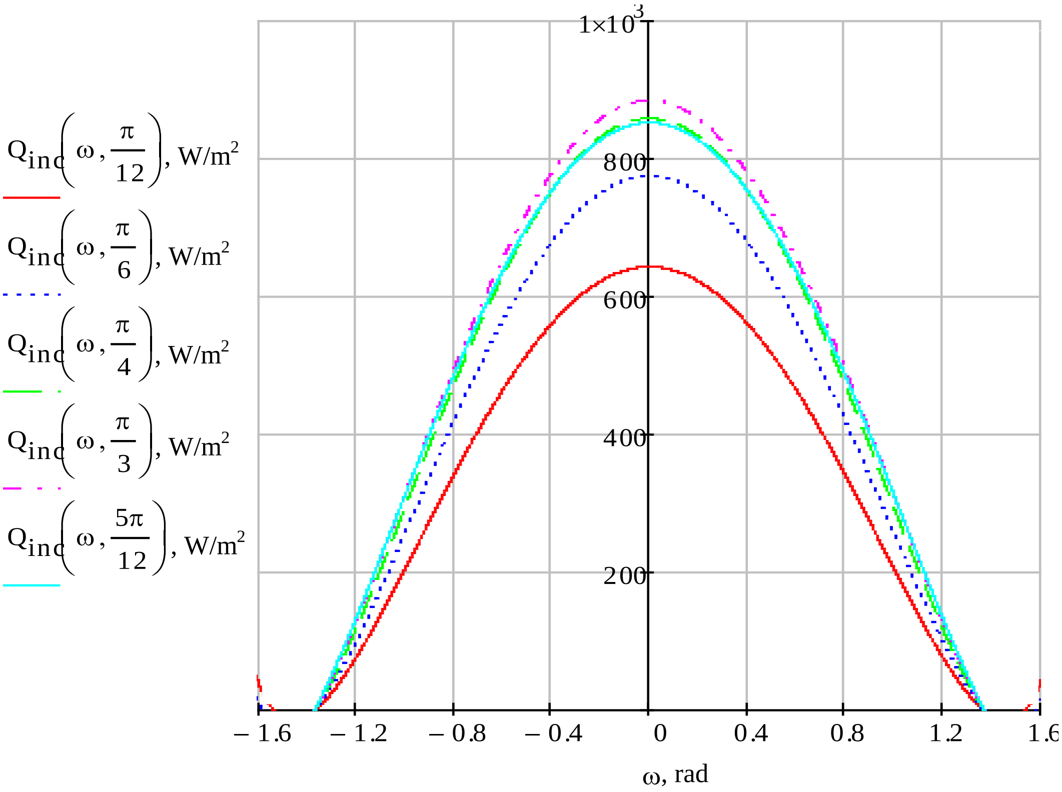


Figure 14. – Solar insolation on the surface inclined at different angels during autumn day of clear sky

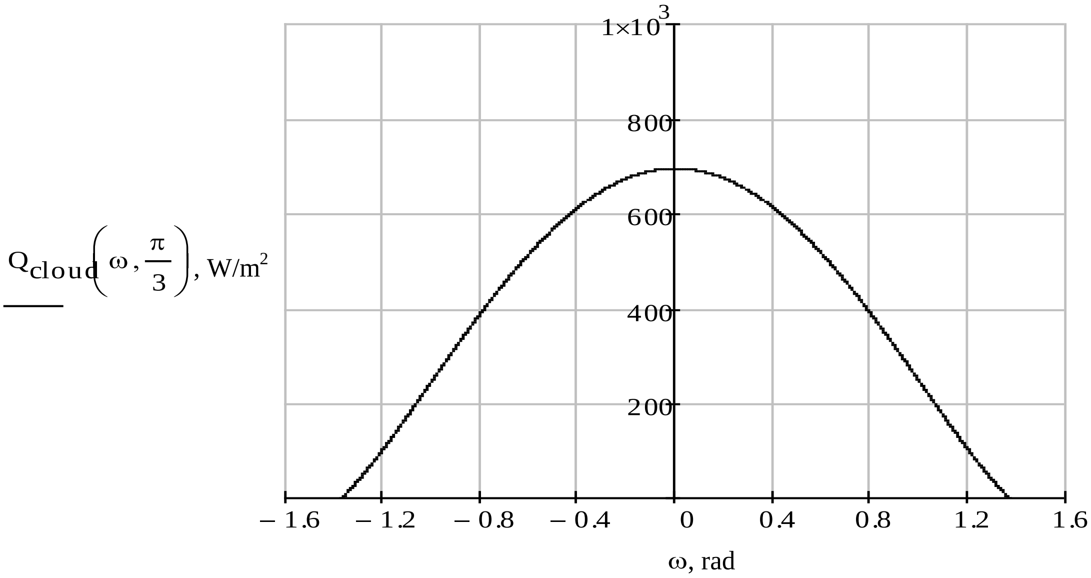


Figure 15. – Solar insolation on the surface inclined at π/3 angel during autumn day of cloudy sky

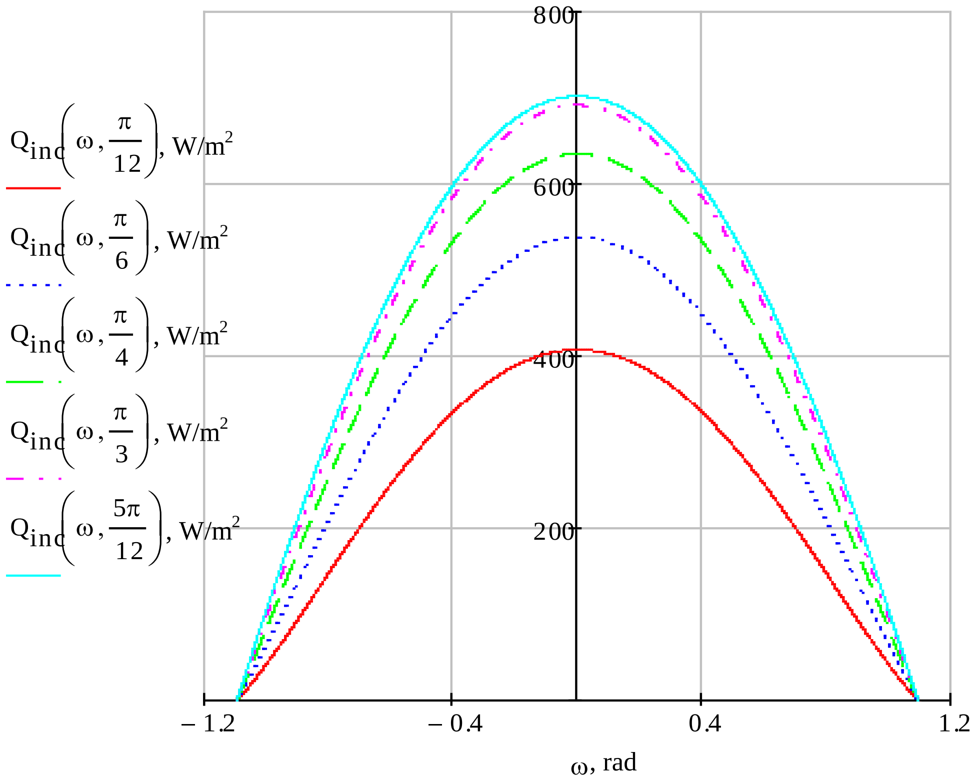


Figure 16. – Solar insolation on the surface inclined at different angels during winter day of clear sky

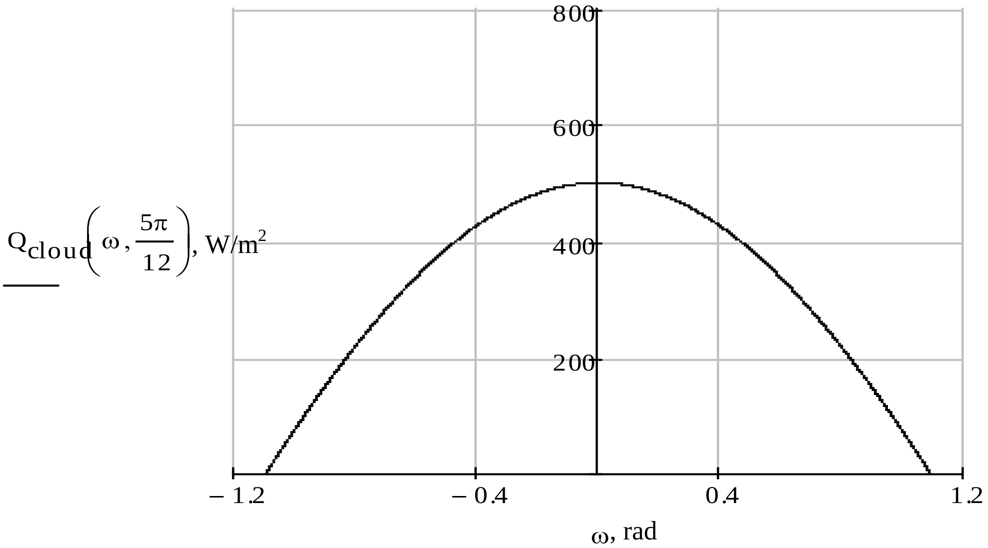


Figure 17. – Solar insolation on the surface inclined at 5π/12 angel during winter day cloudy sky

Comparing solar insolation for different seasons we see that the optimum tilt of PV panel for different seasons is different. Optimum tilt of PV panel plays a key role in terms of energy production of installation. In order to estimate solar insolation in the village more precisely I performed calculations for each month in the same way as it was shown above. The results of solar insolation in Baikalskoe village are summarized in Table 8 and will be used to perform the choice of necessary equipment for a solar power plant.

1.3 Solar power plant

Solar power plant (SPP) is a power station where electricity generates through the direct convertation from solar radiation.

In order to provide reliability of power supply such plant besides PV modules includes additional components which depend on the type and purpose of SPP. Parameters of those components – and consiquently the price of SPP – depend on numerous factors, such as: daily curve and electricity consumption per day, nature of SPP work (seasonal or annual), monthly average incoming solar radiation and number of cloudy days in a row in the area of PV plant installation, solar tracking systems and other factors.

Since PV panels generate electricity during daylight hours only, its installed capacity must be chosen with respect to the amount of energy to be stored for consumption in hours of darkness. This resulted in a notable increase of installed PV capacity and batteries bank capacity as well.

1.3.1 Possible implementation schemes

There are two main types of SPP:

- stand-alone system;
- system working in parallel to the grid.

Besides PV panels, stand-alone SPP, as a rule, have batteries and a charge controller. In supply systems on alternative current and voltage of 220/380V SPP also includes inverter which is used for transformation of DC to AC. A typical scheme of a stand-alone solar power supply system is shown in Figure 18.

Obvious disadvantage of stand-alone SPP is loss of excess energy in a low-load mode. Generally, when batteries are charged the controller turns PV panels off. Excess energy can be used for some ballast resistance like, for instance, water or air heating, but still it does not solve this issue fully.

A major weakness of stand-alone SPP is a need in batteries which have to work in a cycling operation mode. The number of working cycles of widely spread lead-acid batteries is relatively small and it results in quite often replacement of this component. Purchasing of commercial batteries with long lifetime (i.e. nickel-cadmium and lithium-ion batteries) for SPP is much more expensive.

Furthermore, batteries have energy losses about 10% or so caused by charging-discharging process and losses increasing with batteries wearing [19].

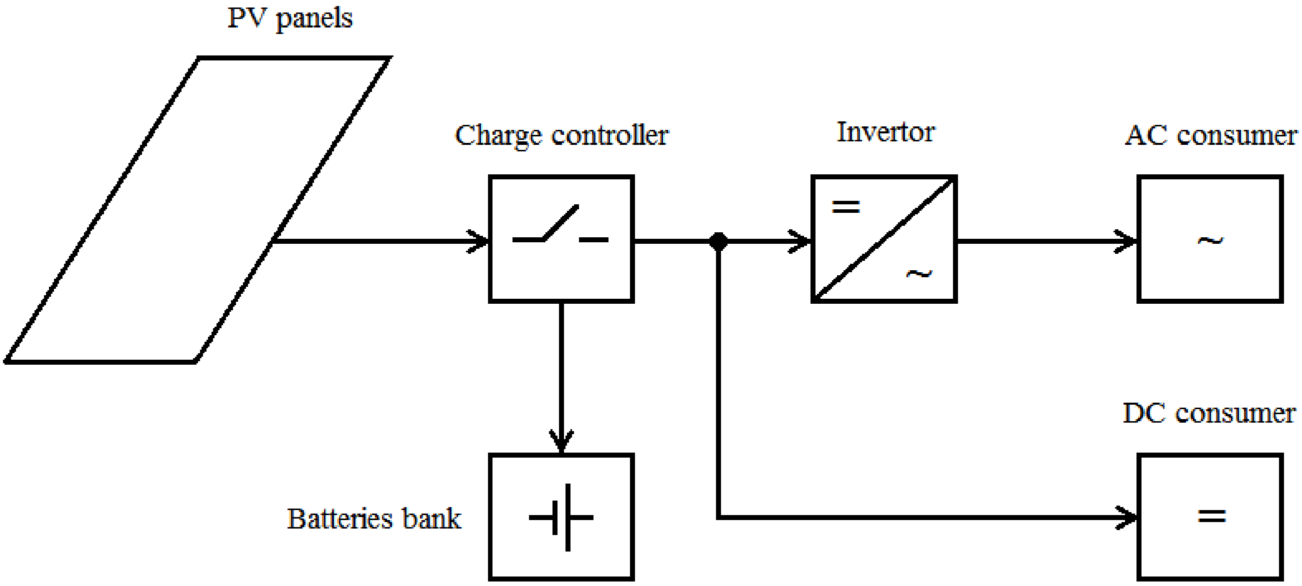


Figure 18. – Block-scheme of stand-alone PV power supply system

Usage of SPP in parallel with the grid allows to avoid many, if not all, of disadvantages of stand-alone systems. In fact, electrical grid is a large battery with 100% coefficient of efficiency which can absorb all excess energy generated by panels. Block-scheme of grid-connected SPP is shown in Figure 19.

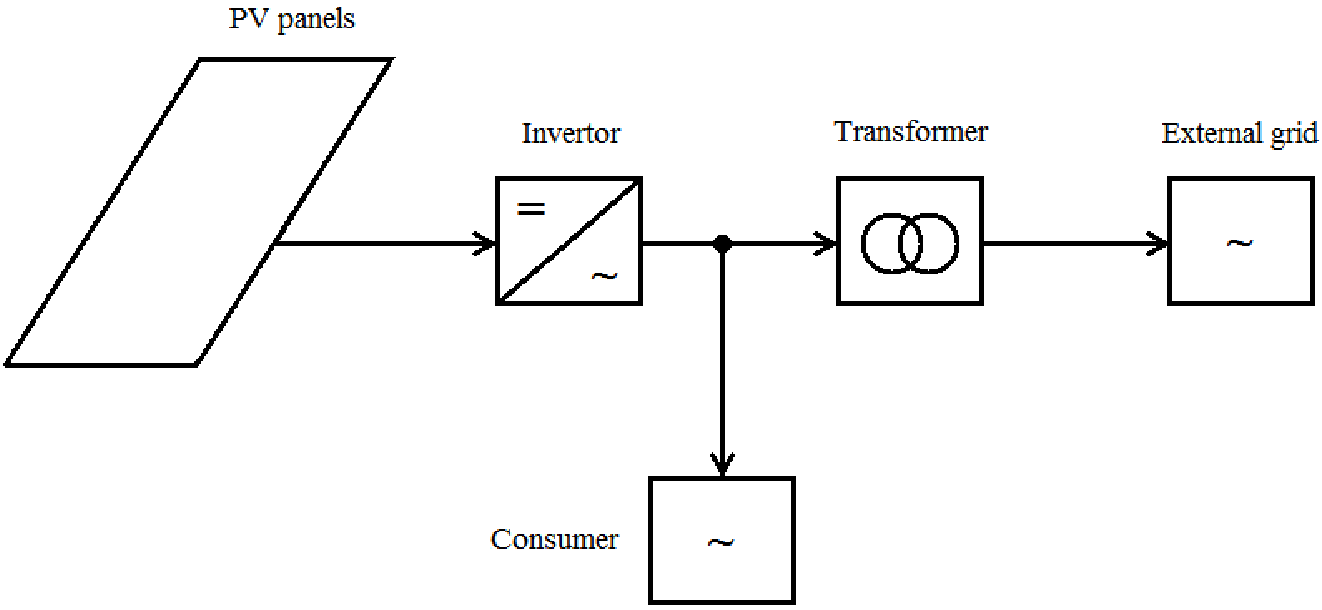


Figure 19. – Block-scheme of grid-connected PV power supply system

In turn, grid-connected SPP fall into two types of construction: with and without batteries. The most widely spread PV power systems, in practice, are systems without batteries. Batteryless SPP has a high reliability and very low maintenance. Such a system has inventors which use external grid as reference voltage, meaning that inverters turning on thanks to this voltage and synchronize SPP with the grid.

In case of the outage of external grid there will be local blackout and electricity supply to consumers stops. It happens because grid inverters create the voltage identical to the grid and without external grid it is not working. This is the main drawback of such a system. But it is necessary from safety reasons: when power line is turned off because of repair and maintenance purposes, grid invertor prevents connecting AC power to this line.

There are additional restrictions for local systems connected to grid based on diesel generators [19]:

- Diesel generators cannot be turned off;
- 40% of electricity supply must be covered by those generators.

When the grid is not reliable SPP with batteries is applied. In comparison with the previous one this system is more complicated but it lets us create an uninterrupted power supply system.

In order to provide maximum efficiency of grid-connected SPP with batteries it is necessary to use stand-alone inverter. There are three options how to build such a system [24]:

1. PV panels charge batteries via charging controller and then energy goes through the inverter right to the load or the grid;
2. Energy from PV panels goes to grid PV inverter which is feeding the load and excess energy charges batteries (or, if batteries are fully charged, it goes to the grid);
3. Hybrid system which includes components of both options mentioned above.

The most simple and applicable option is the first one. Its scheme is shown in Figure 20. There batteries are charged by PV panels via DC charge controller.

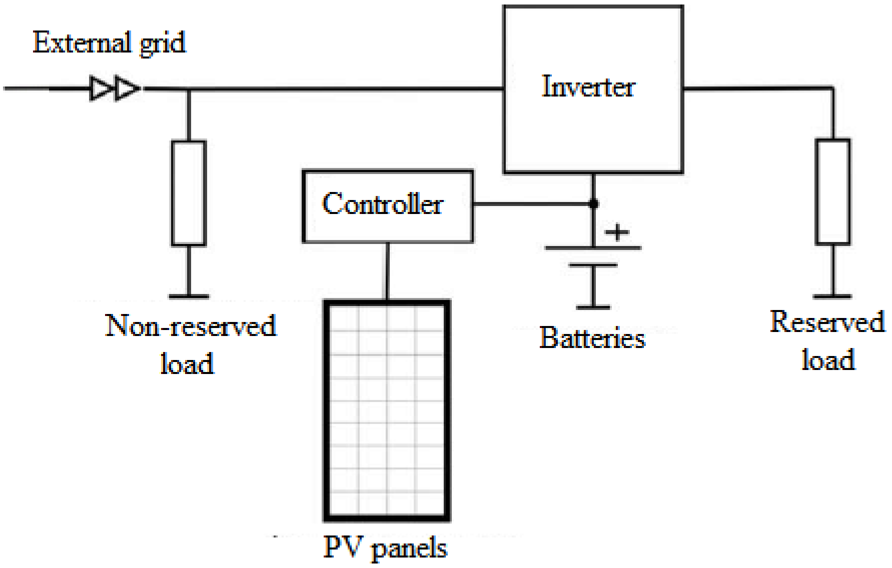


Figure 20. – Scheme of grid-connected PV power supply system with DC charge controller [19]

When standard uninterruptible power supply (UPS) is used, batteries are charged by external grid and solar panels are almost not used. In order to maximize utilization of solar panels maximum power pointing tracker (MPPT) and special inverter with batteries voltage control are applied. In this case, even if batteries are fully charged, solar power goes to the load and it results in reduction of power take-off from the grid. When the load consumes less amount of energy than it is actually generated by PV panels this inverter sends excessive energy either to the grid or to charge batteries [24].

Such a system has the following advantages: solar power is utilized even when grid outages occur; it is possible to recover power supply under long grid outages and deep discharge of batteries because PV panels can charge them.

The disadvantages include: double transformation of solar electricity which leads to additional losses in inverter, controller and batteries; cycling operation mode leads to quick wearing of batteries.

Scheme of grid-connected PV power supply system with grid PV inverter is shown in Figure 21. This system has the following advantages: both grid and stand-alone inverters can be applied even with minimum set of options and are presented on RES market in various variants from numerous producers; batteries are always fully charged and are used in buffer mode only when grid outages occur.

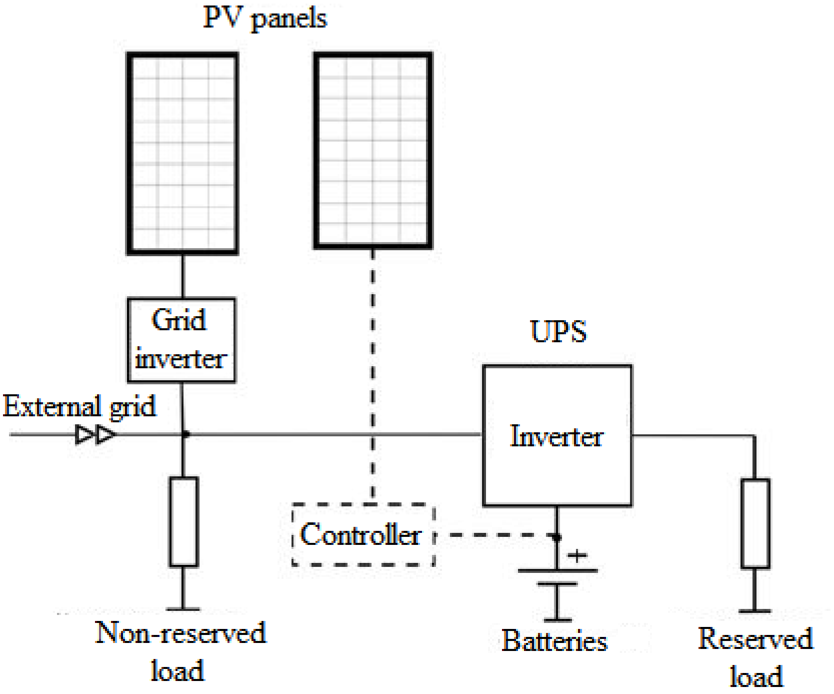


Figure 21. – Scheme of grid-connected PV power supply system with grid PV inverter [19]

Such a system is advisable to use in power supply systems where electricity is consumed mostly during the daylight and grid outages are rare and short. This system has only one disadvantage: solar power production stops when grid outages occur.

UPS capacity there does not depend on PV panels capacity and covers only the most important consumers. For recovering purposes after deep discharge of batteries this system can have a few solar panels connected to batteries via charge controller (shown by dashed line in Figure 21). But if grid outages are short there is no need in such measures.

The most universal system is SPP with grid inverter on the output of UPS (Figure 22). As in the previous system, a high-efficient inverter is applied here. The difference is that solar power supply of both the load and batteries cannot be interrupted by grid outages.

Grid inverter there supplies the most important consumers with electricity normally. If the load energy consumption is less than solar power production, the excessive energy charges batteries. In the opposite case the load and batteries draws power from the grid. After full charge of batteries excessive energy goes to the load and/or to the grid.

If grid outage occurs, UPS is switched over to power supply from batteries. In this case energy of the Sun is used continuously because reference voltage for grid inverter is provided by batteries.

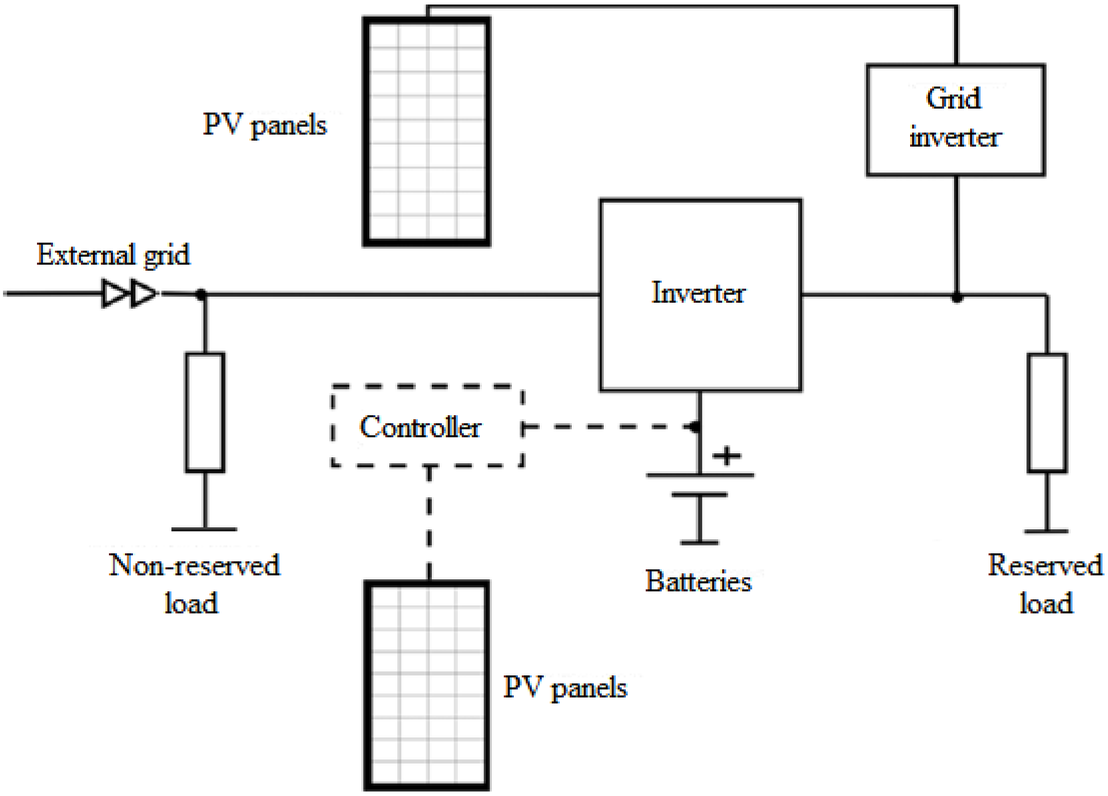


Figure 22. – Scheme of grid-connected PV power supply system with grid inverter connected to the output of UPS [19]

If grid outage occurs, UPS is switched over to power supply from batteries. In this case energy of the Sun is used continuously because reference voltage for grid inverter is provided by batteries.

This system has the following advantages: efficient usage of batteries, of renewable energy of the Sun; it is possible to recover power supply after deep discharge of batteries thanks to few PV panels connected to batteries via charge controller (as it shown by dashed line in Figure 22).

The disadvantages include the need in special hybrid stand-alone inverters which are able to charge batteries from the output side and transmit excess of energy to the grid.

1.3.2 Equipment description

The main part of SPP is PV panel. It is also known as solar panel/module and is basically consisting of series- and parallel-connected PV cells. There are various types of solar modules available on the RES market. The potential difference developed across a solar cell is about 0.5 volt and hence the necessary number of such cells to be serially connected to achieve 14 to 18 volts to charge a standard battery of 12 volts. Solar panels are connected together to create a solar array. Multiple panels are connected together both in parallel and series to achieve higher current and higher voltage respectively. The typical solar panel design is shown in Figure 23.

Figure 23. – The typical PV panel design [25]

Beside solar panels, SPP has three main elements: batteries, controller and inverter. In grid-connected SPP, PV panels cannot be directly connected to the load or batteries bank. That is why SPP also need inverter and controller as a power transformation and distribution centers.

Power generation from PV panels varies significantly over time and depends on the intensity of sunlight. That is why solar modules are not connected directly neither to the load nor to batteries. Usually they feed an inverter which then synchronizes output with external grid. Inverter takes care of the voltage level and frequency of the output power from PV system. As we get power from both solar panels and external grid power supply system, the voltage level and quality of power remain constant. Since power output of solar system may vary significantly, SPP of stand-alone systems has to have store of energy. Batteries bank parallel-connected to this system takes care of that. Batteries let us solve the issue of generation variability and inappropriate quality of energy generated by solar panels. Usually for this purpose deep discharge lead acid batteries are applied. These batteries have relatively high number of charge-discharge cycles which plays a very important role considering frequency of replacements of these elements over time. The battery sets available on the RES market are mainly of either 6 volt or 12 volts. In order to reduce charging currents batteries should be connected serially. In order to increase capacity of batteries bank they should be connected in parallel.

It is not desirable to exceed feasible charge level of lead acid batteries. Both overcharge and too deep discharge badly influence them. To avoid such situations a controller is required to attach with the system to maintain flow of current to and from batteries bank

.

Figure 24. – Deep-discharge batteries of FIAMM company [26]

While electricity produced in a solar panel is DC, electricity we draw from the grid is AC. So for running common equipment from grid as well as solar system, it is required to install an inverter to convert DC of solar system to AC of same level as grid supply. In stand-alone systems the inverter is directly connected to batteries bank so that DC coming from batteries is firstly converted to AC then goes to the load. In grid-connected system PV panels are directly connected to inverter and this inverter then feeds the grid with power of same parameters.

1.3.3 Methods of improving efficiency

Since efficiency of solar panels is still relatively low, people try to improve it by any means. While some factors (i.e. cloudiness, height of the Sun) cannot be changed, there a there are few ways how to influence on efficiency of usage of PV technology. It is not about improving PV technology as itself, but concerns conditions of sunshine delivery to solar panel.

The first method is related with angle of Sun rays falling on solar panel. The amount of sunlight falling on the surface of the panel at acute (or obtuse) angles is relatively less than at right angle. For instance, the table below shows energy losses by fixed PV panel in percents depending on azimuth angle. Caclulations performed for Penza city, Russia [27].

Table 7. – Energy losses of PV panel arising in connection with the Sun movement [27]

Azimuth angle of the Sun,˚	>50	45–50	40–45	35–40	30–35	25–30	20–25	15–20	10–15	5–10	0–5
Annual energy losses, % of feasible generation	44.44	2.14	1.31	0.92	0.69	0.53	0.38	0.26	0.14	0.05	0.01

Note: Reflected and scattered solar radiation were not taken into account.

We can see that non-perpendicularity of sunrays to the surface of solar panel causes high losses. There losses are avoidable if we keep right angle of the panel to the Sun. Such a tool tracks the Sun during the day and is called a solar tracking system [28]. Considering rotation axis, there are two types of solar trackers – single axis tracker (SAT) and dual axis tracker (DAT).

Usually, rotation axis of SAT moves along the North meridian (from north to south), but it can be oriented in any way. When rotational axis of SAT is horizontal it is called Horizontal single axis tracker (HSAT). Such a system has quite simple geometry and, if number of trackers is more than one, it requires rotational axes to be parallel to each other. There is a modification of HSAT that can be placed on a wall of some large buildings which is called Wall horizontal single axis tracker (WHSAT).

Vertical single axis tracker (VSAT) has a vertical rotation axis add rotates from east to west. At high latitudes it is more efficient than HSAT system. Usually working surface of VSAT has fixed tilt to rotation axis. Trackers with rotation axis between horizontal and vertical are considered as Tilted single axis trackers (TSAT).

The last type of SAT is Polar aligned single axis tracker (PASAT). This system orientates with respect to the pole star. Tilt of this tracker is equal to latitude of area of interest. It aligns rotation axis with the Earth’s spin axis.

DAT system has rotation axes which are usually independent but work together. DAT systems fall into two types – Tip-tilt dual axis tracker (TTDAT) and Azimuth-altitude dual axis tracker (AADAT). TTDAT is a long tower with a working surface at the top. Its main axis is horizontal. TTDAT field is a very flexible tracking system due to simple geometry, but in order to avoid shading when the Sun is low in the sky TTDAT fields have a low density of units. The main axis of AADAT is vertical. It is very similar to TTDAT, but has different way of rotation of working surface. Instead of rotation around upper pole of the towel, AADAT system uses large ring with rollers or bearing and is placed on the ground or platform. Such construction has a good distribution of tracker weight, but density of units is even less than for TTDAT.

Another method of improving conditions of sunshine delivery to PV panel is focusing (concentrating) solar radiation. There are two main ways how to direct more sunlight to the panel: by using reflectors or focusing lenses [28].

The most common example of concentrating lenses is Fresnel lens, named after French scientist. It has several sections with different angles and is lighter than usual lenses. There are two possible constructions: in a shape of a circle to provide point focus or is cylindrical shape to provide line focus.

The first type of reflecting technology is parabolic mirrors. In parabolic mirrors incoming light is reflected by the first mirror (collector) onto a second mirror, which also has parabolic shape and reflects the light beams to the center of collector onto the solar cell.

It is possible to use flat reflectors beside PV cell. The tilt of the mirrors depends on the inclination angle, latitude and the panel design, but is basically fixed. For this technology no cooling is required.

The last type of reflectors is luminescent concentrator. Here, light firstly is refracted in a luminescent film and then being channelled to PV panel. This is a very promising technology since it does not use any hard-to-handle reflectors such as mirrors and lenses. Furthermore, luminescent concentrators also work with diffuse light and hence do not require solar tracking system. Moreover, the film could be designed in a way that wavelenghts which cannot be converted by PV panel would just pass thruough. It results in removing of unwanted wavelenghts. No cooling is required.

Chapter II. Estimation of parameters for a solar power plant

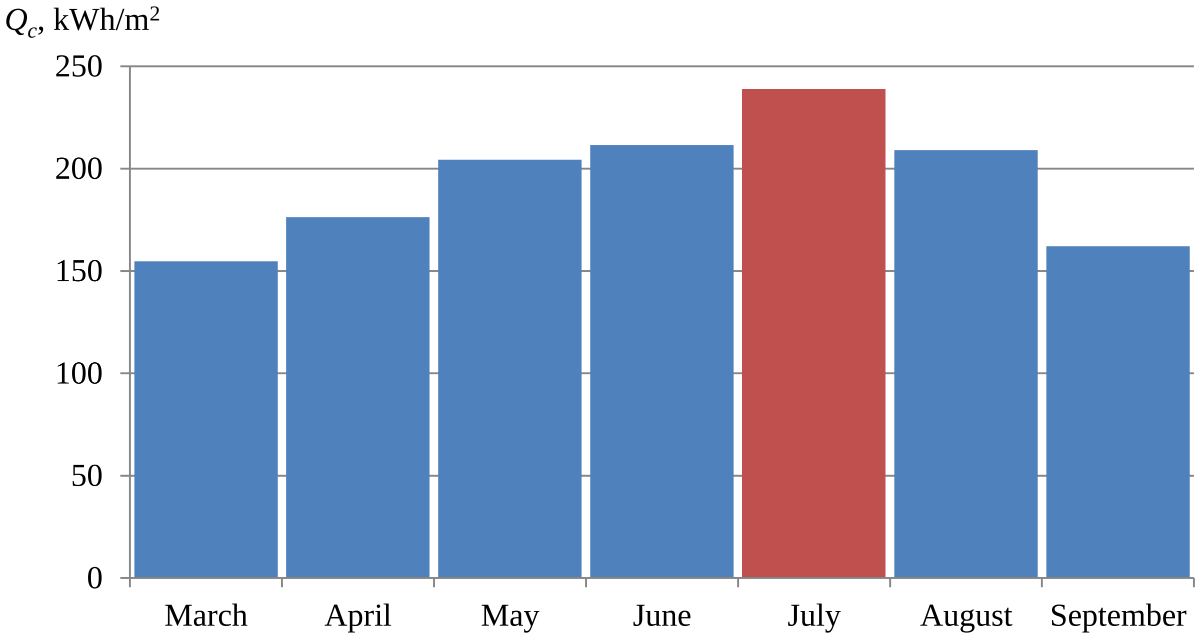
There are two variants of SPP considered. First one is to set up PV panels at fixed tilt and change it only once per season. Second one is to apply solar tracking system which will keep panels at close to right angle. Solar tracking will result in higher output of SPP. Increased efficiency will result in lower necessary capacity of the plant and consequently in lower square of SPP.

2.1 Calculation of the necessary number of photovoltaic panels

In order to calculate the necessary number of PV panels I use solar insolation data (computed in the previous section) and monthly data on electricity consumption of the village for 2015 year (provided by Interregional Distribution Grid Company of Siberia "Severobaikalsk electricity grids"). These input data are summarized in Tables 8–9 and Figures 25–26. The most favorable month for using PV panels is July because it is the most solar month. In other months it is reasonable to combine central electricity supply and solar power plant.

Table 8. – Solar insolation in the village Q_s per month

Solar insolation Q_s, kWh/m^2	March	April	May	June	July	August	September
	155	176	204	212	239	209	162
Tilt of PV panels, rad	π/3	π/6	π/12	π/12	π/12	π/6	π/4

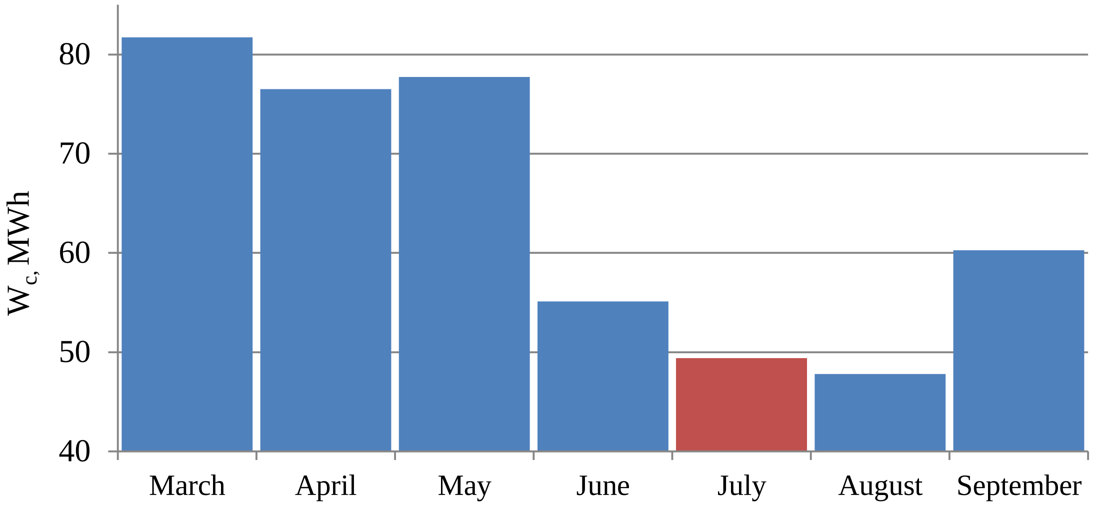


Source: Author's calculations.

Figure 25. – Solar insolation in Baikalskoe village

Table 9. – Electricity consumption W_C of Baikalskoe village during March –September 2015 [29]

W_C, kWh	March	April	May	June	July	August	September
	81740	76520	77720	55100	49400	47790	60270



Note: Red color reflects the most solar month in 2015.

Figure 26. – Electricity consumption W_C of Baikalskoe village [29]

In my calculations I use solar modules FSM-100 made by company Sunways. These panels suit the size of solar trackers which I use for estimation of parameters of SPP with application of solar tracking system. So, for comparison purposes I consider the same type of PV panels for both variants of SPP. The parameters of the module are presented in Table 10. Abbreviation expansion of FSM-100 is given below.

F – Fotoelektricheskiy – Photovoltaic;
S – Solnechnyy – Solar;
M – Modul – Module;
100 – 100 kWp.

Table 10. – FSM-100 parameters [51]

S, m^2	0.65
Price, RUB	7360
η,%	15.3
Dimentions lxwxh, mm	1209x539x35

In order to determine energy generation by solar panels I use monthly data of solar insolation in Baikalskoe village presented in Table 8. Solar insolation that PV panel could absorb during July 2015 can be estimated using the following formula [18]:

$$Q_G = Q_{cloud} \cdot \eta \cdot k, \tag{9}$$

where Q_{cloud}– monthly solar insolation on 1 square meter of solar panel, kWh/m^2;
η – coefficient of efficiency of solar panel;
k=0.5 – correction coefficient which takes into account non-perpendicularity of solar beams and solar panel [18].

Using formula (9) I estimate monthly specific energy production of FSM-100 in July 2015:

$$Q_{G,July} = Q_{cloud,July} \cdot \eta \cdot k = 239 \cdot 0.153 \cdot 0.5 = 18.26 \text{ kWh/m}^2.$$

Monthly energy production of FSM-100 [18]:

$$W_G = Q_G \cdot S, \tag{10}$$

where S – area of PV panel, m^2.

$$W_{G,July} = Q_{G,July} \cdot S = 18.26 \cdot 0.65 = 11.9 \text{ kWh}.$$

The necessary number of solar panels for SPP with fixed position of PV panels can be estimated as [18]:

$$n_{PV} = \frac{W_C}{W_G}. \tag{11}$$

For coverage of July’s consumption using FSM-100 SPP should have

$$n_{FSM} = \frac{W_{C,July}}{W_{G,July}} = \frac{49\,400}{11.9} = 4152 \text{ units.}$$

Coverage of consumption by PV panels [18]:

$$\Delta = \frac{W_G \cdot n_{PV}}{W_C} \cdot 100\%. \tag{12}$$

Coverage of consumption in July by the chosen panels:

$$\Delta = \frac{W_{G,July} \cdot n_{FSM}}{W_{C,July}} \cdot 100\% = \frac{11.9 \cdot 4152}{49\,400} \cdot 100\% = 100.02\%.$$

Calculation results for other months are shown in Table 11. There we can see which part of energy consumption can be covered by the chosen panels during the year.

Table 11. – Calculation results for electricity generation

Month	Consumption	Generation	Shortage	Δ
	MWh			%
January	114.4	17.5	96.9	15.3
February	96.56	26.06	70.5	27
March	81.74	32.01	49.73	39.2
April	76.52	36.46	40.06	47.7
May	77.72	42.29	35.43	54.4
June	55.1	43.79	11.31	79.5
July	49.4	49.4	0	100
August	47.79	43.27	4.52	90.5
September	60.27	33.53	26.75	55.6
October	75.52	28.35	47.17	37.5
November	85.7	22.95	62.75	26.8
Dececmber	74.76	15.71	59.05	21
Annual	781.08	373.82	407.26	47.9

Source: Baikalskoe village consumption data of 2015; author's calculations.

Taking into account solar insolation and consumption of the village in July 2015, the necessary number of PV panels for the first variant should be 4 152 units and installed capacity of the plant equals 415.2 kW. This number of PV panels is able to cover electricity needs during July. In this case the panels' tilt is constant so it makes sense to change the tilt at least once per season. Also it is necessary to highlight that the generation of PV panels reduced due to non-perpendicularity of solar beams and the panel's surface. But in the second variant of SPP solar trackers are used to minimize this deviation and to increase the efficiency of PV panels. Usually usage of solar trackers is not economically efficient because of the fact that its price roughly equals the price of all PV panels when the tracker system adds just 20–30 % of basic efficiency. However, the officers of Tomsk Polytechnic University have created a cheaper solar tracker with 32% adjustment to panel's efficiency [30]. By using these trackers the number of PV panels has been reduced down to 3152 units and installed capacity in this case equals 315.2 kW.

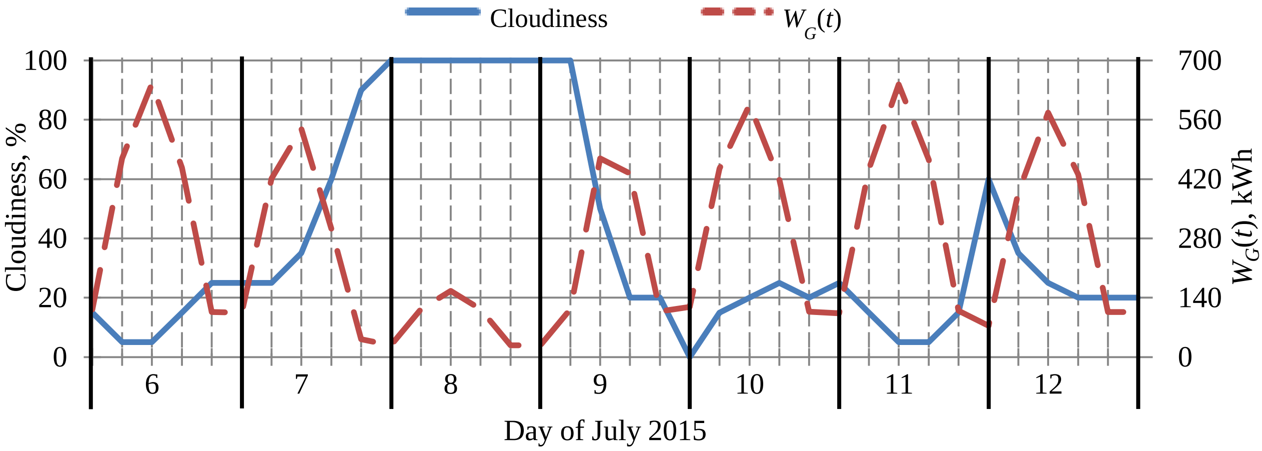
2.2 Calculation of battery storage capacity for July 2015

2.2.1 Electricity generation: patterns and dynamics

The energy generated by PV panels depends on the amount of solar radiation incoming on the panel surface. The main factor that reduces solar insolation is cloudiness. So, calculation of electricity generation is based on data of cloud amount in 2015 year [31] for the nearest meteorological station (Nizhneangarsk city) and also on sunshine duration [32]. The sunshine data of the village in July 2015 is provided in Appendix 3.

From Appendix 3 we can see that the longest duration of the sunshine in Baikalskoe village was observed on the 1st of July. Sunrise and sunset were observed at 4:05 and 21:31, respectively. I rounded it up to 17.5 hour time period of sunshine and divided into five time zones each of 3.5 hours. There are also two time zones without sunshine in a day: from 0:00 to 4:00 and from 21:30 to 24:00. Thus, I have seven time zones in a day and the Sun is shining during five of them.

For time zones of sunshine I averaged the amount of clouds and computed the energy that could be generated by solar panels. Calculation results are shown in Appendix 4. The graph below shows changes of cloudiness and energy generation across time zones of sunshine during the second week of July 2015 and is based on data in Appendix 4.



Source: Wind statistics of Baikalskoe village for July 2015; author’s calculations.

Notes: $W_G(t)$ – energy generated by solar panels, kWh. Solid black lines divide the graph area into seven days. Dashed vertical separation refers to time zones when there is sunshine (II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30). Time zones of darkness (I – 0:00 – 4:00 and VII – 21:30 – 24:00) are excluded from the graph because there is no energy generation. The graph for the whole month is shown in Appendix 5.

Figure 27. – Changes of cloudiness and energy generation $W_G(t)$ across time zones of sunshine during the second week of July 2015

From Figure 27 we can see that energy generation strongly depends on amount of clouds – the more cloudy sky, the less energy is generated by solar panels. For instance, cloudiness reaches 100% on the 8th of July 2015 and the peak of energy generation at noon of this day is much lower than in other days. Such a decline in generation can result in the increase of total capacity of batteries in order to cover electricity needs.

During the day the amount of clouds in the sky changes all the time. It leads to lowering of power output of PV installations and this is the main disadvantage of this technology [28]. As I mentioned in section 1.2.2, solar insolation near Lake Baikal is higher than in other areas around. This is most likely connected with high water evaporation of such a large lake which leads to clouds slipping away from the area of the lake. But the reason of high insolation there is not of great importance in our case and I consider it as it is.

In order to analyze the behavior of both cloudiness and energy generation the coefficients of variation (CV) are calculated. Since generation changes through time zones and is related to position of the Sun in the sky, five CV for each variable have been obtained (one for each time zone) and summarized in Table 12.

Table 12. – Average values of cloudiness $\bar{C}$ and energy generation $\bar{W}_G$ in July 2015 and their CV

Time zone	$\bar{C}$, %	CV_C, %	$\bar{W}_G$, kWh	CV_G, %
II	22,3	126	98	22
III	21,6	115	412	21
IV	20,2	105	574	18
V	21,9	96	414	17
VI	24,7	94	97	21

As we see from the table above, average values of cloudiness are just around 20% but coefficients of cloudiness variation CV_C are significantly high. We can therefore say that cloudiness has too many extremes and it results in low informative value of CV_C.

But despite the fact that cloudiness varies significantly we can see that coefficient of variation of energy generation CV_G is just around 20%. It can be explained as follows: PV panels generate electricity not only from direct solar beams, but they are also affected by reflected and scattered solar radiation which are also contribute some part to energy generation.

Analysis of generation results (partially reflected in Figure 27) shows that indirect solar radiation contribute about 24% to power output of solar panels. Another reason of relatively small value of CV_G is that the number of time zones with medium and extremely high values of cloudiness is relatively small in comparison with the number of time zones with low and extremely low values of cloudiness.

In order to describe electricity consumption of Baikalskoe village I use typical load curve of rural areas [33]. Since it is given in relative units, I need to transform it to absolute values. The first step to obtain load curve in absolute values is to find the average amount of energy consumed per day in July 2015 as follows:

$$\bar{W}_{daily} = \frac{\sum W_{daily,July}}{31} = \frac{W_{July}}{31} = \frac{49\,400}{31} = 1593.6 \text{ kWh.} \tag{13}$$

This amount of energy consumed per day is given in kWh and reflects the amount of energy in % given in [33] which is equal to 1 400% of maximum load per day. Formula (9) allows to find loads in every hour of the day.

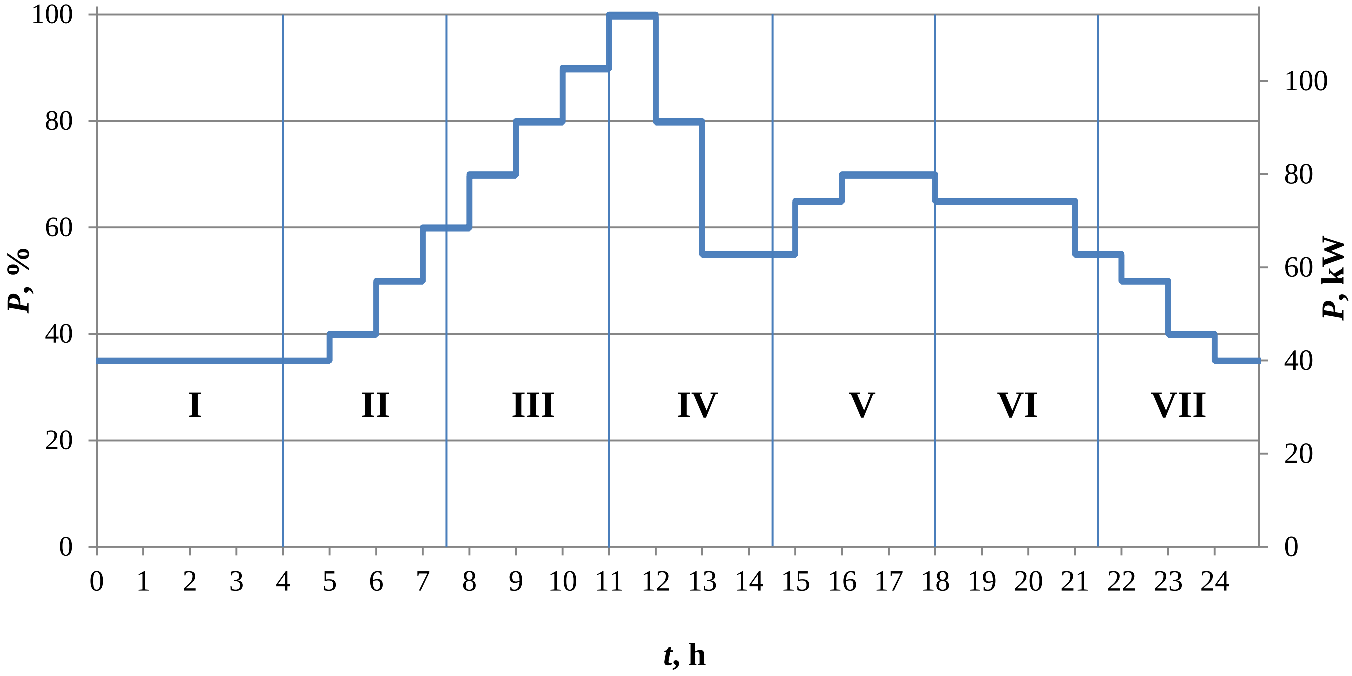
$$P_i = \frac{\bar{W}_{daily,kWh}}{\bar{W}_{daily,\%} \cdot t} \cdot P_{i,\%}, \tag{14}$$

where $\bar{W}_{daily,\%}$ – the relative amount of energy consumed per one day, %;
$P_{i,\%}$ – the relative value of the load, %;
t – 1 hour duration of $P_{i,\%}$, h.

For instance, the load maximum in the average day of July 2015 will be:

$$P_{\max,\ July} = \frac{\bar{W}_{daily,kWh}}{\bar{W}_{daily,\%} \cdot t} \cdot P_{\max,\%} = \frac{1\,593.6}{1\,400\% \cdot 1} \cdot 100\% = 113.83 \text{ kW}.$$

Obtained load curve of Baikalsoe village in July 2015 is shown below.



Source: Online Electrician Database; author's calculations.

Notes: Vertical lines divide load curve into time zones. Time zones are named by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00).

Figure 28. – Daily load curve in Baikalskoe village across time zones in July 2015

In my further calculations I will use amounts of energy consumed in each time zone of the day. To calculate them I use the following formula [7]:

$$W_C = \sum_t P_i \cdot t_i, \tag{15}$$

where W_C – Energy consumed during time t, kWh;
P_i – i level of the load, kW;
t_i – duration of the load P_i, h.

Example of calculation of consumption for the first time zone is shown below. Results of my calculations are shown in Table 13.

$$W_{C1} = \sum_0^4 P_i \cdot t_i = 39.8 \cdot 4 = 159.2 \text{ kWh}.$$

Table 13. – Energy consumption W_C across time zones in July 2015

Time zone	I	II	III	IV	V	VI	VII
W_C, kWh	159	176	307	299	265	253	134

In the next section I evaluate the number of batteries and the level of its charge and discharge by combining generation and consumption data of Baikalskoe village during July 2015.

2.2.2 Computation of charge and discharge dynamics of batteries

Generation by solar power plant (SPP) and consumption by the village may vary significantly. To maintain electricity supply during low generation (e.g. night time) and to deal somehow with excess energy during peaks of generation SPP should have a batteries bank. Evaluation of different batteries performed in [34] picked up the optimum model of battery for application in SPP. Therefore, I choose the same model: deep discharge batteries LM OPzS 3500 of company FIAMM with nominal capacity of 3500 Ah and nominal voltage of accumulator cell of 2 V [26]. Abbreviation expansion is given bellow.

LM – Low Maintenance;
The abbreviation *OPzS* is German, and refers to German standard *DIN* 40737 [35].
O: Ortsfest = Stationary;
Pz: Panzerplatte = Tubular plate (+);
S: Spezial = Special, fluid electrolyte with special separator.

In order to reduce charging currents these cells should be connected serially to give 48 V (i.e. 24 series-connected cells). Such accumulation battery has nominal capacity E_B = 3500 Ah and nominal voltage U_B = 48 V. In order to prolong battery's lifetime its feasible depth of discharge k_d equals 70%. It means that in fact I can use only 70% of batteries capacity. In view of this, necessary capacity of batteries E_C can be estimated as follows [34]:

$$E_C = \frac{W_{daily}}{U_B k_d}, \tag{16}$$

$$E_C = \frac{W_{daily}}{U_B k_d} = \frac{1593.6}{48 \cdot 0.7} = 47.43 \text{ kAh}.$$

Then the number of parallel-connected batteries N_B can be found by dividing E_C on E_B:

$$N_B = \frac{E_C}{E_B}, \tag{17}$$

$$N_B = \frac{E_C}{E_B} = \frac{47.43 \cdot 10^3}{3\,500} = 13{,}55 \approx 14.$$

Thus, total capacity of batteries bank is:

$$E_{total} = E_B \cdot N_B, \tag{18}$$

$$E_{total} = E_B \cdot N_B = 3\,500 \cdot 14 = 49\,000 \text{ Ah}.$$

Multiplication of this value by voltage of parallel-connected batteries (48 V) gives us expression of batteries bank capacity in kilowatt hours (2352 kWh).

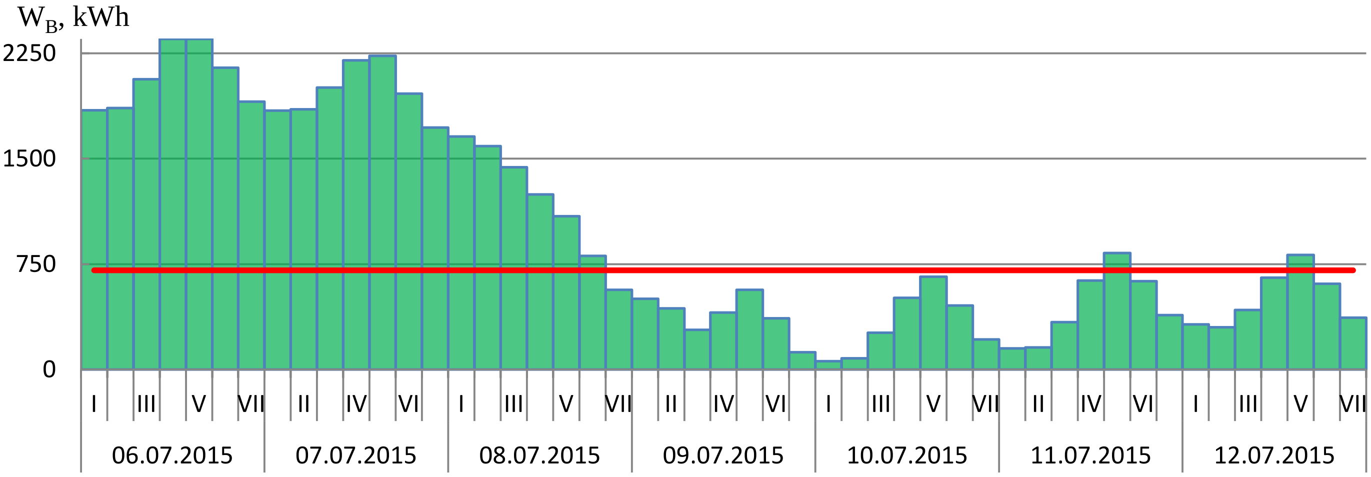
To be sure that the batteries do not exceed feasible range of discharge I perform calculation of charge and discharge dynamics of those batteries for July 2015 based on Appendix 4 and Figure 28 assuming that initially those batteries are fully charged (E_{B0} = 49 000 Ah or W_{B0} = 2 352 kWh).

The charge level of batteries is calculated as follows:

$$W_B(t+1) = W_B(t) - W_C(t) + W_G(t), \tag{19}$$

where $W_B(t+1)$ – the charge level of batteries at time (t+1), kWh;
$W_C(t)$ – energy consumed at time t, kWh;
$W_G(t)$ – energy generated at time t, kWh;
t – time zone, h.

Obtained data are summarized in Appendix 6. The graph below shows changes of the charge level of 14 parallel-connected batteries during the second week of July 2015 and is based on Appendix 6.

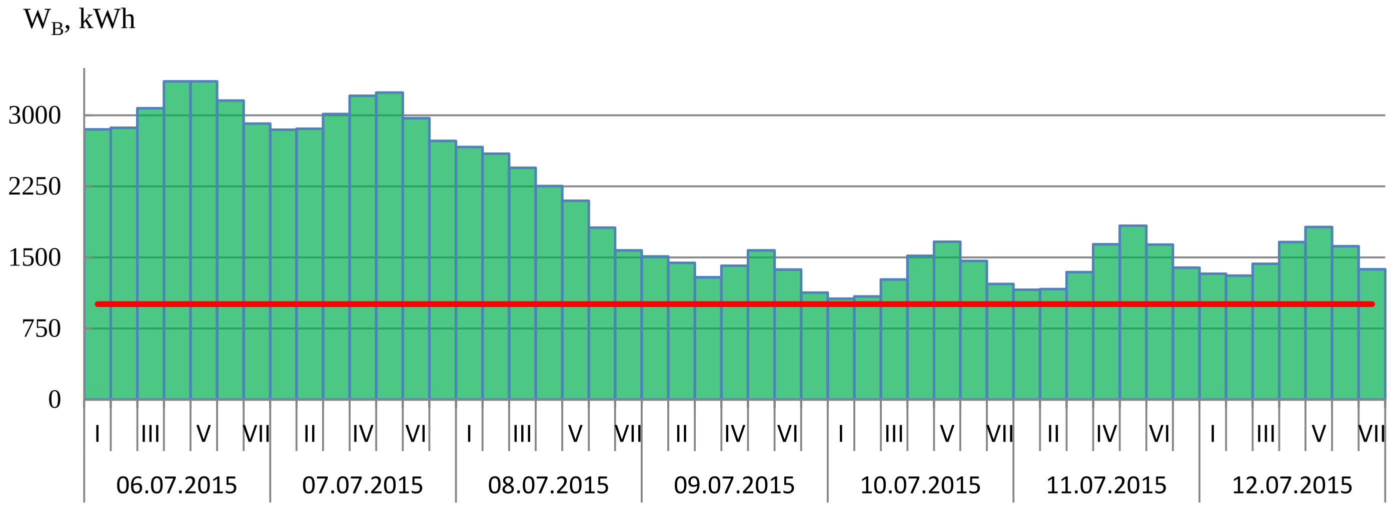


Source: Author's calculations.

Notes: Red line reflects the lowest appropriate level of charge for batteries which is 30%. Time zones are shown by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00). This graph for the whole month is shown in Appendix 7.

Figure 29. – The charge level of 14 parallel-connected batteries during the second week of July 2015

In Figure 29 the minimum level of charge of batteries is also shown. As I noticed in the previous part, low generation caused by high cloudiness on 8th of July 2015 results in deep discharge of batteries. From Figure 29 we can see that the charge of batteries bank exceeds feasible range so it is necessary to increase the number of parallel-connected batteries from 14 up to 20. The results for July 2015 are presented in Appendix 8 and Figure 30. The graph below shows changes of the charge level of 20 parallel-connected batteries during second week of July 2015 and is based on Appendix 8.



Source: Author's calculations.

Notes: Red line reflects the lowest appropriate level of charge for batteries which is 30%. Time zones are shown by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00). This graph for the whole month is shown in Appendix 9.

Figure 30. – The charge level of 20 parallel-connected batteries during the second week of July 2015

The deepest discharge of batteries bank of 68% is observed on 10 of July 2015 and it is acceptable for the chosen batteries. Thus, to supply the village in the most solar month only with energy generated by SPP total capacity of batteries should be E_{total} = 63 000 Ah (or W_{total} = 3 360 kWh). The number of accumulator cells $N_{C\ total}$:

$$N_{C\ total} = N_B \cdot N_C,$$

$$N_{C\ total} = N_B \cdot N_C = 20 \cdot 24 = 480 \text{ cells.}$$

Since each FIAMM LM OPzS 3500 has four accumulator cells the number of OPzS 3500 is 120 units.

In order to maintain power supply of consumers even in case of grid outages I decided to apply the first type of SPP from section 1.3.1. Scheme of such a plant was shown in Figure 20.

For keeping charge level of batteries within feasible range and consequently to prolong batteries lifetime controllers are used. For the size of USP proposed in this work the appropriate to use controllers of relatively high nominal power. Thus, I choose ECO MPPT Pro 200/100 controller produced by MicroART company and designed for PV systems.. This controller can deal with PV capacity up to 11 kW. Total installed power of PV panels connected to the controller should be less than its maximum power. That is why I connect PV panels' complex of 10 kW to one controller unit. 10 kW of chosen PV panels is 100 units. So, SPP without solar trackers requires 42 controllers and SPP with solar trackers – just 32.

Abbreviation expansion for ECO MPPT Pro 200/100:

ECO – Ecofriendly energy;
MPPT – Maximum Power Point Tracking;
Pro – Professional;
200/100 – Maximum input voltage is 200 V/ maximum charge current is 100 A.

To supply consumers with AC electricity inverters are used. In order to avoid loss of large capacities in case of inverters' breakdown all installed capacity should be divided between a number of inverters. It will provide higher reliability of SPP: in case of inverter breakdown SPP loses small number of PV panels and can continue feeding the load. RES market has various models of inverters proposed by a number of companies. One of the companies which have excellent reputation in RES market is SMA company. It make sense to find an inverter which has nominal power multiple of controller nominal power. From their equipment list I choose STP 20000TL with maximum DC power of 20.44 kW. Two controllers will be connected to one inverter and to batteries bank. So, SPP without solar trackers requires 21 inverter and SPP with solar trackers – just 16.

Abbreviation expansion for STP 20000TL:

STP – Sunny TriPower;
20000 – nominal power of 20 000 W;
TL – TransformerLess.

For the case of SPP with solar tracking system I apply solar trackers ST-800 designed by Solar Technic company. Such a tracker can contain 8 FSM-100 panels. So, SPP with solar trackers requires 394 units of ST-800.

Abbreviation expansion for ST-800:

ST – Solar Tracker;
800 – installed capacity of 800 W.

Chapter III. Techno-economic comparison of supply scheme scenarios

There are two possible solutions to the existing issue of Baikalskoe power supply. Traditional solution for the task of improvement of power supply system is to replace existing OTL 10 kV with OTL 35 kV. The main advantage of such solution is that power transmission on a higher voltage class results in lower power and voltage losses which are directly connected to the line lengh. However, considering relatively low power consumption of the village, the construction costs of such OTL are expected to be too high to apply this scenario.

Alternative solution for this task is application of local or distributed generation (DG) which can be implemented to existing power supply system. In terms of DG an economically attractive solution for the electrification task could be RES. Renewable power has two main advantages: many technologies have no fuel expenses and generally they are environmentally friendly. The drawback of RES is their variability over time meaning that sometimes they can be just not available [8].

Due to the new requirements to quality and reliability of power supply, the grid company has to either replace the current power line with a higher voltage power line in terms of centralizing strategy, or to build a local power plant in order to use it in combination with the current power line.

Calculation of costs of OTL replacement by higher voltage OTL is performed using consolidated index of construction cost. Considering type of poles, the traditional solution falls into two scenarios: using either metal or reinforced concrete poles.

Possible sources for a new power plant were evaluated in the first chapter. According to it, solar power in the area of interest has a high potential. Considering the orientation of PV panels, the nontraditional scenario is divided into the following two subscenarios: using fixed mount system and using solar tracking system. The necessary equipment was evaluated in the second chapter. In this chapter the economical comparison of possible alternatives is performed.

3.1 Consolidated index of construction cost for switching to a higher voltage power line

Estimation of construction cost of a higher voltage class OTL is performed using consolidated indices of construction cost (CICC) of 35 kV power grids [36, 37].

CICC are given in base values (on 01.01.2000) and do not include value added tax (VAT). Estimation of construction cost in current values is performed by using sector indices of cost recalculation (in accordance with order of OJSC “FGC UES”). CICC take into account all costs of OTL construction for industrial purposes. CICC of OTL take into account ice and wind loads and meet the requirements of [38]. CICC for OTL supported by steel and reinforced concrete poles are shown in Table 14.

Table 14. – CICC for AC OTL supported by steel and reinforced concrete poles [36]

Voltage class of OTL, kV	Type of towers/poles	Cross-sectrion of steel-cored aluminum wire, mm^2	Number of circuits	CICC for OTL, thsd RUB/km		
				Latticed steel towers	Steel poles	Reinforced concrete poles
35	Self-supporting	95	1	–	635.1	452.6*
			2	–	901.8	687.5
		Up to 150	1	–	754.6	576.0*
			2	927.8	988.6	852.4*

Notes: * angle-tension poles/towers are steel.

In order to obtain full construction costs we add associated costs, which are:

- 3.3% – temporary facilities ($k_1 = 1.033$);
- 5.0–6.0% – miscellaneous works and expenditures. Minimal value is applied for objects which have total cost of main components more than 100 mln RUB in base value. Maximal value is applied for objects placed in remote regions with lack of main production resources. Since Baikalskoe village falls into second definition I apply 6.0% ($k_2 = 1.06$);
- 2.6–3.18% – maintenance of construction manager activity and construction compliance monitoring. The value of percentage depends on construction costs and is defined by Guidelines for estimation of rate maintenance costs of construction manager activity [39];
- 7.5–8.5% – survey and design works, costs of the expert examination of project documentation and design supervision (8% for the new construction; $k_4 = 1.08$);
- 3% – unforeseen expenses ($k_5 = 1.03$).

Costs of right-of-way clearing is estimated for the forest of medium height and bushiness taking into account stump removal for roads and bearing area for poles. For the cases of lack of information, these costs can be defined by Table 15.

Table 15. – Costs of right-of-way clearing and plank roads [36]

Name of work item	Voltage class of OTL, kV					
	35	110	220	330	500	750
right-of-way clearing, thsd RUB/km	105	165	275	330	389	550
plank roads, thsd RUB/km	193–780					

In order to take into account additional costs caused by complicating conditions of construction the following coefficients can be applied.

Table 16. – Coefficients for complicating conditions of OTL construction [36]

#	Conditions of construction	Coefficient
1	Mountains/rocky ground	1.012
2	Urban and industrial development area	1.013
3	Wetlands	1.053
4	Impassability and first bottom	1.028
5	Nearby objects under voltage	1.018
6	Wind pressure 0.61–0.75 kPa	1.003
7	Wind pressure more than 0.75 kPa	1.006

From the table above we need to apply coefficients #1 (k_{rg} = 1.012) and #3 (k_{wl} = 1.053). Since consumers belong to the first category, OTL have only one circuit. Total costs of OTL construction without first five associating costs mentioned above can be calculated using the following formula:

$$\sum C^{OTL} = l_{OTL} \cdot (C^{OTL} + C_{clearing} + C_{road}), \tag{20}$$

where l_{OTL} – the length of OTL, km;

C^{OTL}, $C_{clearing}$, C_{road} – relative costs of OTL construction, right-of-way clearing and plank road construction, respectively, thsd RUB/km.

Using the formula above I found total costs of OTL construction for cases of steel and reinforced concrete poles:

$$\sum C^{OTL}_{steel} = l_{OTL} \cdot (C^{OTL}_{steel} + C_{clearing} + C_{road}) = 35.509 \cdot (635.1 + 105 + 193) = 33133.45 \text{ (thsd RUB)},$$

$$\sum C^{OTL}_{RC} = l_{OTL} \cdot (C^{OTL}_{RC} + C_{clearing} + C_{road}) = 35.509 \cdot (452.6 + 105 + 193) = 26\,653.06 \text{ (thsd RUB)},$$

where C^{OTL}_{steel} – relative cost of OTL construction using reinforced concrete poles, thsd RUB/km;

C^{OTL}_{RC} – relative cost of OTL construction using metal poles, thsd RUB/km.

From these values I found coefficients for associating cost of maintenance of construction manager activity and construction compliance monitoring. For steel poles k_3=0.0318, for reinforced concrete poles k_3=0.031 [39].

In view of the above, total cost of OTL construction in base values with associated expenses can be calculated using the following formula:

$$\sum C^{OTL}_{as} = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_{rg} \cdot k_{wl} \cdot \sum C^{OTL}. \tag{21}$$

In case of steel poles

$$\sum C^{OTL}_{steel,as} = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_{rg} \cdot k_{wl} \cdot \sum C^{OTL}_{steel} =$$
$$= 1.033 \cdot 1.06 \cdot 1.0318 \cdot 1.08 \cdot 1.03 \cdot 1.012 \cdot 1.053 \cdot 33133.45 = 44\,375 \text{ (thsd RUB)},$$

and in case of reinforced concrete poles

$$\sum \mathrm{C}_{RC,as}^{OTL} = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_{rg} \cdot k_{wl} \cdot \sum \mathrm{C}_{RC}^{OTL} =$$
$$= 1.033 \cdot 1.06 \cdot 1.031 \cdot 1.08 \cdot 1.03 \cdot 1.012 \cdot 1.053 \cdot 26\,653.06 = 35\,668.25 \text{ (thsd RUB)}.$$

In both cases it is necessary to use transformers for a new power line on both line-ends. Transformer bays are given in [37]. CICC of transformer take into account all equipment installed (transformer, cables, switch panel, relay panel, flexible connections of transformers and others), materials and constructing works. I choose transformer bay with nominal power of transformer of 2.5 MVA which costs 1 290 thsd RUB in base value.

Using sector indices [40] for Siberian Federal District I recalculate construction costs of OTL and substations in current values. For Buryatia Republic there are indices $i_{OTL} = 4.87$ for OTL and $i_{oth} = 7.63$ for substations. Total investment in construction of OTL and substations in current values can be calculated using formula:

$$\sum \mathrm{C}_{steel}^{current} = i_{OTL} \cdot \sum \mathrm{C}_{steel,as}^{OTL} + i_{oth} \cdot n_{Tr} \cdot C_{Tr} \tag{22}$$

where n_{Tr} – the number of transformer bays;
C_{Tr} – CICC of transformer bay, thsd RUB.

Then, in case of steel poles total investment will be

$$\sum \mathrm{C}_{steel}^{current} = i_{OTL} \cdot \sum \mathrm{C}_{steel,as}^{OTL} + i_{oth} \cdot n_{Tr} \cdot C_{Tr} = 4.87 \cdot 44\,375 + 7.63 \cdot 2 \cdot 1\,290 =$$
$$= 235.79 \text{ (mln RUB)},$$

and in case of reinforced concrete poles

$$\sum \mathrm{C}_{RC}^{current} = i_{OTL} \cdot \sum \mathrm{C}_{RC,as}^{OTL} + i_{oth} \cdot n_{Tr} \cdot C_{Tr} = 4.87 \cdot 35\,668.25 + 7.63 \cdot 2 \cdot 1\,290 =$$
$$= 193.39 \text{ (mln RUB)}.$$

In order to estimate economy from OTL replacement, energy losses in power line are calculated using annual average value of current [41]. Annual average value of current can be found using the formula below:

$$I_{ann}^{avg} = \frac{W_{ann}}{\sqrt{3} \cdot U_n \cdot T_{ann} \cdot \cos\varphi}, \tag{23}$$

where U_n – nominal voltage of OTL, kV;
T_{ann} – operating time of OTL, h;
$\cos\varphi = 0.85$ – power factor [Consumption_2015].

Annual average value of current in 10 kV OTL with AS–70 wire (resistance r_0 = 0.428 Ohm/km [7]) is calculated below. Abbreviation expansion of AS-70 is given below the example.

$$I_{ann,10kV}^{avg} = \frac{W_{ann}}{\sqrt{3} \cdot U_n \cdot T_{ann} \cdot \cos\varphi} = \frac{1\,362\,547 \cdot 10^3}{\sqrt{3} \cdot 10 \cdot 10^3 \cdot 8\,760 \cdot 0.85} = 10.57 \text{ A.}$$

AS – Stalealyuminevyy provod – steel-cored aluminum wire;
70 – cross-section of aluminum part of a wire, mm^2 [7].

Energy loss in a wire is caused mainly by resistance heating. It is expressed by the following formula:

$$\Delta W_P = n_p \cdot (I_{ann}^{avg})^2 \cdot \frac{r_0 \cdot l_{OTL}}{n_c} \cdot T_{ann} \tag{24}$$

where n_p – the number of phases in a wire;
r_0 – resistance of AS – 70 wire, Ohm/km;
n_c – the number of circuits in OTL.

Annual energy loss in AS–70 wire at 10 kV:

$$\Delta W_{P,10kV} = n_p \cdot (I_{ann}^{avg})^2 \cdot \frac{r_0 \cdot l_{OTL}}{n_c} \cdot T_{ann} = 3 \cdot 10.57^2 \cdot \frac{0.428 \cdot 35.509}{1} \cdot 8\,760 = 44\,580 \text{ kWh/yr.}$$

In case of switching to a higher voltage class annual average value of current in AS–95 (minimal cross-section for 35 kV) wire (with resistance r_0 = 0.306 Ohm/km [7]) is:

$$I_{ann,35kV}^{avg} = \frac{W_{ann}}{\sqrt{3} \cdot U_n \cdot T_{ann} \cdot \cos\varphi} = \frac{1\,362\,547 \cdot 10^3}{\sqrt{3} \cdot 35 \cdot 10^3 \cdot 8\,760 \cdot 0.85} = 3.02 \text{ A.}$$

Annual energy loss in AS–95 wire at 35 kV:

$$\Delta W_{P,35kV} = n_p \cdot (I_{ann}^{avg})^2 \cdot \frac{r_0 \cdot l_{OTL}}{n_c} \cdot T_{ann} = 3 \cdot 3.02^2 \cdot \frac{0.306 \cdot 35.509}{1} \cdot 8\,760 = 2\,602 \text{ kWh/yr.}$$

Annual energy savings from replacement of 10 kV OTL by 35 kV OTL is the difference between annual energy losses of these wires:

$$\Delta W_{P,ec} = \Delta W_{P,10kV} - \Delta W_{P,35kV} = 44\,580 - 2\,602 = 41\,978 \text{ kWh/yr.}$$

Money savings are calculated as a product of annual energy savings and electricity tariff for household consumers of the village. Electricity tariff is discussed later in this chapter.

Maintenance and other cost of OTL, including partial replacement of small parts of OTL (i.e. strings) are set as 0.05% of investment per annum.

The company uses straight-line depreciation [42]. OTL has 6th depreciation group with economic lifetime of 11–15 year. Transformer bay has 7th depreciation group with lifetime of 16-20 years. The most favorable way of depreciation is to pick the shortest period from proposed range. So, I apply 11 year depreciation period for OTL and 16 year depreciation period for transformer bays. However, useful life of 35 kV OTL is supposed to be no less than 50 years [7]. According to [43], estimated period of time required for construction of 35 kV OTL (with OTL length shorter than 50 km) is up to 2 years. Thus, lifetime of replacement project is 52 years.

Since IDGC of Siberia is a large energy company tax shield can be applied for reduction of tax payment. Thus, in years with negative value of tax it is considered as savings of company‘s money.

In order to evaluate cash flows for these projects I use the following rates.

- Average inflation rate in Russia is 4.5%. According to [44] this rate in Russia will be up to 5% till 2020. It is very similar to forecasts given by The Ministry of Economic Development of the Russian Federation [45] which also shows that inflation in 2021-2025 is estimated as 3.9% maximum per year, in 2026–2030 as 3% maximum per year. Average annual inflation for the period 2016–2030 is estimated as 3.8%. In order to avoid underestimation of this parameter, in my calculations I assume inflation rate of 4.5%.

- Inflation rate for German equipment prices is 2.5%. Nowadays technologies prices will decrease through the time because of displacement by new technologies. Part of equipment used in in my calculations is produced in Germany. Some of them should be replaced few times during the project. To estimate future prices of such equipment more precisely I use a forecast for producer prices change in Germany [46]. According to it, inflation rate for equipment is expected to be 2.3%. In my calculations I round it up to 2.5%.

- Inflation rate for Russian equipment prices is 4.1%. Similarly to inflation rate for German equipment prices, I use a forecast for producer price changes in Russia [44].

- Inflation rate for electricity price is equal to average inflation rate which is 4.5%. In Baikalskoe village electrical energy is used for household purposes. Looking at the price of electricity across the years which is shown in the Figure below we can see that it has significantly more ups than downs. But it has deceleration trend, so I assume that in future electricity tariff for household consumers will rise not faster than with average inflation speed.

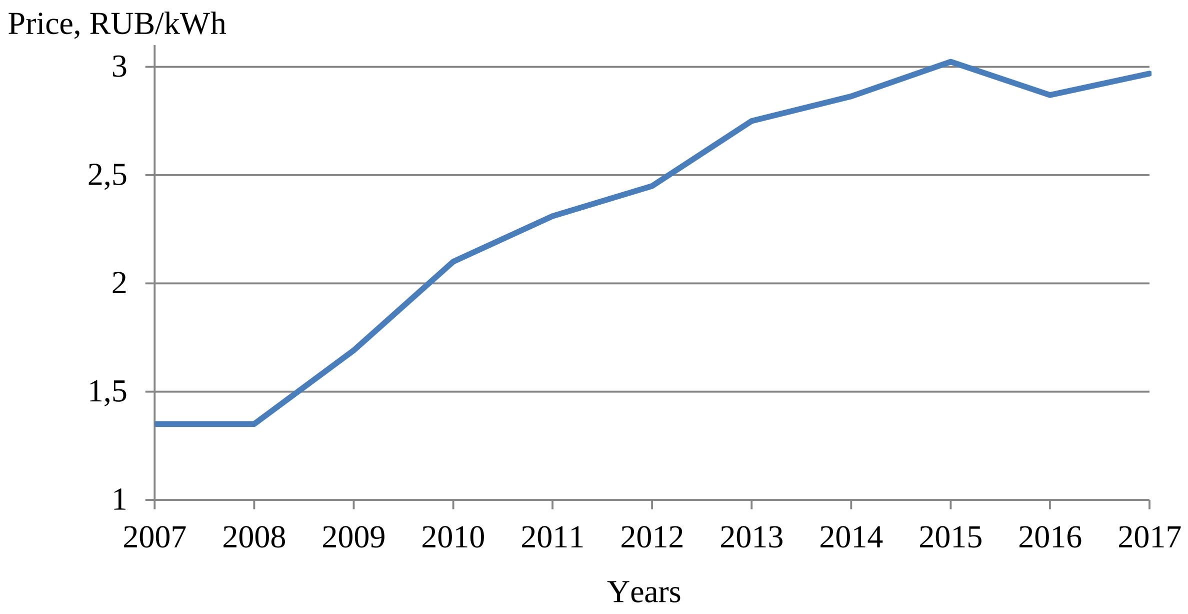


Figure 31. – Electricity tariff changes in the Republic of Buryatia, Russia, for household consumers in 2007–2017 [47]

- PJSC "IDGC of Siberia" is a subsidiary of PJSC ROSSETI – the operator of energy networks in the Russian Federation. The controlling shareholder is the State represented by the Federal Agency of the State Property Administering of the Russian Federation that owns 87.9% of capital share [48]. In view of the above, and also taking into account reasons mentioned in section of Statement of the problem, discount rate for the project should be equal to government securities from PJSC "IDGC of Siberia" point of view. According to the Central Bank of the Russian Federation, government securities yield rate of Russia is 8.445% [49]. Thus, in my calculations I use discount rate of 8.445%.

- Corporate tax rate is 20% [50].

Calculation results for 35 kV OTL construction are shown in Table 17 below.

Table 17. – Calculation results for construction of 35 kV OTL

Economic parameter	OTL supported by steel poles	OTL supported by reinforced concrete poles
Investment, mln RUB	235.79	193.39
NPV, mln RUB	–221.07	–181.86

3.2 Hybrid power supply system without solar trackers

Equipment prices and number of units required for the scenario of SPP without solar trackers are shown in Table 18.

Table 18. – List of chosen equipment with its prices and lifetimes for scenario of SPP without solar trackers [26, 51, 52, 53, 54]

Equipment	Price of the unit, RUB	The number of units required	Lifetime of the unit, yrs
Sunways FSM-100M	4 505	4152	25
FIAMM LM OPzS 3500	76 050	120	25
Electrolyte, 1 liter	59.78	6720	–
Racks E-PGV 2-68 SH	142 752.5	4	–
SMA Sunny Tripower 20000TL	251 334	21	25
ECO MPPT Pro 200/100	40 900	44	6

Prices of batteries, electrolyte and racks already include transportation costs. Using instructions [55] cost of delivery of the rest equipment is estimated and rounded up to 80 000 RUB.

In order to avoid damaging of batteries by deep discharge and overcharge charge-controllers are used.

According to producer’s information, estimated lifetime of LM OPzS is 20 years under float condition [56]. But lifespan of batteries strongly depends on depth of discharge (DoD) during the main number of cycles. The number of working cycles is a finite number and as well depends on DoD. In view of this, it is necessary to evaluate lifespan of the battery for this project.

To find the volume of energy that OPzS battery can provide over the lifespan, firstly it is necessary to estimate how many kilowatt hours batteries should output per one cycle and then to multiply this by the estimated number of cycles that OPzS batteries will provide before it needs to be replaced. For example, for DoD of 20% the volume of energy that will be provided with the chosen batteries will be:

$$W_{lifespan} = \frac{U_B \cdot E_B \cdot N_B \cdot DoD \cdot N_{cycles}}{1\,000}, \tag{25}$$

where U_B – nominal voltage of a battery, V;
E_B – nominal capacity of a battery, Ah;
N_B – the number of parallel-connected batteries;
N_{cycles} – the estimated number of charge-discharge cycles of a battery;

$$W_{lifespan} = \frac{U_B \cdot E_B \cdot N_B \cdot DoD \cdot N_{cycles}}{1\,000} = \frac{48 \cdot 3500 \cdot 20 \cdot 20\% \cdot 5\,000}{1\,000} = 3\,360\,000 \text{ kWh.}$$

Since voltage drops at the consumer end have a place only when the demand on power is high, this is the very time to use the energy stored by batteries bank. Unfortunately, due to lack of information we have no precise numbers of power which leads to exceeding of voltage limits of the end-consumer. In all likelihood, it should be about summer peak values or so. In order to escape underestimation, for the further calculation we will assume that voltage drops appear when the load is more than 80% of summer peak load.

As we have seen it from Figure 25, June's energy consumption by the village was the higher during summer 2015. Consequently it leads us to the summer peak load which can be calculated using formulas (9, 10):

$$\bar{W}_{daily,June,kWh} = \frac{\sum W_{daily,June}}{30} = \frac{W_{June}}{30} = \frac{55\,100}{30} = 1836.7 \text{ kWh}, \tag{26}$$

$$P_{summer,\max} = \frac{\bar{W}_{daily,June,kWh}}{\bar{W}_{daily,\%} \cdot t} \cdot P_{\max,\%} = \frac{1836.7}{1\,400\% \cdot 1} \cdot 100\% = 131.2 \text{ kW},$$

then the load of the voltage drop appearance:

$$P_{drop} = P_{\text{summer,max}} \cdot 80\% = 131.2 \cdot 80\% \approx 105 \text{ kW}.$$

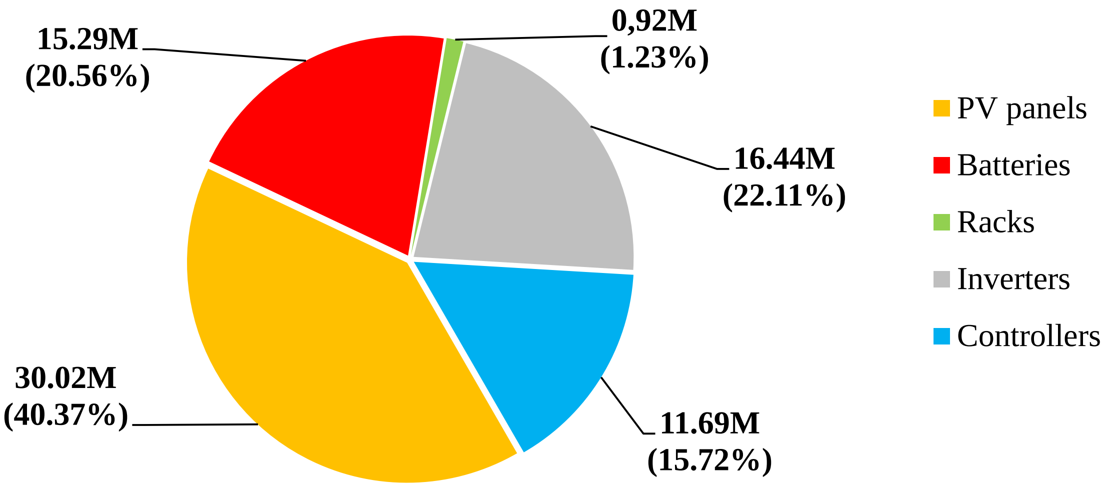
Using formulas (9, 10) we obtain load curve for each month and then we easily calculate how much energy must be covered by batteries. For instance, applying P_{drop} to daily load curve in the village in July 2015 (Figure 28) we see that the load exceeds P_{drop} at 11 a.m.. Thus, batteries will have to supply additional (113.8 - 105) = 8.8 kWh. Multiplication by the number of days in July gives us (8.8 · 31) = 273.5 kWh. Repetition of these calculations for other months results in annual value of 136 865 kWh. This is the amount of energy that batteries should be able to provide. From this we can estimate batteries lifetime for our project:

$$T_B = \frac{W_{Lifespan}}{W_{Drop,annual}} = \frac{3\,360\,000}{136\,865} = 24.55 \text{ yrs}, \tag{27}$$

where T_B – estimated lifetime of batteries, yrs;
$W_{Drop,annual}$ – annual energy that should be provided by batteries, kWh.

Thus, the chosen batteries can be used for our purposes about 25 years. Assuming investment in 0 year and start of SPP in the 1st year, live of SPP projects seems to be 26 years. Lifetimes of SPP projects and OTL construction are different. To perform a comparison of SPP project with OTL construction projects I can apply two instruments. First of them is a calculation of Internal Rate of Return (IRR) of each project. Second one is a repetition of SPP project in order to make lifetimes of SPP and OTL reconstruction projects equal each other.

Taking into account data of Table 17 I estimate the value of total investment for 52 years which is reflected in Figure 32. NPV of this 52-year project is –19.91 mln RUB while IRR of 26-year project is 1.32%.



Note: Upper number of a region shows total discounted investment in mln RUB, lower number of a region shows share of total discounted investment in %.

Figure 32. – Present value of total investment in SPP without solar trackers (52-year project)

3.3 Hybrid power supply system with solar trackers

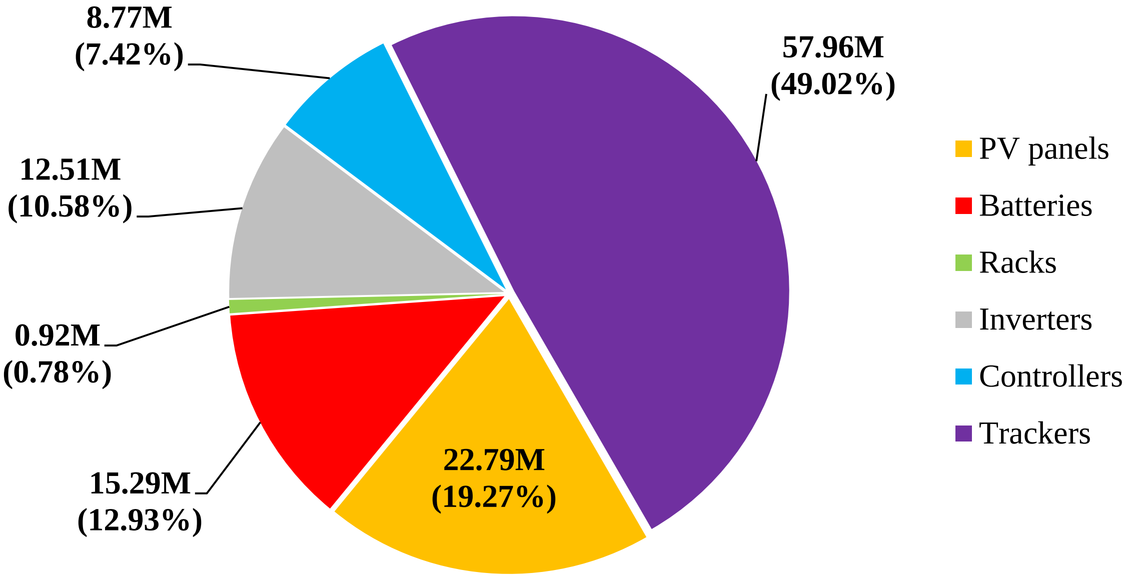
Equipment prices and numbers of units required for the scenario of SPP without solar trackers are shown in Table 19.

Table 19. – List of chosen equipment with its prices and lifetimes for scenario of SPP with solar trackers [26, 51, 52, 53, 54, 56]

Equipment	Price of the unit, RUB	The number of units required	Lifetime of the unit, yrs
Sunways FSM-100M	4 505	4152	25
FIAMM LM OPzS 3500	76 050	120	25
Electrilythe, 1 liter	59.78	6720	–
Racks E-PGV 2-68 SH	142 752.5	4	–
SMA Sunny Tripower 20000TL	251 334	16	25
ECO MPPT Pro 200/100	40 900	33	6
ST-800	39 800	394	25

According to information provided by producer, lifetime of solar tracker ST-800 is 10 years under heavy-duty operation conditions [57]. Lifetime can vary from 10 to 30 years depending on climate conditions. Baikalskoe village is placed on the north-west coast of Lake Baikal. Despite the fact that Siberia has strongly continental climate, it is quite soft nearby this lake. The weather there is softened by Lake Baikal which contains 20% of the world’s total unfrozen freshwater reserve [58]. Baikal’s water warms up cools down more slowly than the ground around. Topographic features there also contribute a lot to local climate: Primorskiy and Baikal mountains get in a way of clouds and cold winds from the North-West of Siberia. It results in soft summer and relatively warm winter. The west coast of the lake also has much less atmospheric precipitates than the east one thanks to mountains mentioned above. Winds there blow from the west to east so that amount of snow on the west coast is much smaller than on the west one. Annual average air temperature there is about 0°C [59].Thus, we can consider the weather conditions in Baikalskoe village for ST-800 as soft and apply 25-year lifetime for our project. There is also quantity discount of 20% for a large purchase [57].

Taking into account data of Table 19 I estimate the value of total investment for 52-year project which is reflected in Figure 33.



Notes: Upper number of a region shows total discounted investment in mln RUB, lower number of a region shows share of total discounted investment in %.

Figure 33. – Present value of total investment in SPP with solar trackers (52-year project)

NPV of this 52-year project is –19.54 mln RUB while IRR of 26-year project is 1.48%. Summarized results for OTL and SPP projects are shown in the Table 20 below. As we can see from this Table, traditional solutions to our task are not rational. In the current conditions more attractive solutions are SPP projects. Even though I have got negative NPV it does not mean that all of projects are not worth investing (see Figure 34). It is necessary to highlight that both models of solar projects have been built as the most pessimistic scenarios: prices of PV equipment changes with producer prices change rate, lifetime for each kind of equipment is considered to be minimal.

Table 20. – Economic parameters of traditional and alternative projects

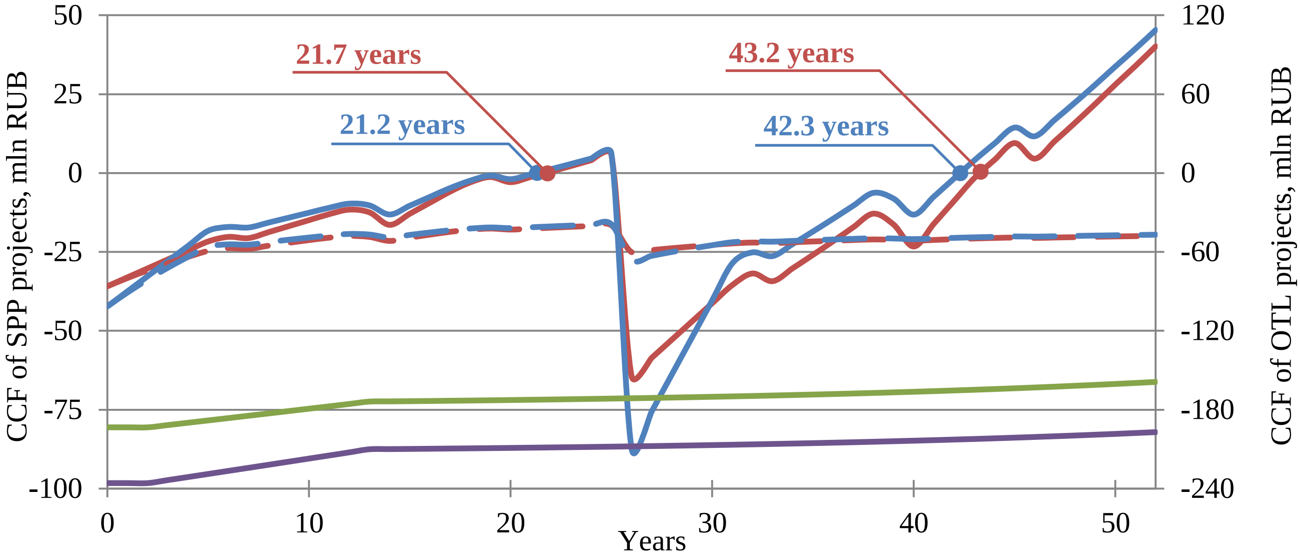
Project	Investment, mln RUB	NPV, mln RUB	IRR, %
OTL supported by steel poles	235.79	–221.07	–**
OTL supported by reinforced concrete poles	193.39	–181.86	–**
SPP without solar trackers	74.369*	–19.91	1.32/2.37***
SPP with solar trackers	118.244*	–19.54	1.48/2.64***

Notes: NPV of projects are negative. Nevertheless, the company has to take the lesser of evils in order solve the problem.

* Values show the sum of initial investment and present values of all reinvestments.

** Since initial investment is too high and expected cash flows are relatively low I could not find IRR.

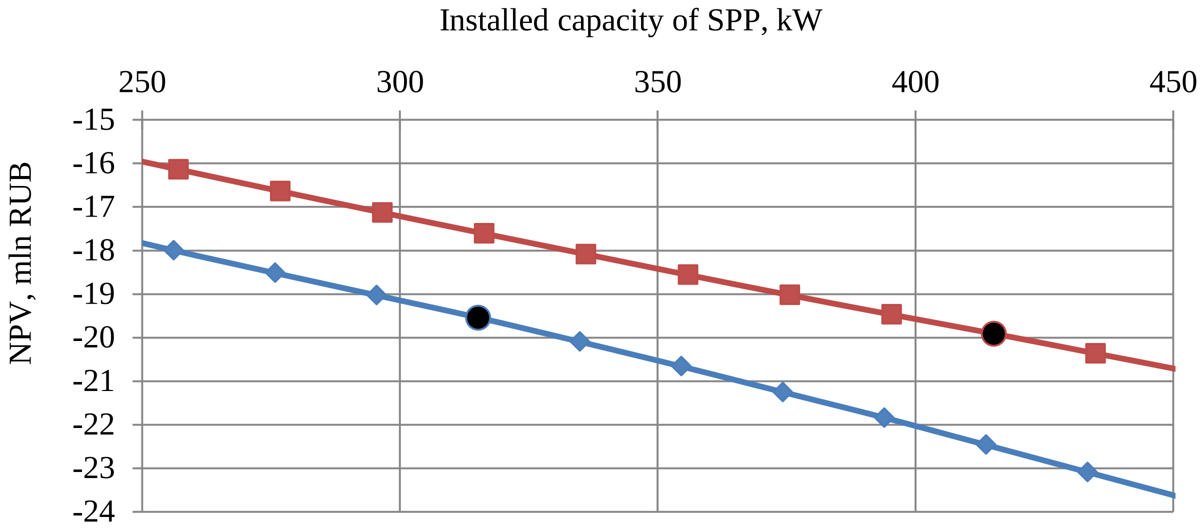
*** IRR are calculated for 26- /52-year projects, respectively.



Notes: CCF – cumulative cash flows. Red, blue, green and purple lines reflect cases of SPP without and with solar trackers and cases of OTL replacement with reinforced concrete and steel poles, respectively. Solid and dashed lines reflect cumulative not discounted and discounted cash flows, respectively.

Figure 34. – CCF of projects

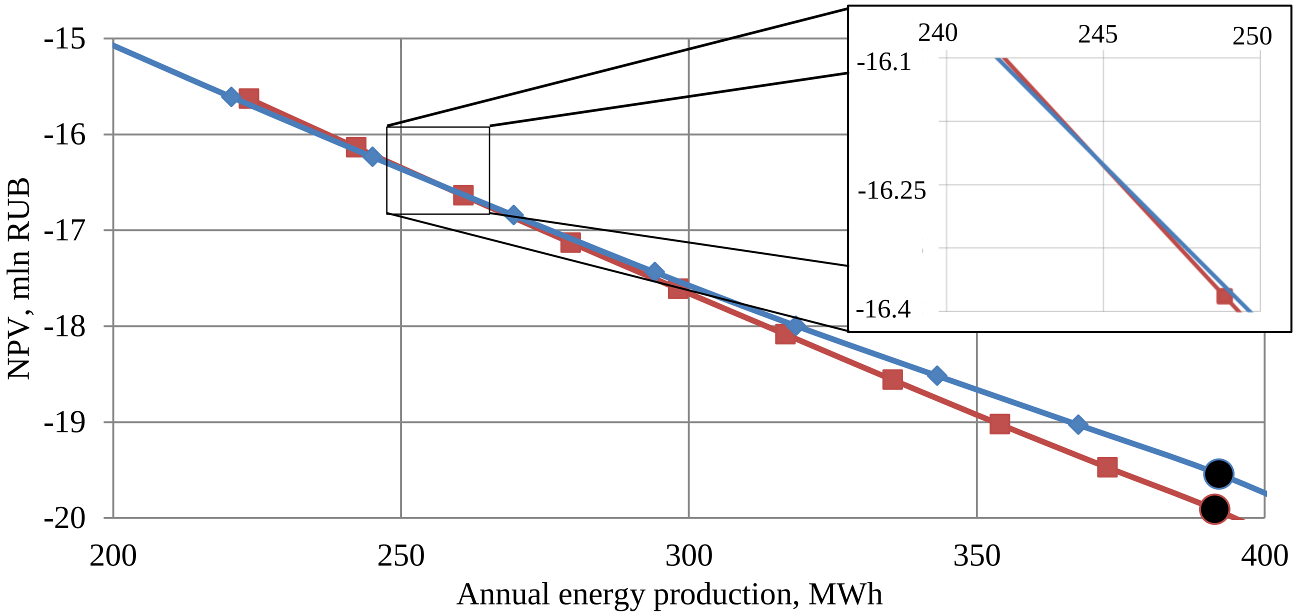
In Figure 34 CCF of conventional and nonconventional solutions are shown. Cumulative not discounted CF of OTL replacement projects do not have payback period within the lifetime of these projects. Payback periods of SPP projects for 26 and 52 project lifetimes are shown in the figure. We can see that these projects have no discounted payback period. The reason is that discount rate of projects is higher than their IRR.



Notes: Red and blue lines reflect cases of SPP without and with solar trackers, respectively. Black dots show optimal installed capacities from the technical point of view.

Figure 35. – Dependences of NPV on installed capacity of SPP plant

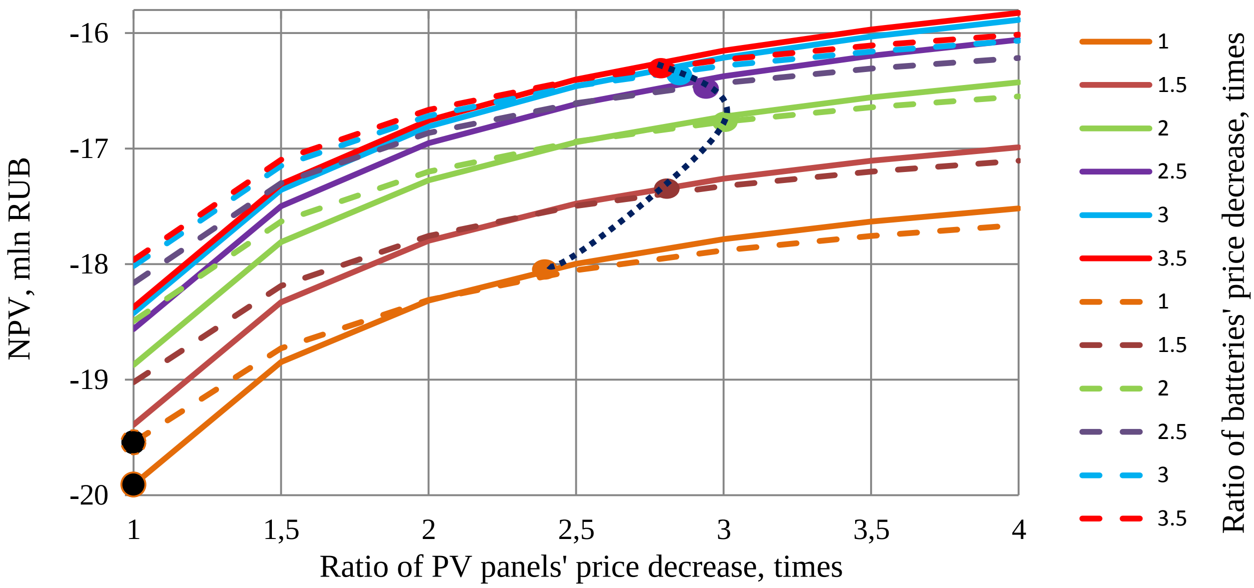
From the Figure 35 above we can see that the lower installed capacity of the plant the better the value of NPV. These dependences take into account all other equipment related to total capacity of PV panels. For instance, in case of SPP with solar trackers my model increases the number of trackers, controllers of batteries charge and discharge and inverters once total PV capacity increases. We also see that SPP can have smaller capacity but better NPV thanks to introducing solar trackers. Due to negative dependence, it is rational to left minimal capacity of SPP in order to minimize company's costs. From Figure 35 it is not obvious what is happening with energy production. When we invest more in installed capacity of our plant it provides us with more energy.



Notes: Red and blue lines reflect cases of SPP without and with solar trackers, respectively. Black dots show energy production and NPV for optimal installed capacities from the technical point of view.

Figure 36. – Dependences of NPV on electricity generation by SPP

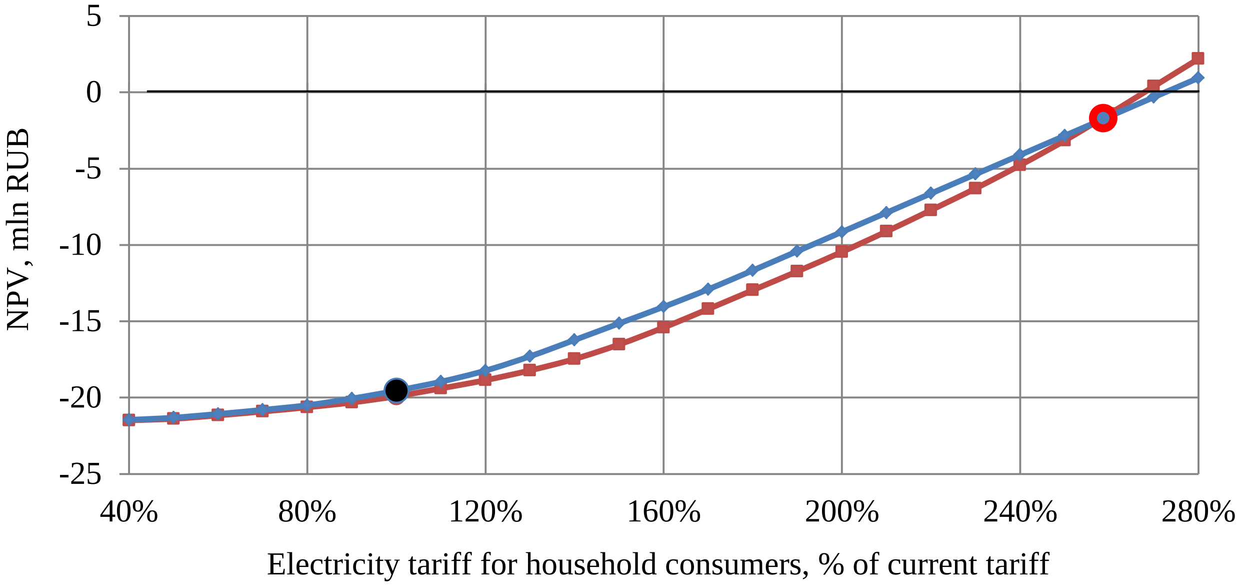
From Figure 36 we can see that NPV of SPP with solar tracking system decreases more slowly than of SPP without trackers. Also we can observe crossing of dependences approximately at annual electricity production of 245 MWh. In this point installed capacities of SPP without solar tracking system and with it are about 257 kW and 197 kW, respectively. We also can see that from economical point of view project without solar trackers can be attractive for us only when generation of the plant is less than 245 MWh per annum. Such generation level of power plants will be when installed capacities of SPP with and without solar tracking system are 197 kW and 277 kW, respectively. Otherwise, usage of solar tracking system is more attractive and the higher difference between annual energy production and crossing point of dependences the higher difference in NPVs of those scenarios.



Notes: NPV dependence of SPP without and with solar tracking system are shown by solid and dashed lines, respectively. The intersection of solid and dashed lines forms the boundary line (dashed dark blue). In these intersection points the NPV from both alternatives are equal. Positive effect of solar trackers usage on NPV is observed for ratios of decrease in prices of PV panels and batteries. Black dots on the vertical axes show ratios which are used in economic models.

Figure 37. – Dependences of NPV on decrease in PV panels’ price after 25 years

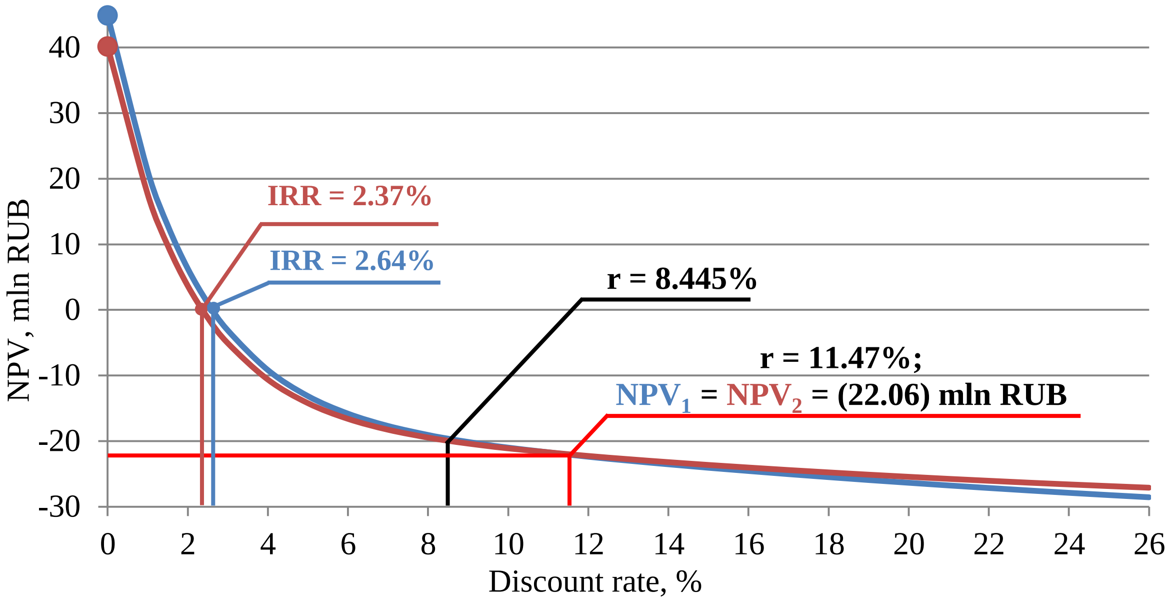
In Figure 37 we can see how values of NPV of SPP projects are dependent on decrease in prices of PV panels and batteries after 25 years. At this time the company will have to make reinvestment in main equipment of SPP. This is quite expensive reinvestment, so we need to find out how price changes can affect projects. There NPV and ratio of decrease in prices seem to have logarithmic dependence. Firstly, with decrease in price of equipment NPV increases rapidly and then tends to the value of NPV of the first 26 years of the project. It is necessary to highlight the boundary line of solar tracking system advantage: tracking system has positive effect on NPV when future prices of equipment are located on the left side from the boundary line and has negative effect when future prices of equipment are located on the right side. In case when future prices of equipment are on the boundary line NPV of SPP project with solar trackers equals NPV of SPP project with fixed orientation of PV panels.



Notes: Red and blue lines reflect cases of SPP without and with solar trackers, respectively. Black dot marks current tariff (100%) for electricity which is used in economic models.

Figure 38. – Dependences of NPV on electricity tariff

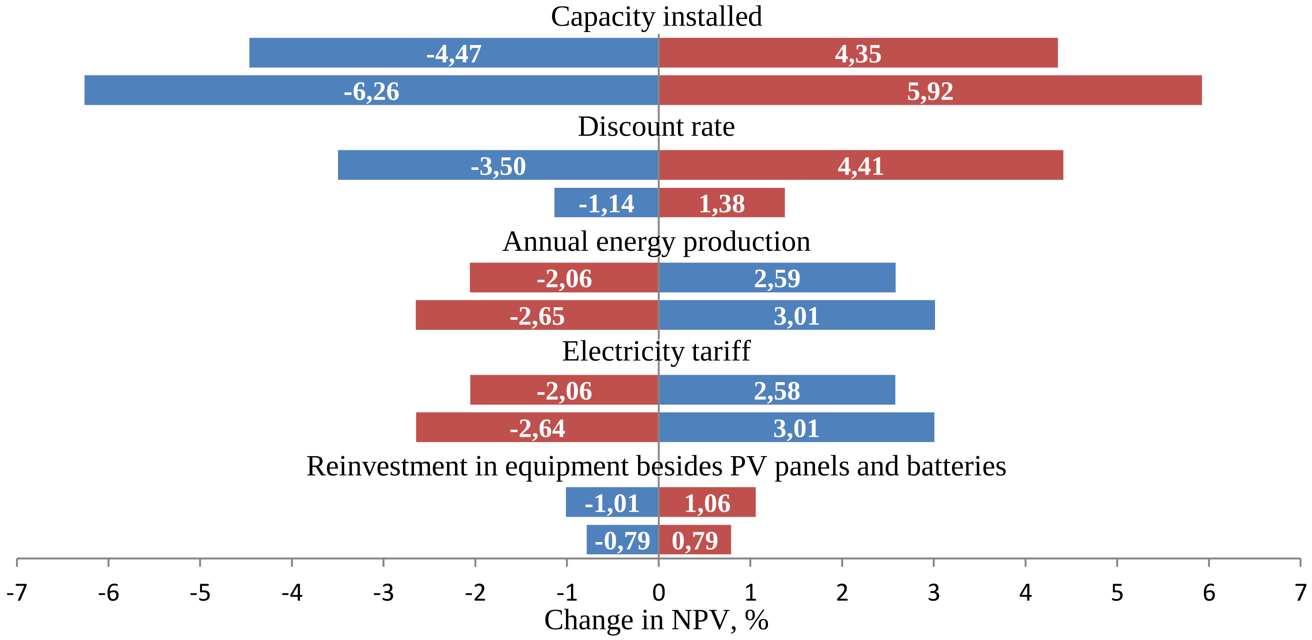
In Figure 38 dependences of NPV on electricity price for household consumers is shown. It is logical that the lower electricity tariff the flatter dependences. Red point with blue center marks crossing of NPV dependences of SPP projects. Up to this point SPP project with solar trackers is more attractive than SPP project with fixed orientation of PV panels. After this point solar tracking system loses attractiveness in comparison to SPP without solar trackers. If electricity tariff will be set more or equal to 270% of the current value then SPP without solar trackers has positive NPV.



Notes: Red and blue lines reflect cases of SPP without and with solar trackers, respectively. Dotes on the vertical axis are cumulative CF. Intersection of dependences with NPV = 0 give IRR of projects.

Figure 39. – Dependences of NPV on discount rate

From Figure 39 we can see dependences of NPV of SPP projects on discount rate. As we have seen from previous calculations, the project with application of solar tracking system has slightly better NPV value. Crossing of dependencies is observed when discount rate is 11.47%. Thus, solar tracking system is attractive scenario when discount rate is lower than this value. And vice versa: if discount rate will be higher (which is usual for cases of non-governmental company but not our) then SPP without solar trackers is more attractive option.



Notes: Blue and red colors reflect changes in NPV when a parameter increase and decrease by 10%, respectively. First and second column of a parameter are changes in NPV of SPP with and without solar tracking system, respectively.

Figure 40. – Tornado chart of change in NPV with 10% change in parameters

In Figure 40 Tornado chart for SPP projects is shown. There are NPV changes are shown in % and caused by change in corresponding parameter by ±10%. We can see that NPV of SPP projects have positive relationship with annual energy production and electricity tariff parameters and negative with the rest. The largest impact on NPV has capacity installed. It is also obvious that projects have different sensitivity to these parameters. For example, SPP project with application of solar tracking system is more sensitive to discount rate and reinvestment in equipment besides PV panels and batteries.

Conclusion

In this master thesis the solution to electricity supply problem of Baikalskoe village is proposed. Quality and transmission issues of rural grids of Russia in general and Baikalskoe village in particular were discussed in the section of statement of the problem. During data collection the author has faced a number of difficulties related to consumption details and quality of electricity at different loads. Also the real load curve of the village was not available, so the typical load curve of rural areas was used. Quality of electricity in the village is affected by the other loads spread across OTL feeding the village. In order to get such information it is necessary to make deeper research and consequently to attract financing for this purpose. Nevertheless, the author discusses possible reasons of long-term voltage changes in power supply system of the village which can be fixed by either conventional or non-conventional solutions.

Conventional solution for this task is switching to a higher voltage power line. In terms of type of poles supporting an OTL, this scenario falls into two alternatives: with application of either steel or reinforced concrete poles. Nonconventional solution is to build a hybrid power supply system which can combine centralized power supply with local generation based on renewables.

In Chapter 1 available RES for building a hybrid power supply system in Baikalkoe village, namely wind and solar powers, were discussed and evaluated. Usage of these sources and share of each source in all RES were shown using global and national figures. Estimation of wind power potential using annual average of wind speed in Baikalskoe village shows that application of wind turbines for this place is not recommended. Estimation of solar power potential was performed using simulation model in Mathcad. According to simulation results performed by the author, this region has high solar insolation. Obtained results are consistent with statistical data concerning solar insolation which was collected and shown in section 1.2.2.

Based on simulation results of solar insolation in the village, estimation of parameters of SPP was performed. This scenario falls into two alternatives: SPP with fixed position of PV panels and SPP with application of solar tracking system. For both of them the desired number of equipment was calculated by the author and presented in Chapter 2.

In Chapter 3 economic models for conventional and non-conventional solutions to existing problem of Baikalskoe village are described. NPV of all scenarios have upper estimates of investment costs. Although the author understands that the cost of RES equipment is decreasing over the time. Estimation of construction cost of OTL is performed using consolidated indices of construction cost. It is shown that from economic point of view hybrid power supply system is much more attractive solution to the problem in comparison to scenarios of construction of a higher voltage OTL.

Cost and benefit analysis of SPP scenarios performed by the author clarifies stability of projects and shows to which extent application of solar tracking system is recommended.

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Appendix 1. – Global trends in renewable energy investment [10]

Technology	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
	Billion USD										
Solar power	16.1	22.2	38.9	61.6	64.4	103.7	154.8	146.2	119.1	143.8	161
Wind power	29	39.8	61.2	75.4	79.8	98.7	84.2	21.9	90.6	105.7	109.6
Total in solar and wind	45.1	62	100.1	137	144.2	202.4	239	168.1	209.7	249.5	270.6
Total in RES	**72.8**	**112**	**154**	**182.2**	**178.7**	**239.2**	**278.5**	**257.3**	**234**	**273**	**285.9**

Appendix 2. – Map of the area of interest [Yandexmaps_2016]

Appendix 3. – Astronomical data of the village in July 2015, hh:mm:ss [32]

Day	Time of sunrise	Time of high Sun	Time of sunset	Sunshine duration
1	4:04:53	12:47:45	21:30:38	17:25:45
2	4:05:40	12:47:56	21:30:12	17:24:32
3	4:06:31	12:48:07	21:29:43	17:23:12
4	4:07:25	12:48:18	21:29:10	17:21:45
5	4:08:23	12:48:28	21:28:33	17:20:10
6	4:09:23	12:48:38	21:28:08	17:18:45
7	4:10:27	12:48:47	21:27:08	17:16:41
8	4:11:33	12:48:57	21:26:20	17:14:47
9	4:12:42	12:49:06	21:25:29	17:12:47
10	4:13:54	12:49:14	21:24:35	17:10:41
11	4:15:09	12:49:23	21:23:36	17:08:27
12	4:16:26	12:49:30	21:22:35	17:06:09
13	4:17:45	12:49:38	21:21:30	17:03:45
14	4:19:08	12:49:45	21:20:22	17:01:14
15	4:20:32	12:49:52	21:19:11	16:58:39
16	4:21:58	12:49:58	21:17:57	16:55:59
17	4:23:27	12:50:04	21:16:40	16:53:13
18	4:23:58	12:50:09	21:15:20	16:51:22
19	4:24:57	12:50:14	21:13:57	16:49:00
20	4:28:05	12:50:18	21:12:31	16:44:26
21	4:29:41	12:50:22	21:11:03	16:41:22
22	4:31:19	12:50:25	21:09:32	16:38:13
23	4:32:58	12:50:28	21:07:58	16:35:00
24	4:34:39	12:50:30	21:06:22	16:31:43
25	4:36:21	12:50:32	21:04:43	16:28:22
26	4:38:04	12:50:33	21:03:02	16:24:58
27	4:39:51	12:50:33	21:01:32	16:21:41
28	4:41:35	12:50:33	20:59:33	16:17:58
29	4:43:22	12:50:33	20:57:45	16:14:23
30	4:45:10	12:50:32	20:55:55	16:10:45
31	4:46:59	12:50:31	20:54:03	16:07:04

Appendix 4. – Energy production by PV panels $W_G(t)$ in July 2015

Day	Time zones	Cloudiness,%	$W_G(t)$, kWh	Day	Time zones	Cloudiness,%	$W_G(t)$, kWh
1	II	15	114	8	II	100	28
	III	20	436		III	100	113
	IV	25	581		IV	100	156
	V	15	449		V	100	113
	VI	20	111		VI	100	28
2	II	25	107	9	II	100	28
	III	25	423		III	100	113
	IV	20	599		IV	50	469
	V	20	436		V	20	433
	VI	15	114		VI	20	108
3	II	0	122	10	II	0	118
	III	5	471		III	15	445
	IV	5	647		IV	20	596
	V	5	471		V	25	419
	VI	5	119		VI	20	107
4	II	10	116	11	II	25	103
	III	0	480		III	15	444
	IV	5	646		IV	5	643
	V	5	470		V	5	466
	VI	0	122		VI	15	109
5	II	25	106	12	II	60	74
	III	15	448		III	35	389
	IV	20	598		IV	25	577
	V	15	448		V	20	431
	VI	20	110		VI	20	106
6	II	15	112	13	II	20	105
	III	5	469		III	20	430
	IV	5	645		IV	20	595
	V	15	447		V	30	403
	VI	25	106		VI	45	87
7	II	25	105	14	II	15	107
	III	25	421		III	20	430
	IV	35	539		IV	20	594
	V	60	303		V	25	416
	VI	90	42		VI	25	101

Appendix 4. – Energy production by PV panels $W_G(t)$ in July 2015 (continued)

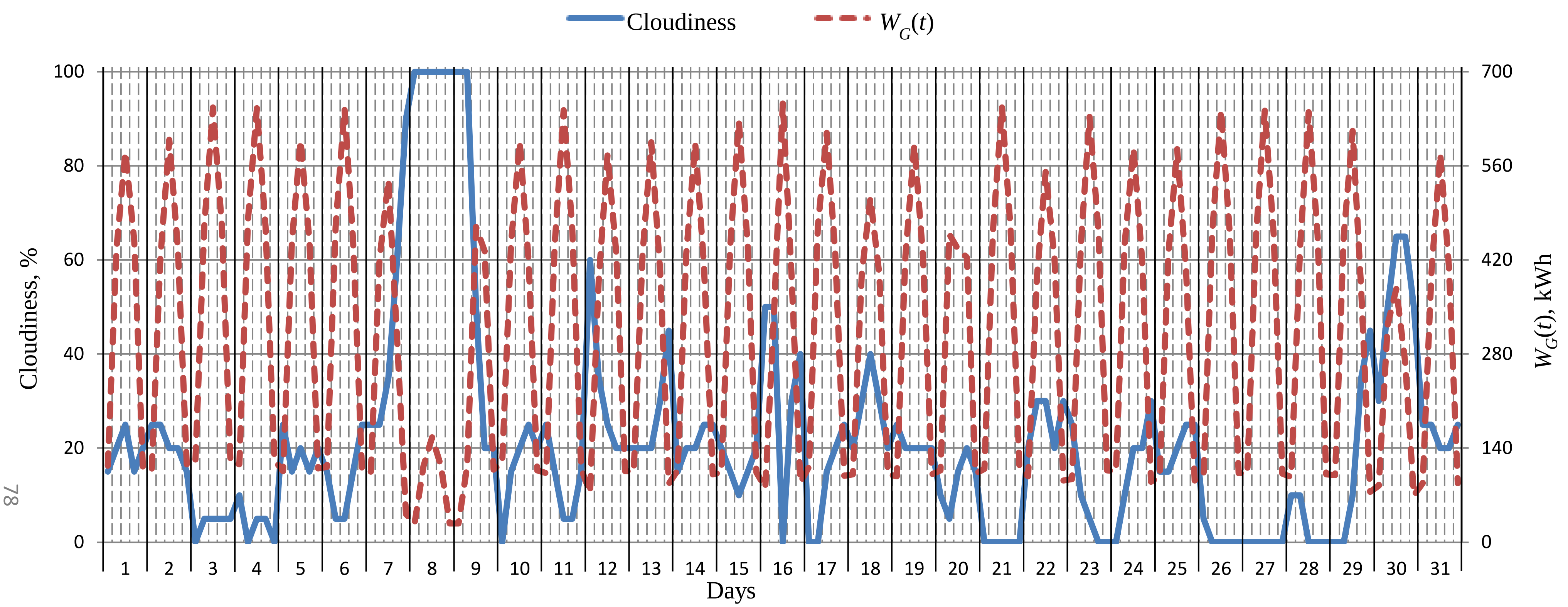
Day	Time zones	Cloudiness,%	$W_G(t)$, kWh	Day	Time zones	Cloudiness,%	$W_G(t)$, kWh
15	II	20	104	22	II	20	98
	III	15	441		III	30	396
	IV	10	626		IV	30	551
	V	15	441		V	20	422
	VI	20	104		VI	30	92
16	II	50	81	23	II	25	94
	III	50	336		III	10	444
	IV	0	653		IV	5	633
	V	30	401		V	0	464
	VI	40	89		VI	0	107
17	II	0	112	24	II	0	106
	III	0	470		III	10	443
	IV	15	609		IV	20	586
	V	20	427		V	20	420
	VI	25	99		VI	30	90
18	II	20	101	25	II	15	98
	III	30	399		III	15	431
	IV	40	512		IV	20	585
	V	30	399		V	25	406
	VI	20	101		VI	25	92
19	II	25	98	26	II	5	101
	III	20	426		III	0	460
	IV	20	591		IV	0	643
	V	20	426		V	0	460
	VI	20	101		VI	0	103
20	II	10	107	27	II	0	102
	III	5	458		III	0	459
	IV	15	436		IV	0	642
	V	20	424		V	0	459
	VI	15	102		VI	0	102
21	II	0	109	28	II	10	97
	III	0	466		III	10	438
	IV	0	648		IV	0	640
	V	0	466		V	0	457
	VI	0	109		VI	0	101

Appendix 4. – Energy production by PV panels $W_G(t)$ in July 2015 (continued)

Day	Time zones	Cloudiness,%	$W_G(t)$, kWh	Day	Time zones	Cloudiness,%	$W_G(t)$, kWh
29	II	0	100	31	II	25	88
	III	0	456		III	25	399
	IV	10	612		IV	20	578
	V	35	373		V	20	411
	VI	45	75		VI	25	88
30	II	30	84	Total generation of electricity during July 2015			49642
	III	50	324				
	IV	65	377				
	V	65	268				
	VI	50	70				

Source: Wind statistics of Baikalskoe village during July 2015; author's calculations.

Notes: Time zones of sunshine are shown by Roman numerals (II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00 and VI – 18.00–21.30).



Source: Wind statistics of Baikalskoe village for July 2015; author's calculations.

Notes: $W_G(t)$ – energy generated by solar panels, kWh. Solid black lines divide the graph area into 31 days. Dashed vertical separation refers to time zones when there is sunshine (II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30). Time zones of darkness (I – 0:00 – 4:00 and VII – 21:30 – 24:00) are excluded from the graph because there is no energy generation.

Appendix 5. – Changes of cloudiness and energy generation $W_G(t)$ across time zones of sunshine during July 2015

Appendix 6. – The charge level of 14 parallel-connected batteries $W_B(t)$ during July 2015

Time zone	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh
I	1	2193	7	1911	13	375	19	510
II		2130		1840		304		629
III		2260		1954		427		921
IV		2352		2194		723		1083
V		2352		2232		861		931
VI		2210		2021		695		797
VII		2076		1887		561		638
I	2	1917	8	1727	14	402	20	568
II		1848		1579		333		719
III		1963		1385		455		857
IV		2264		1242		750		1016
V		2352		1091		902		866
VI		2213		866		750		732
VII		2079		732		616		572
I	3	1919	9	572	15	457	21	505
II		1865		424		384		663
III		2028		230		518		1013
IV		2352		400		845		1214
V		2352		568		1021		1070
VI		2218		422		872		936
VII		2084		289		738		776
I	4	1925	10	129	16	579	22	698
II		1865		71		483		786
III		2038		208		512		1038
IV		2352		506		866		1196
V		2352		660		1002		1034
VI		2220		514		838		900
VII		2086		380		704		741
I	5	1927	11	221	17	545	23	658
II		1857		147		481		795
III		1997		284		644		1129
IV		2297		628		954		1329
V		2352		829		1116		1182
VI		2208		685		962		1048
VII		2075		552		828		889
I	6	1915	12	392	18	669	24	818
II		1851		289		594		954
III		2013		371		686		1241
IV		2352		649		899		1396
V		2352		816		1033		1233
VI		2205		668		881		1099
VII		2071		535		748		510

Appendix 6. – The charge level of 14 parallel-connected batteries $W_B(t)$ during July 2015 (continued)

Time zone	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh
I	25	940	27	1131	29	1441	31	993
II		861		1057		1364		904
III		984		1208		1513		996
IV		1271		1551		1826		1275
V		1412		1745		1935		1422
VI		1251		1594		1756		1256
VII		1117		1460		1623		1122
I	26	958	28	1301	30	1463		
II		882		1221		1371		
III		1035		1352		1388		
IV		1379		1694		1465		
V		1574		1886		1469		
VI		1424		1734		1286		
VII		1291		1600		1152		

Source: Author's calculations.

Notes: $W_B(t+1) = W_B(t) - W_C(t) + W_G(t)$, where $W_B(t+1)$ – the charge level of the batteries at time $(t+1)$, kWh; $W_C(t)$ – energy consumed at time t, kWh; $W_G(t)$ – energy generated at time t, kWh. Time zones are shown by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00).

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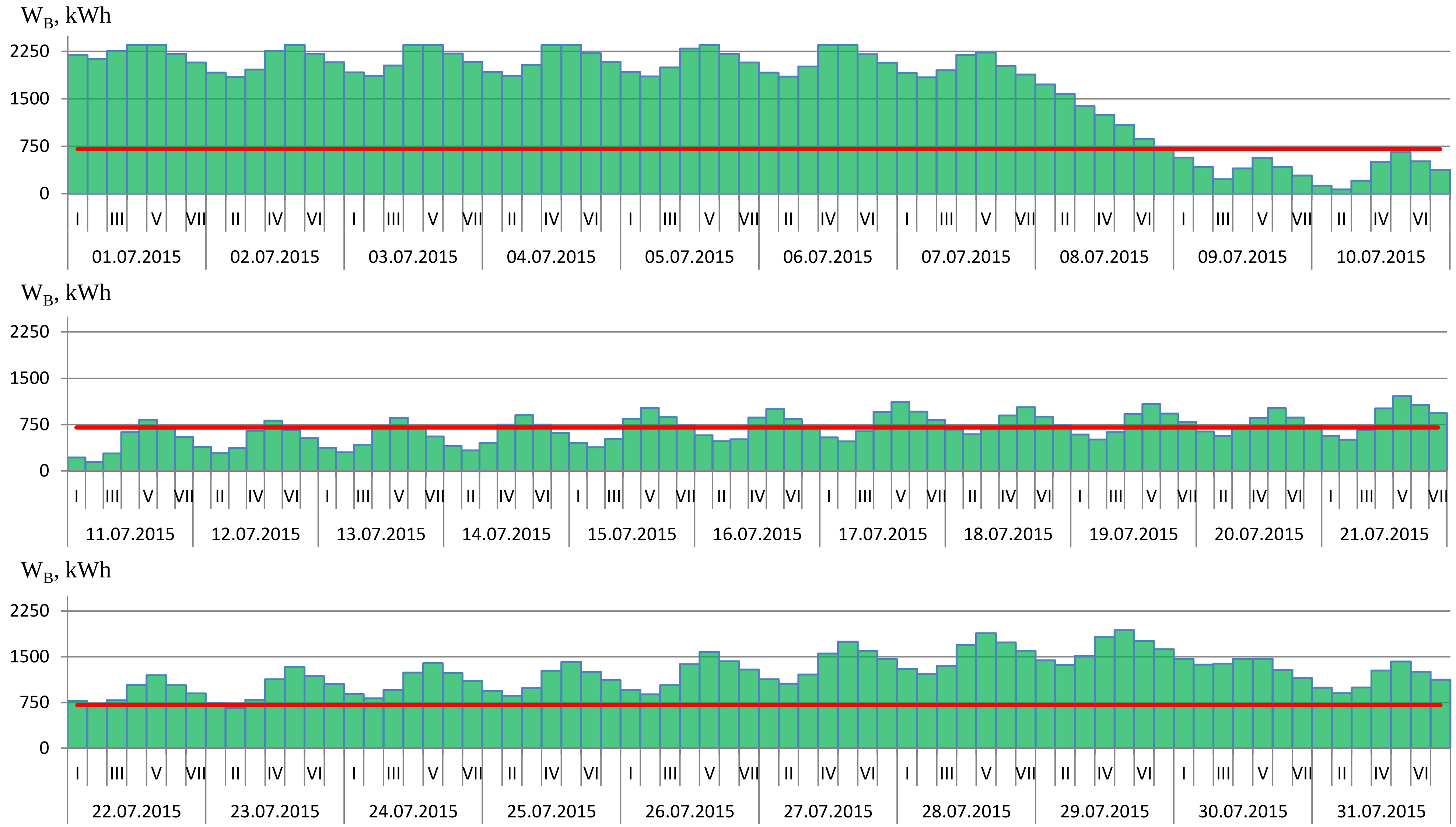


Source: Author’s calculations.

Notes: Red line reflects the lowest appropriate level of charge for batteries which is 30%. Time zones are shown by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00).

Appendix 7. – The charge level of 14 parallel-connected batteries during July 2015

Appendix 8. – The charge level of 20 parallel-connected batteries $W_B(t)$ in July 2015

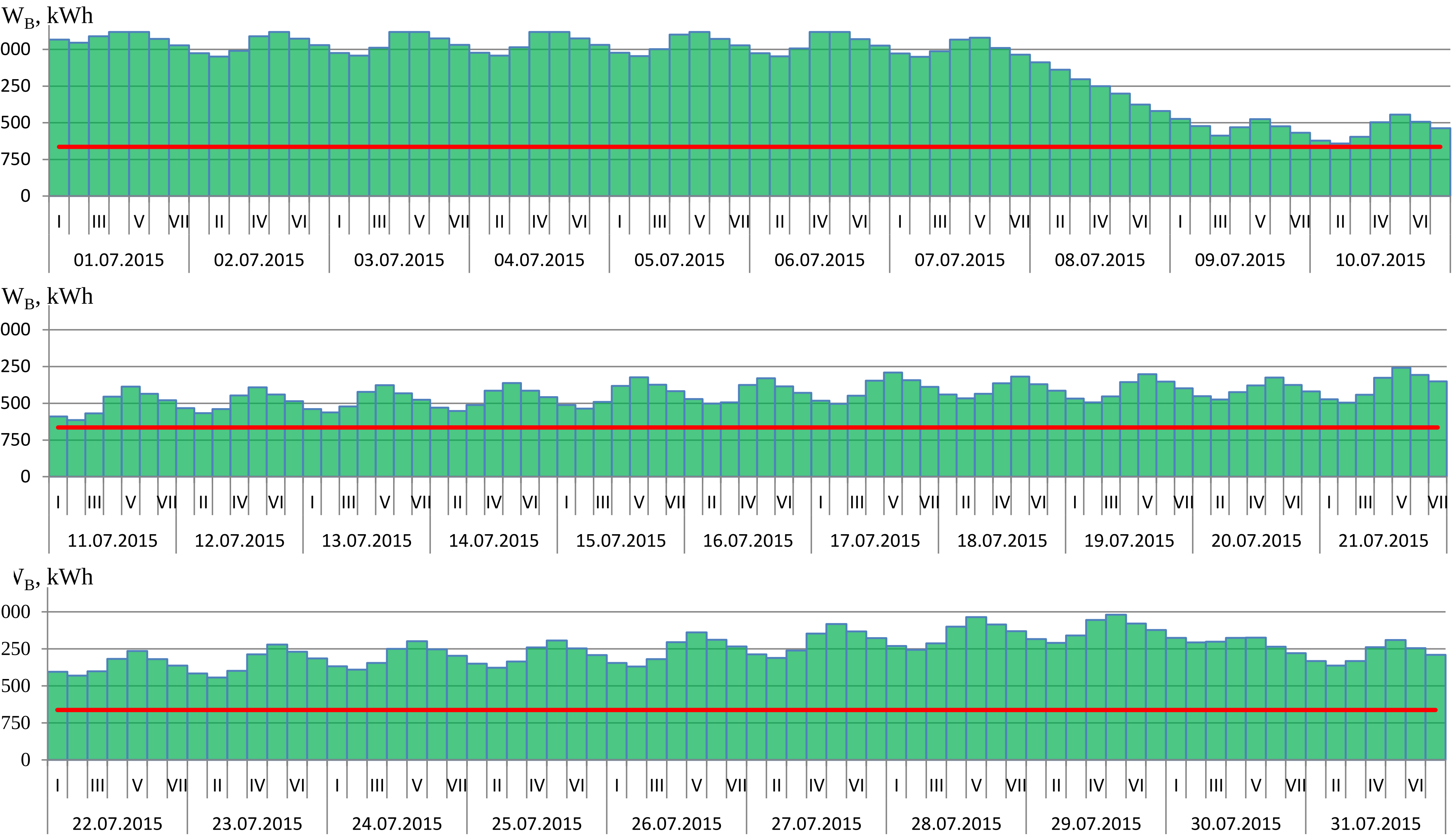
Time zone	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh
I	1	3201	7	2919	13	1383	19	1596
II		3138		2848		1312		1518
III		3268		2962		1435		1637
IV		3360		3202		1731		1929
V		3360		3240		1869		2091
VI		3218		3029		1703		1939
VII		3084		2895		1569		1805
I	2	2925	8	2735	14	1410	20	1646
II		2856		2587		1341		1576
III		2971		2393		1463		1727
IV		3272		2250		1758		1865
V		3360		2099		1910		2024
VI		3221		1874		1758		1874
VII		3087		1740		1624		1740
I	3	2927	9	1580	15	1465	21	1580
II		2873		1432		1392		1513
III		3036		1238		1526		1671
IV		3360		1408		1853		2021
V		3360		1576		2029		2222
VI		3226		1430		1880		2078
VII		3092		1297		1746		1944
I	4	2933	10	1137	16	1587	22	1784
II		2873		1079		1491		1706
III		3046		1216		1520		1794
IV		3360		1514		1874		2046
V		3360		1668		2010		2204
VI		3228		1522		1846		2042
VII		3094		1388		1712		1908
I	5	2935	11	1229	17	1553	23	1749
II		2865		1155		1489		1666
III		3005		1292		1652		1803
IV		3305		1636		1962		2137
V		3360		1837		2124		2337
VI		3216		1693		1970		2190
VII		3083		1560		1836		2056
I	6	2923	12	1400	18	1677	24	1897
II		2859		1297		1602		1826
III		3021		1379		1694		1962
IV		3360		1657		1907		2249
V		3360		1824		2041		2404
VI		3213		1676		1889		2241
VII		3079		1543		1756		2107

Appendix 8. – The charge level of 20 parallel-connected batteries $W_B(t)$ in July 2015 (continued)

Time zone	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh	Day	$W_B(t)$, kWh
I	25	1948	27	2139	29	2449	31	2001
II		1869		2065		2372		1912
III		1992		2216		2521		2004
IV		2279		2559		2834		2283
V		2420		2753		2943		2430
VI		2259		2602		2764		2264
VII		2125		2468		2631		2130
I	26	1966	28	2309	30	2471		
II		1890		2229		2379		
III		2043		2360		2396		
IV		2387		2702		2473		
V		2582		2894		2477		
VI		2432		2742		2294		
VII		2299		2608		2160		

Source: Author's calculations.

Notes: $W_B(t+1) = W_B(t) - W_C(t) + W_G(t)$, where $W_B\left(t+1\right)$ – the charge level of the batteries at time (t+1), kWh; $W_C(t)$ – energy consumed at time t, kWh; $W_G(t)$ – energy generated at time t, kWh. Time zones are shown by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00).



Source: Author's calculations.

Notes: Red line reflects the lowest appropriate level of charge for batteries which is 30%. Time zones are shown by Roman numerals (I – 00:00–4:00, II – 4.00–7.30, III – 7.30–11.00, IV – 11.00–14.30, V – 14.30–18.00, VI – 18.00–21.30 and VII – 21:30–00:00).

Appendix 9. – The charge level of 20 parallel-connected batteries during July 2015