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

HYBRID POWER SUPPLY OF AN OFFGRID RURAL AREA IN TOMSK REGION
MASTER THESIS

Study program: Electrical Engineering, Power Engineering and Management
Branch of study: Management of Power Engineering and Electrotechnics
Scientific adviser: Ing. Tomáš Králík Ph.D.

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MASTER'S THESIS ASSIGNMENT

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II. Master's thesis details

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Master's thesis title in Czech:

Decentrální systém pro zásobování elektrickou energií v oblasti Tomsku

Guidelines:

1. Describe current situation and solutions of power supply in remote areas
2. Describe and analyze the energy needs of a chosen remote area
3. Propose and optimize the hybrid system based on available natural resources
4. Perform economic evaluation of the proposed variants

Bibliography / sources:

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2. SsennogaTwahaa, Makbul A.M.Ramli; A review of optimization approaches for hybrid distributed energy generation systems: Off-grid and grid-connected systems; Sustainable Cities and Society; 2018
3. EVANS, L.R. Fueling Our Future: An Introduction to Sustainable Energy. New York: The United States of America by Cambridge University Press, 2007.

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt Student's signature

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

Date *Signature*

Abstract

The aim of this master's thesis is to analyze the energy needs and to design a hybrid power supply for an off-grid village in Russia, Tomsk region. This area can be quite efficient in terms of small and medium-sized solar power plants. In the theoretical part of the project I have described current situation in the world and in Russia regarding the problem of decentralization. I have suggested possible solutions for power supply in remote areas. I have also investigated the location of the area and assessed its climatic feature in terms of renewable energy sources. The thesis contains the description and analysis of the energy needs of a chosen village (Sujga) and a daily load diagram construction. Moreover, the options for hybrid power supply system have been proposed and the economic evaluation of investigated scenarios has been performed. As a result, I recommend a more economically efficient power supply system in terms of project cost reduction.

Key words

Renewable energy source, decentralized power supply, off-grid, hybrid power supply, photovoltaic generation, economic evaluation

CONTENTS

List of abbreviations

Abbreviation	English
BMS	Battery management system
CTU	Czech Technical University
DG	Diesel generator
GDP	Gross domestic product
HPP	Hydro power plant
LED	Light-emitting diode
$LiFePO_4$	Lithium-iron-phosphate batteries
MPPT	Maximum power point tracking
NPV	Net present value
PV	Photovoltaic
PWM	Pulse width modulation
SPP	Solar power plant
TPU	Tomsk Polytechnic University
US	The United States

Introduction

The problem of lack of access to centralized power supply in developing countries due to geographical location or places with low population density has a number of disadvantages. First of all, the main disadvantage of such systems is the very expensive cost of electricity, due to the high price of fuel. In decentralized and isolated power systems that do not have access to the country's main electricity system, the main electricity producer is a diesel generator. Due to poor geographical conditions, fuel is often delivered from far away, which is why a huge percentage is spent on logistics.

The current development of energy supply in Russia is characterized by an increase in the cost of energy production. The largest increase in energy costs is observed in remote areas of Siberia and the Russian Far North, Kamchatka, Kuril Islands, where decentralized power supply systems based on diesel power plants running on imported fuel are mainly used. The total cost of electric energy in these decentralized areas often exceeds the world price level and reaches 22 – 237 rubles (in Russia) per 1 kW·h for the public use, which is 5-55 times higher than the average in Russia (2017) [2].

Due to the constant development of technologies in the electric power sector, alternative energy, which has a number of advantages, has become a relevant solution to the problem of providing remote areas with electricity. Renewability, environmental aspect, wide distribution, availability, low cost of energy production in the foreseeable future are the main aspects of why the renewable energy is one of the main potential solutions of the investigated problem [1].

However due to some major disadvantages of renewable energy power systems, such as inconstancy and dependence on weather conditions and time of day, there is a growing interest in hybrid power supply systems that contain the usual generation of electricity through the burning of fossils and eco-friendly photo-voltaic systems and wind turbine systems. Renewable energy can make a huge contribution to solving one of the most important problems of energy supply in Russia's decentralized regions, which account for up to 70% of the country's territory with a population of up to 20 million people. The most promising method for building autonomous energy supply systems is the integration of wind and photovoltaic power stations into the diesel power supply system [7].

The purpose of this master's thesis is to develop a decentralized power supply system, using the renewable energy source, providing a continuous power supply to a small village located in Tomsk region. In addition, an economic evaluation will be carried out.

The following tasks are set to fully meet the requirements of the work and the previously mentioned objective:

- To analyze the problem of decentralized areas, and describe possible solutions;
- To describe the investigated area and assess its climatic features;
- To model the power consumption of the village and obtain a load diagram;
- To define the structure of the power supply system and to select the necessary equipment;
- To obtain and calculate the different scenarios for hybrid power supply;
- To create an economic model of the power system and to analyze the influence of economic factors on results.

This thesis is the result of double-degree program between Tomsk Polytechnic University (TPU) and Czech Technical University (CTU). This project is based on the data of TPU research and it has an extension in a form of a master's thesis of the similar topic. The work consists of six main chapters. The first chapter deals with the problem of decentralized power supply and possible solutions. The second chapter is devoted to the description of the location and the assessment of its climatic features. The third chapter copes up with the consumption load modeling. At the end of this chapter, I will have a daily load diagram that I am going to use in the work. The fourth chapter deals with the structure of the power supply system and the selection of the electrical equipment. In the fifth chapter I am going to analyze the selected scenarios in terms of generation-consumption balancing and I am going to provide the fuel cost calculations as well. Finally, the last chapter is devoted to the economic evaluation of the proposed variants and the sensitivity analysis.

1. Problem of decentralized areas, and possible solutions of power supply in remote areas

1.1 World

As it is shown in Figure 1, according to the Visual Capitalist, in 2017 only about 84% of population in the world had access to electricity with the most deficit of access in such countries as Burundi, Malawi, D.R.C, Tanzania, North Korea, Haiti, Nigeria, Pakistan, etc. [8].

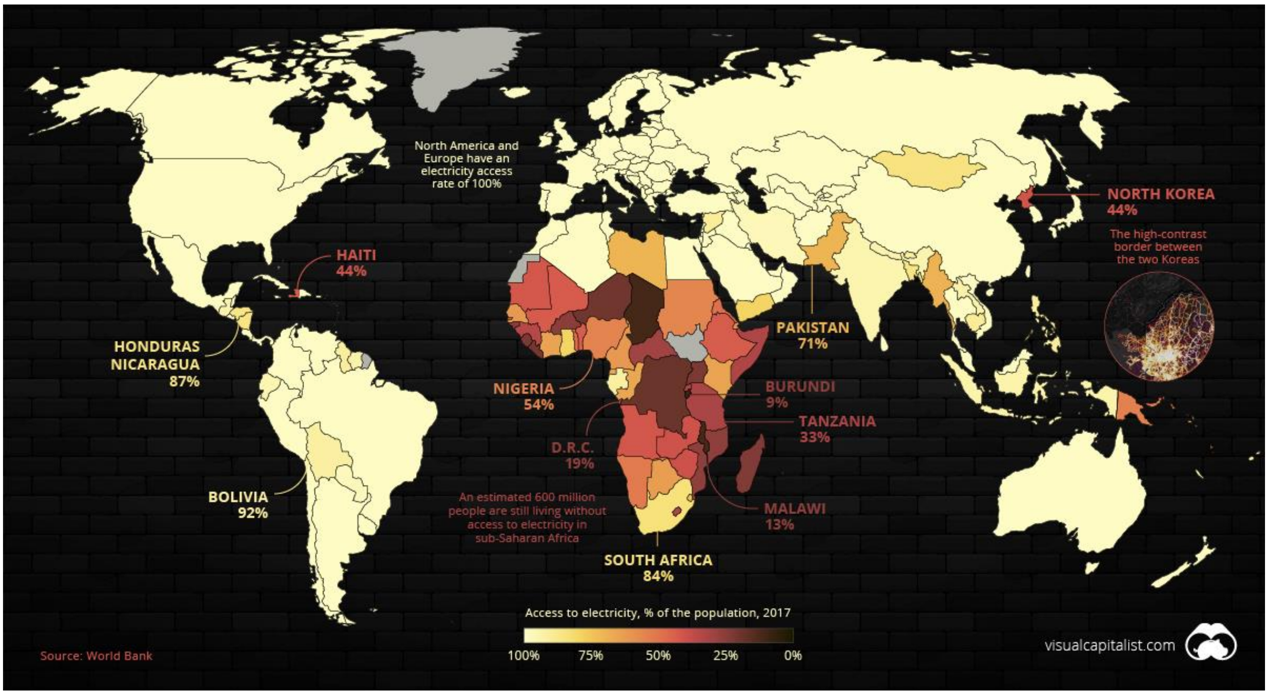


Figure 1 – Global access to electricity in 2017 [8]

According to the World Bank, World Development Indicators and UN Population Prospects, from 1990 to 2016 the population of the world has grown by two billion people, and the number of people without access to electricity has decreased by only half a billion people. The diagram of people with and without the access to electricity is shown in Figure 2 [9].

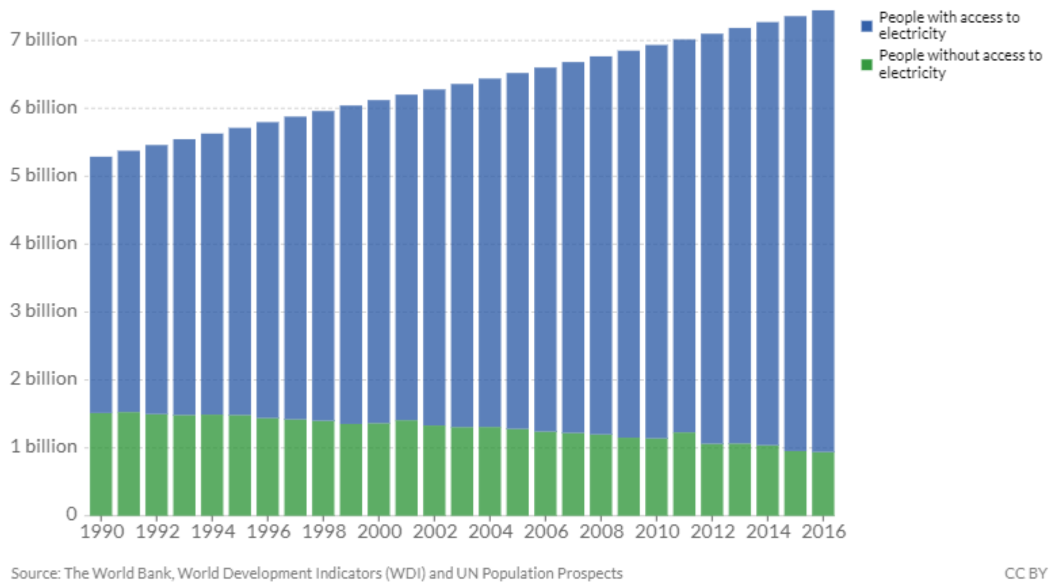


Figure 2 – Number of people with and without electricity access (from 1990 to 2016) [9]

As we can see from Figure 3, the most nonelectrified areas are located in Sub-Saharan Africa, South Asia, East Asia and Pacific. Although Europe and Central Asia do not have much deficit of electrified areas, a lot of remote areas share stand-alone power supply system due to vast territories and therefore high costs of transportation of fuel [9].

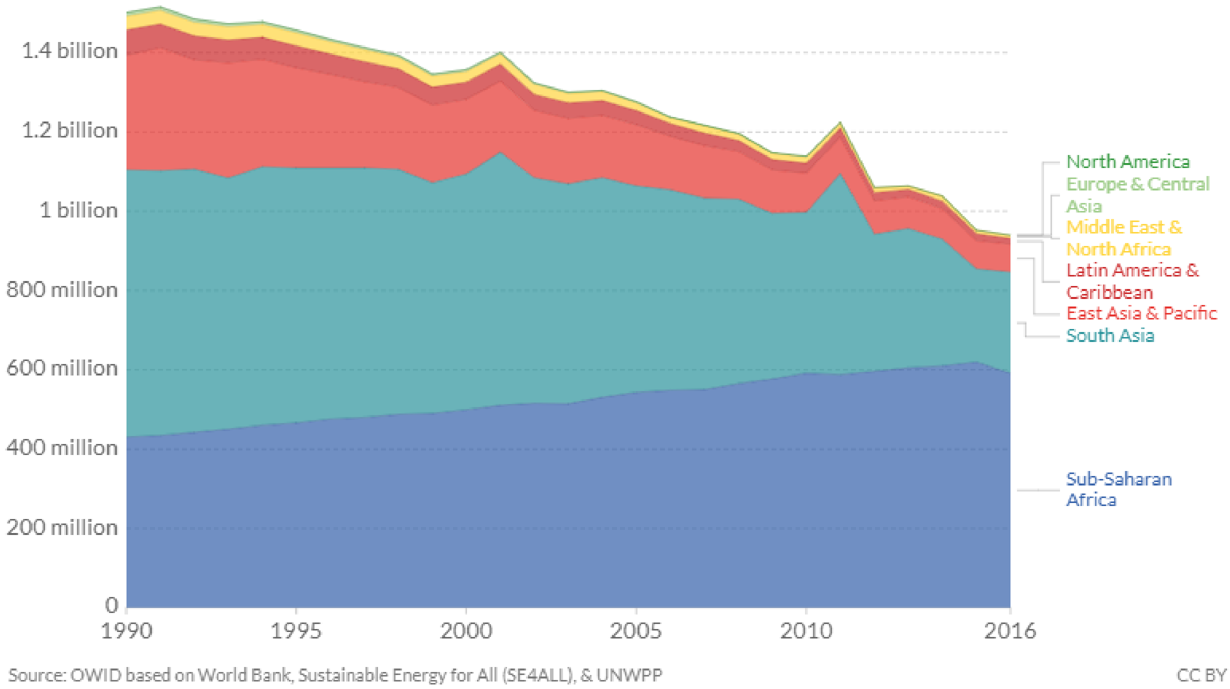


Figure 3 – Number of people without access to electricity [9]

Access to electricity provides a high quality of life for people, improving the quality of education, and comfortable conditions of living. From a technical and economic point of view, access to electricity increases the country's financial security, technological progress, urbanization, and much more.

In order to provide electricity, the following types of solutions are used: connection to the Central power grid, an autonomous/stand-alone power supply system that can be implemented through the use of a diesel generator, own small power plant and the use of renewable energy sources such as solar, wind, water flow, geothermal sources, and others. It has also recently become relevant, ecologically efficient and sometimes economically profitable to use hybrid installations based on alternative energy sources. Solar and wind installations, diesel generators together with PV panels or wind generators, and others are most widely used nowadays [1].

The easiest way of supplying a populated area with electricity is to connect it to the main central power grid, where the main factor is the cost of the required construction works, setting up necessary electric units such as transmission lines, transformers, etc. If there is no possibility of central power grid connection, some other feasible solutions have to be considered. One of them is the utilization of diesel generator. Diesel generators are asynchronous electric machines that produce three-phase current with the help of internal combustion engine. This type of solution has some drawbacks: rapid wear-out of parts and internal components of the equipment when the equipment is in idle-mode. In this regard, it is recommended to use diesel generators with a load of at least 40% of the rated capacity of the units [19]. In addition, there is high level of noise and sound pressure during operation of diesel generating devices. However, the major problem of this type of solution is a big cost of energy tariffs, due to great distances of fuel transportation and also the cost of the fuel itself. One liter of diesel fuel in Russia, for instance, in

2020 costs around half a euro [12]. Therefore, if we take a 200 kWt diesel generator, that is working alone for one hour with 50% load, it will consume around 28 liters of diesel fuel, which will cost about 15 euros in Russia in 2020 [12]. While the energy from the sun, wind or other renewable source is free to use.

As the investigated area of my master's thesis is located in Russia, the next part of the work is going to be devoted to the problem of decentralized areas in the Russian Federation. In addition, there will be possible solutions to electric supply mentioned below.

1.2 Russia

Area of Russia can be divided into three main groups in order of centralization: the first zone consists of economically developed regions that are located in the field of operation of the main power grid. The second zone consists of less developed power supply systems in terms of centralization. In addition, there are some stand-alone systems. The third zone includes many rural-type settlements, areas that are not affected by the main power grid, areas that have complicated transportation scheme, that require a lot of expenses and areas that are far from the fuel bases. These mentioned-above areas are scattered across the territory of Russia, including Far North, Siberia, Far East [7].

About 40% of the Russian territory has no centralized power supply from unified power system. In such regions, it is very common to use autonomous power supply systems based on diesel or gas-turbine, which can, in the absence of communication with the external power system, provide long-term power and heat supply to various facilities.

These facilities include settlements of workers in gas and oil field, builders, sailors and border guards, oil and gas drilling rigs, industrial facilities for pumping and processing oil and gas, as well as many other facilities in different industries and agricultures.

Sometimes these autonomous or stand-alone power supply system are called isolated or decentralized power supply systems. These are such power supply systems, which due to its remoteness and hard accessibility does not have connections with the main power supply system. The distribution of local isolated power supply systems is shown in Figure 4. As we can see, there is a vast territory that remains nonelectrified due to low population density and specific geographical conditions. Most of the country that has centralized power supply is located in the European part of Russia and in the South part of the country, connecting the biggest cities together. Stand-alone power supply systems, however, are scattered across Russia.

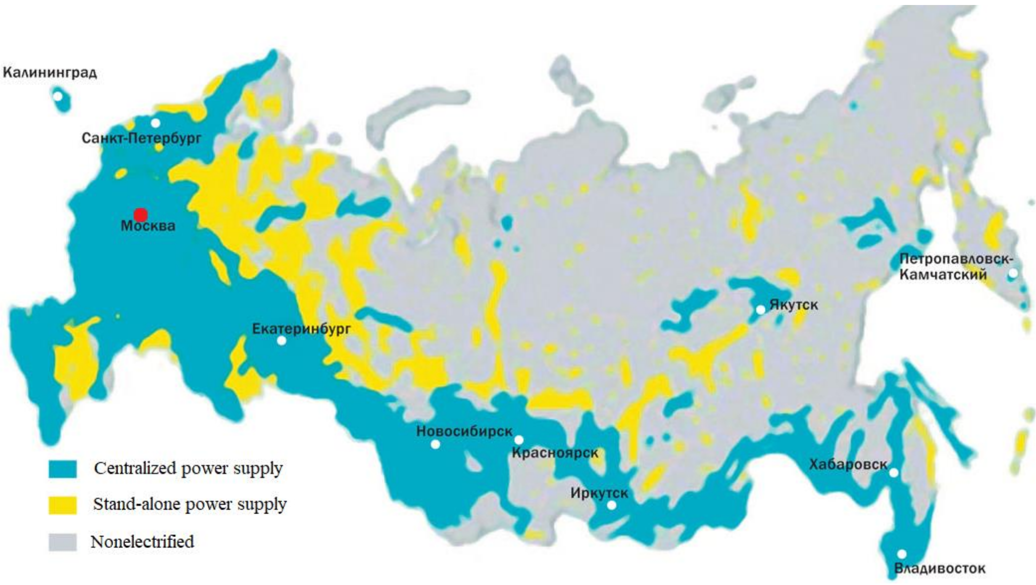


Figure 4 – Distribution of power supply systems in Russia [15]

Weak economic activity, low population density and certain geographical peculiarities in large areas of Russia determine the autonomous nature of energy supply to consumers. Almost the only way to keep decentralized power supply systems is to use diesel power plants, which are characterized by high deterioration of equipment, high losses in local power networks and, as a result, high costs of electrical energy. As the strongest example of decentralized energy supply to consumers in vast territories, I can mention Yakutia, with its 2.2 million km of territory with a population of 150 thousand people, which is provided with electricity and heat from 129 autonomous diesel power plants. This decentralized area of the power supply is run by OAO "Sakhaenergo"[13]. The lack of energy and its high cost constrain the development of the local economy and limit the ability to provide comfortable living, and hence the attractiveness of the territory.

In addition, considering the Northern regions of Russia, about 8% of the whole population of the country lives there, 76% of Russian oil, 93% of natural gas, 95% of gold and coal, almost 100% of salmon caviar and diamonds are obtained from these areas which makes up about 15% of Russian GDP. One of the biggest problems of such territories is its geographical conditions, which influence the successful supplying of energy. The heating season is about 10 months and the transportation of goods, including the fuel for electrical supply operation is very expensive and difficult due to lack of constant aboveground transfer. The total cost of diesel fuel for electrical energy generation in 2015 was about 1-1.3 billion of dollars and this sum does not include the oil. [7]

The problem of electrical supplying occurs not only in rural areas, but also in those places, which are characterized by small amount of consumed power. A lot of the time it is not reasonable to connect these areas to the main grid due to increase of expenses on maintenance of power lines, roads and services for transportation of diesel.

As these places struggle with continuous reliable power supply sources, the next part of the chapter is devoted to the main solutions for supplying areas with electricity.

1.3 Possible solutions of power supply in remote areas [1]

1. Centralized power supply system, which generally requires the investigated area to be very close to the main electrical grid or be very important to construct long communication via transmission lines.
2. Diesel stand-alone system. This method is one of the most frequently used in Russia, due to its simplicity and versatility; however, this method can be quite expensive.
3. Power supply systems based on renewable sources of energy: wind energy, solar energy, energy or water flows, geothermal energy, etc. One of the main criteria for using this method is to make sure the investigated area has sufficient amount of the energy from the sources listed above.
4. Hybrid power supply system. This is a power plant, that usually includes some kind of a diesel generator and a power plant based on renewables, for instance, wind-diesel power plant or even photovoltaic-wind power station. This method is used more and more every year due to its flexibility. It can adapt to the weather changes by using the diesel-generator, but at the same time, it can save fuel by using the renewable sources when it is reasonable to do so.

These methods in detail are described below.

Diesel stand-alone systems [22]

These systems are based on a stationery or mobile power plant, which consists of an electric generator and internal combustion engine, that is powered by diesel fuel. The main principle of operation of such machines is quite simple; it converts mechanical energy of rotating shaft of rotor into electric energy. These systems are mostly used in areas where there is no centralized power supply or where there are some difficulties with the electricity supply. Usually, it refers to small remote areas, agricultural enterprises, suburban settlements, production facilities of oil, gas and other resources, located in hard-to-get spot.

Diesel power supply systems have some significant advantages, which make them a viable decision. Diesel power plants are easy to install and construct, also they have high degree of mobility and portability. However, there are some disadvantages to these systems. They have low reliability (the fault occurrence is quite frequent). Moreover, there is air pollution, the need of their constant maintenance and limited variety of diesel generators (the most reliable cost more and are foreign in comparison to the Russian analogs.

Renewable-based power supply systems

Power supply systems based on renewable or alternative sources of energy are very popular today due to many factors, which are going to be discussed later in the paper. The renewable types of energy include energy from the sun, wind, water, excluding the use of this energy in hydro-accumulating power plants, energy of waves and tides, geothermal energy, bioenergy.

Nowadays, humanity thinks about using renewable energy sources, since gas, oil and other fossil fuels are exhausted. Use of fossil fuels causes environmental problems, mainly greenhouse gas emissions. According to "Our World in Data" 75% of total greenhouse gas emissions results from burning the fossil fuels and these emissions cause the air pollution which is a health problem that leads to 5 million deaths every year [11].

As we can see from Figure 5, in 2019 Russia obtained only 17.55% of energy from renewables. In comparison, the most production of electricity from renewables has been observed in Brazil, Iceland, Norway, New Zealand, Canada, Paraguay, many parts of Africa, etc. with the percentage from 60 to 100. Totally, around 25% of the global electricity comes from renewable sources [11].

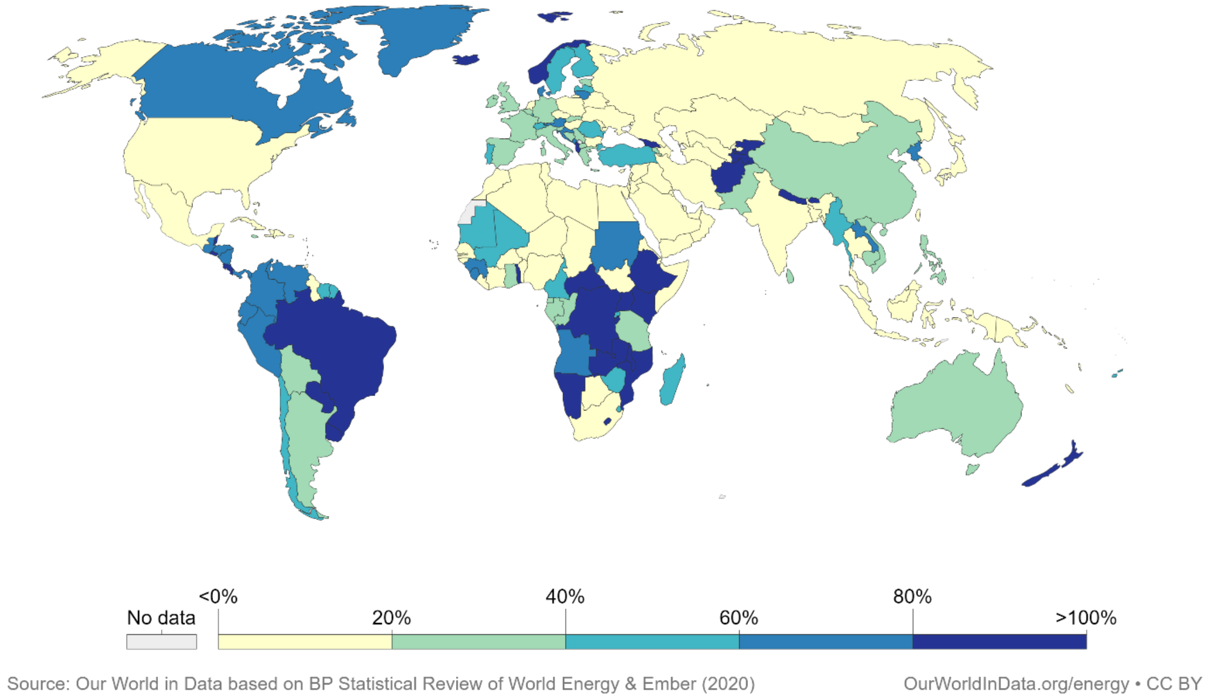


Figure 5 – Electricity production from renewables in 2019 [11]

Traditional energy is obtained by burning the fossil fuels, whose reserves are limited. Renewable energy, however, is based on a wide variety of natural resources that are ecologically viable for a better future. They are environmentally friendly; there is almost no release of pollutants into air or water. Moreover, in most cases such systems are easily automated and can operation without human intervention.

Factors for utilization of renewable stand-alone systems [23]:

1. Low power consumption, when cost of transmission lines supply is unreasonably high.
2. Remoteness, inaccessibility.
3. Big number of low-power consumers, which complicates the connection to the main power grid, its maintenance and installation.
4. Lack of power capacity of networks and their unreliability.

Let me state the major advantages and disadvantages of implementation of renewable-based stand-alone power systems [10].

Advantages:

1. Inexhaustible
2. No greenhouse gas emissions
3. It is more effective to use such energy systems in most remote areas of the country comparing to a traditional way of supplying
4. Giant potential of resources in the world
5. Simultaneous use of land for economic purposes and energy generation

Disadvantages:

1. Unstable probabilistic nature of energy input
2. Back-up needs
3. Need for accumulation
4. Lack of infrastructure (especially in Russia)
5. Lack of staff and companies that produce the needed equipment

Hybrid power supply systems

Hybrid power supply systems are systems that consist of usually two or more source of energy. Solar panels, wind generators, diesel generators, and others are usually used as sources of electricity in hybrid power supply systems. The main source of energy can be a diesel generator or a plant based on renewable energy. A stable diesel power plant combined with an unstable renewable power source allows building good power supply systems in terms of technical and economic indicators. These systems, combined with the correct algorithms and intervals of operation of equipment, can increase the efficiency of such systems. Moreover, reducing the duration of operation of a diesel electrical installation by using renewable sources saves fuel and extends the service life of such a machine. The use of multiple energy sources within one power supply system is cost-effective for the following reasons. It allows you to forget the centralized power supply. The service life of the entire power plant drastically increases and repair and maintenance costs are significantly reduced. Although, the equipment installation costs are quite high, this method of integrated systems quickly pays off.

The typical hybrid power supply systems are shown in Figure 6. In this case, the sources of energy are photovoltaic panels (PV panels), wind turbine and diesel generator. Storage batteries are used for the accumulation.

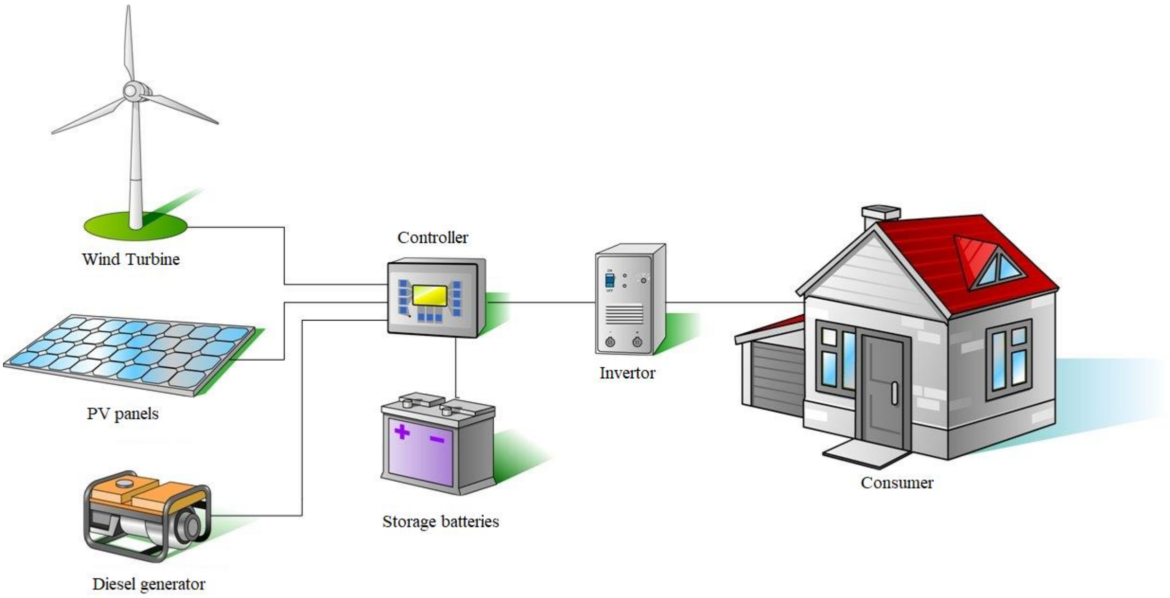


Figure 6 – The scheme of hybrid power supply system with three sources [16]

Hybrid power supply system can be an economically profitable solution to the electrification problem in case of rural areas, where centralized power grid is too far and is not reliable or it is simply too expensive to connect this area to the main power grid. The main convenience for using a renewable energy in such power supply systems is that it does not consume fuel, meaning it reduces the cost of operation and it is economically friendly. However, it is difficult to build a stable hybrid power supply system and many sources of renewable energy might not be available for some time when needed, therefore they are not very reliable.

Although hybrid power supply systems have some drawbacks and could be quite complicated, this is one of the best decision, in terms of ecological factor, money savings, modern trends and efficiency, especially for rural areas with high number of low-power consumers. Therefore, my further work will be focused on the hybrid power supply system.

2. Investigated location description and climatic features assessment

In this chapter, I am going to describe a small village that is located in Russia in Tomsk region. Tomsk, per se, is located on the River Tom in Western Siberia in Russia. It was founded in 1604, therefore it is 417 years old. The population of Tomsk is about 597 819 people according to the Tomsk Government Website in 2020 [14].

In addition, there will be an assessment of climatic features of the village.

2.1 Location description

The investigated village is named Sujga. It is located in Tomsk region, Molchanovskij district. Coordinates are 57° 52' 39" N. 84° 43' 18" E. The village is situated on the River Sujga. The rural settlement of Sujga consists of only one village Sujga, which is the administrative center. The village includes eight shops, a bakery and a post office. About five per cent of the Sujga population are entrepreneurs. The main occupation of the residents is agriculture, fishing, collecting wild plants, because the area is rich in natural resources, such as nuts, berries, fish, plants, pines, mushrooms, etc. About 40% of the registered population goes hunting, fishing and work in the agriculture field. Around 30% is retail trading and about 30% provide other types of services. [24]

Sujga is located 128 km far from Molchanovo and about 330 km from Northwest of Tomsk [27].

The map of Tomsk region with the location of Molchanovskij district is in the Figure 7.

Figure 7 – Location of the investigated area [25]

The population of Sujga is 576 people. The area of Sujga is 610 000 m^2 [26].

The territory of Sujga is quite special; it has a protected natural reserve of regional significance. This reserve is named Karegodskij. It has a number of animals and birds from the list of endangered species of Tomsk region, such as swans, white-tailed eagle, black stork, and muskrat. In addition, this reserve is a home to many valuable animals, such as elk, bear, beaver, otter, squirrel, ermine, white hare, fox, lynx, ferret, badger, wolverine and many more [27].

Power supply of the village

Sujga village is supplied with electricity from the local diesel power plants. There are two diesel generators (DG) in operation on the territory of the village. The streets in the settlement do not have street lighting [27].

The heating of the village is provided mostly by burning the wooden logs or coal (in some parts of the village). There is no central electric heating [27].

2.2 Climatic features assessment

The climatic features of the area are important in the design of hybrid power supply system; therefore, it is necessary to review the data corresponding to different renewable energy sources.

The climate of Sujga area is continental. Summers are quite humid and moderately warm, while winters are moderately harsh and snowy. The average temperature in January is -19.5 C. The average temperature in July is +18.1 C. The average annual precipitation of Sujga is 482 mm [27].

Chulym river – the largest feeder of the Ob River is considered the main waterway of the Suijga village. The rest of the rivers are quite small. These rivers are characterized by a low fall, slight slopes, and rather slow flow. The main peculiarity of the rivers is a long period of freezing. Taking into account all the above factors, electricity supply based on water energy cannot be performed in this area [27].

In the Figure 8, there is a map of renewable energy potential, 2011 [17]. From the location of the investigated area, we can roughly assume that the best options for renewable energy sources are solar and hydropower, because it is located right between the two zones. Keeping in mind the previous paragraph it is advisable to not use the hydropower.

In the next couple of pages, you can see the provided information about the main renewable energy sources available in the village.

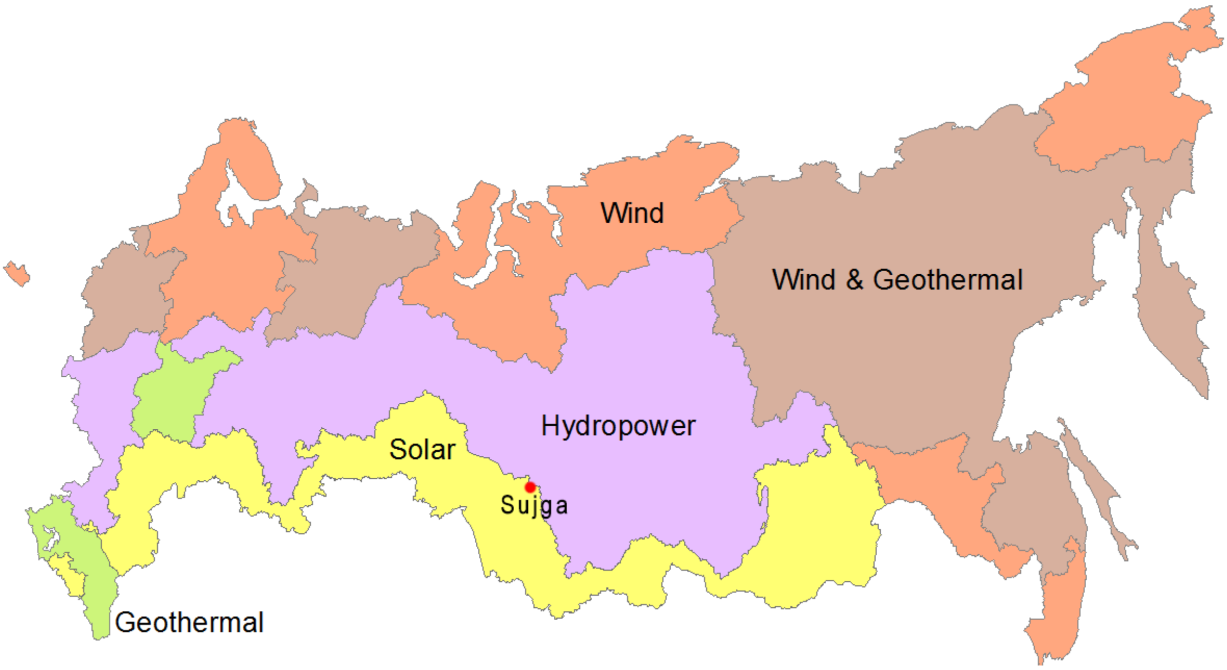


Figure 8 – Map of renewable energy potential in Russia, 2011 [17]

Renewable energy resources can be classified by the type of energy: [1]

- Mechanical energy
- Thermal energy
- Chemical energy

Mechanical energy is used in energy of the wind and flow of the water. The thermal energy is used in heating of the Earth and the energy of solar radiation, and chemical energy can be extracted from biomass.

Wind energy potential

Wind speed is one of the main characteristics of wind energy and it is characterized by its randomness in space and time. The basis of the probabilistic approach for describing the change in the wind energy potential is the discretization of the time process. While hours, days, seasons, and years are often chosen as time intervals.

Peculiarities of atmospheric circulation prevail in winter and during the transition seasons on the territory of southern winds. On average, southwesterly winds prevail throughout the year. The average annual wind speed is rather low and is around 3.8 meters per second; the maximum speed is observed in November [27].

According to [1], the average wind speed and unit power for the Molchanovskij district in the Tomsk region is shown in the Table 1.

Table 1 – Energy characteristics of the wind in Molchavskij district [1]

Name	Winter		Spring		Summer		Autumn		Year	
Molchanovo	V (m/s)	P (W/m^2)	V (m/s)	P (W/m^2)	V (m/s)	P (W/m^2)	V (m/s)	P (W/m^2)	V (m/s)	P (W/m^2)
	4.0	200	4.2	216	3.0	76	4.5	274	3.9	176

According to [6], the average speed of wind during the year has to be at least 4 meters per second in order for small and medium-sized wind power plants to operate efficiently. In this case, the average yearly wind speed is 3.9 m/s which is less than the recommended speed of wind.

Solar energy potential

Solar energy is another type of energy that exists in every spot of the Earth surface. The power of the solar radiation covering an area of 10 square kilometers is 7-9 million kW on a cloudless day [20]. And that is an enormous amount of energy, which is even more than the power of the Krasnoyarskaya Hydro Power Plant (HPP) [1].

For Sujga, the annual number of sunny days is about 265-275 days. The total amount of solar radiation per year is 90 kcal / cm2 [27].

In the Figure 9, there is a map of solar energy resources in Russia [18]. Given the location of investigated area, I tracked the position and put it on the map. As we can see, it lies in the zone of 1700-2000 hours of sunshine duration per year. According to [29], the duration of sunshine in Tomsk (the data for Sujga is unavailable) is approximately 2048 hours per year. This amount is sufficient for efficient utilization of solar power plant in the investigated area [6].

Figure 9 – Map of solar energy resources in Russia [18]

In the Figure 10, you can see the map of Tomsk region with 3 different zones: South-West (1), Central (2) and North East (3). The investigated village is located in the middle of the 2nd zone. Therefore, according to [5], the annual average value of energy resources is 1000-1100 kWh / m^2 with average values of cloud cover, atmospheric transparency and open horizon. The following zone mainly meets the operating requirements of small and medium-sized solar power plants, thus, the solar power plant can be installed in the investigated area with an efficient operating.

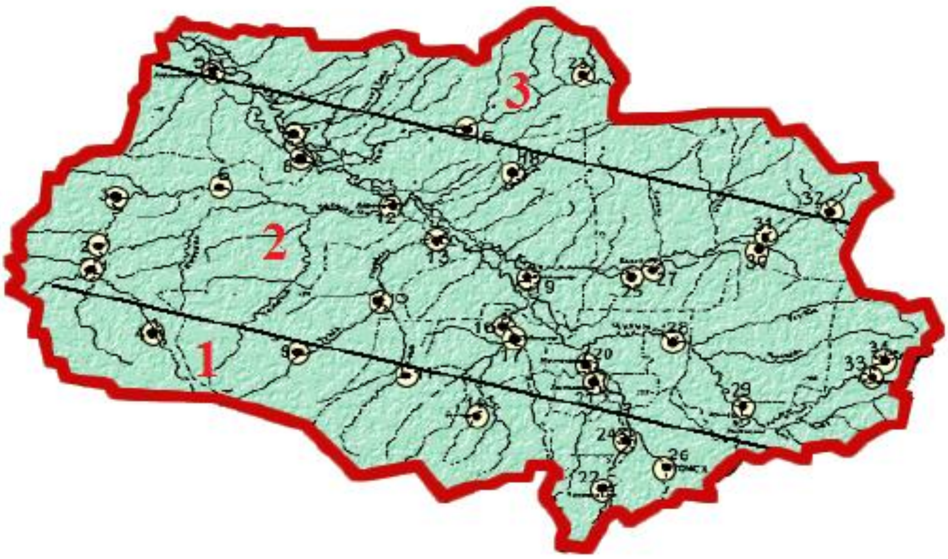


Figure 10 – Solar energy resources in Tomsk region [5]

Sunny and frosty days are very common in Sujga village. Regarding this fact, people mistakenly believe that PV panels produce less energy on a frosty sunny day than on a hot sunny day. This is not true, since solar panels do not need temperature; they need light to generate electricity. Moreover, the temperature reduces the efficiency of PV panels operation. Bright sun and low temperatures are excellent conditions for the efficient use of PV panels. In cloudy weather, the panels produce less energy than usual, due to the fact that not much light could go through. In such situations, it is advisable to use the accumulated energy of the storage batteries, which are usually charged during the day [28].

Taking into account all the above mentioned information, the Tomsk region (including Molchanovo district) is characterized by quite wide opportunities for solar power plants implementation, especially in rural areas.

Biomass energy potential

Biomass was the first type of energy that humanity used in their daily life. In 2002, the biomass fuel made up about 10% of total production of energy in the world [3]. Biomass includes such energy resources as peat, wood, agricultural waste, etc. Russian areas often contain sufficient amounts of energy resources, especially wood and peat. One of the main advantages of using biomass energy is the independence of the potential of energy resources from the time of year [1]. The drawbacks, on the other hand, can be quite severe. The usage of biomass power plant could lead to deforestation. The efficiency of the biomass fuel is less than fossil fuels. Biomass could be described as carbon neutral, however, pollution created from wood burning could make as much harm as burning coal or other natural resources. Moreover, regarding the transportation, harvest and storage of the fuel, it could be very expensive to deal with the mentioned problems, especially when comparing to the other energy like wind or solar [21].

Geothermal energy potential

This form of energy is characterized by the high temperatures that exist deep in the earth crust. The use of geothermal energy is efficient for those areas where the ground temperature is close to the earth's surface. The most effective utilization of the geothermal energy is usually observed in the regions that provide hot springs or geysers (e.g. in Iceland) [3]. Nowadays, high costs and technological difficulties seriously affect Russia in using this form of energy as an everyday energy source.

The main value for geothermal energy is the waters of volcanic and rift regions. Unfortunately, the percentage of these waters in Russia is very small and does not exceed 5-7% [1].

The towns and villages such as Belyj Yar, Kargasok, Parabel, Nazino, Narym, Chazhemto, Kolpashevo have the highest geothermal potential in Tomsk region due to the availability of some drilled oil wells, which brings the thermal water to the surface at approximately 66 degrees Celsius. Unfortunately, the Molchanovo district and therefore Sujga village does not lie in the mentioned area.

Conclusion

To sum it all up, the most efficient method of supplying Sujga village with electricity is to use solar energy in the process of generation. Sujga has quite a high number of sunny days, as well as the duration of sunshine per year. According to [6], the duration of sunshine greater than 2000 hours per year would lead to efficient use of the chosen method of solar power supply. In this case the duration is greater than 2000 hours per year. Moreover, the amount of solar radiation on the horizontal surface should be not less than 1000 kWh / m^2. In this case, this number is approximately 1000-1100 kWh / m^2 with average values of cloud cover, atmospheric transparency and open horizon. This corresponds to basic requirements of operation for small and medium-sized solar power plants which is exactly the case for Sujga village.

In the next chapter, the model of power consumption in Sujga will be created, providing the graphs and making a conclusion in the approximate amount of power consumed by village per day.

3. Power consumption modeling

This chapter is devoted to the description of power consumption in Sujga and its modeling, as well as plotting daily load diagram with a two-minute step.

As it is known from the previous chapter, Sujga village is supplied with electricity from the local DG. The streets have no lighting, the heating of the village is provided mostly by burning wood pellets or coal (in some parts of the village). No central electric heating is used [27].

3.1 Assumptions

Taking into account the map of Sujga, the number of streets and its population it has been roughly assumed that the amount of houses in Sujga is 150. Therefore, if there are 576 people living in the village [26], it is almost 4 people in average in one building, which is realistic, because the village has some big buildings such as: administrative center, shops, bakeries, warehouses and just large families with children.

For the simplification, model of the power consumption will be created for 10 houses and after some calculations and modeling, the results and values of the graphs will be multiplied by 15, which is going to give us relevant information about the power consumption of the whole Sujga village.

I have assumed that a common villager has the following equipment at home: fridge, microwave oven, electric kettle, television, cooker, lighting and sometimes computer and iron. All the calculations are done using Microsoft Excel software. The modeling of power consumption of the village is performed by taking the duration of the whole day (24 hours) and dividing it into equal intervals of two minutes. The whole time axis is 1440 minute, which is exactly 24 hours. After that, I used the power of different electric equipment and applied it to the axis of duration in each cell. I have tried to use a very realistic approach when placing the power in the cells. For instance, the cooker is most frequently used in the evening. The kettle can be used during the day, especially during breakfast, lunch and dinner times. The same applies to the microwave. The fridge has its own regime of operation; it turns on automatically once every 1-4 hours to keep the food cold. The lighting is turned off at night. The computer usually consumes about 100-180 W·h in a typical utilization (internet and other processes that do not consume much power) [30]. I have added 30 W·h to the consumption because of the monitor. Therefore in average a computer and a monitor consume from 130 W·h to 210 Wh. Power consumption of the computer is highly dependent on the use of its processor and a graphics card, thus, I will model different utilization of them throughout the day. The cooker and the iron turn off automatically once in a while to avoid overheating, therefore I have taken that into account. Moreover, consumed power of the cooker depends on the turned on burners as well as the position of the tumbler of the each burner; this has also been taken into account. Kettle, microwave and lighting do not change the power consumption during use, it stays constant and depends only on the time of operation. The period from 12-1 am to 6-7 am is the period of minimum load, the only thing that works from time to time at night is the fridge.

Every house is different: one uses incandescent light bulbs, has a small television, uses computer a lot, often cooks in the evenings, the other uses LED (Light-emitting diode) light bulbs, does not own a computer, does not cook a lot, has a big television, often turns on the electric kettle, etc. Every house has unique power consumption; this has been done specifically to diversify the consumption of electric energy.

Another important assumption is that the power consumption does not depend on the month, due to the fact, that villagers do not use electric heaters for space heating. They use fireplace stoves which require wooden logs as a fuel [27]. Therefore, I will assume that the power consumption stays more or less the same every day throughout the year.

Average power of the electric devices is shown in the Table 2 [31].

Table 2. Average power of the electric equipment

Name of the device	Power, W	Range of consumed electrical energy per hour, W
Fridge	400	0-400
Microwave oven	1700	500-1000
Kettle	2000	2000
Computer	300-500	130-210
Iron	2000	2000
TV	115-160	115-160
Cooker	1000-3000	800-3000
Lighting	Up to 300	Up to 300

Additionally I have added 0.01 kW to every cell for the losses and stand-by operation.

You can see the power consumption of each electric device for one arbitrary house below in the Figures 11-18. The vertical axis is power in kW. The horizontal axis is time in minutes, which means that the left side of the axis is midnight and 720 minutes is midday.

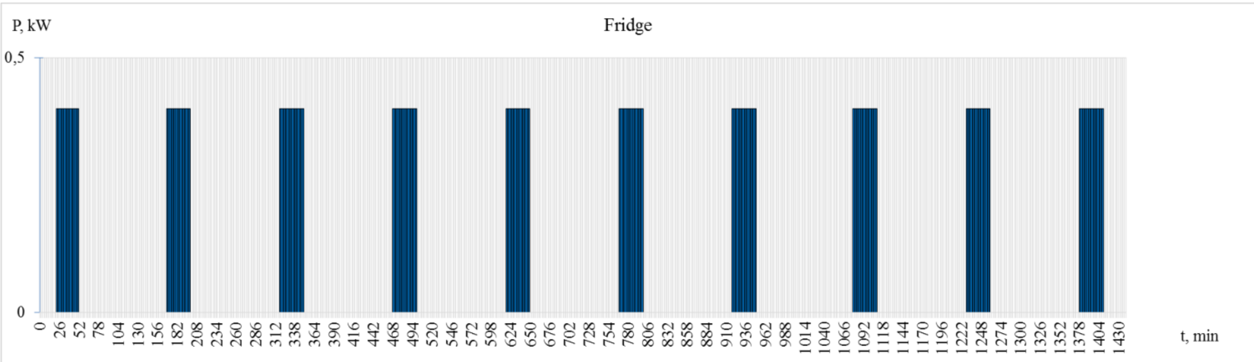


Figure 11 – Power consumption of the fridge

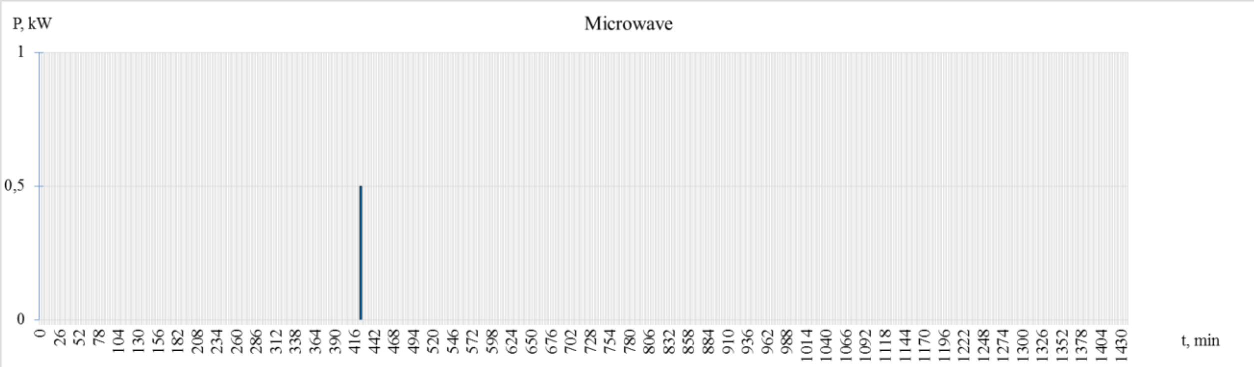


Figure 12 – Power consumption of the microwave oven

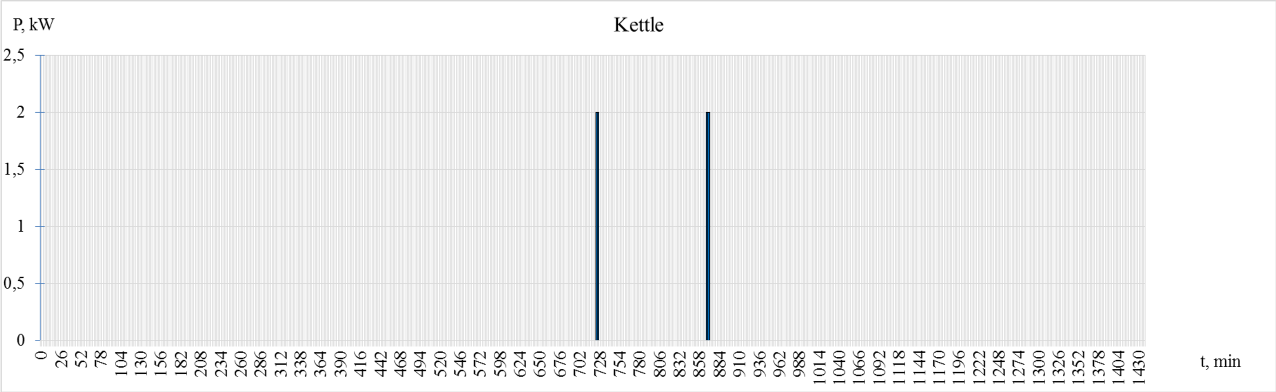


Figure 13 – Power consumption of the kettle

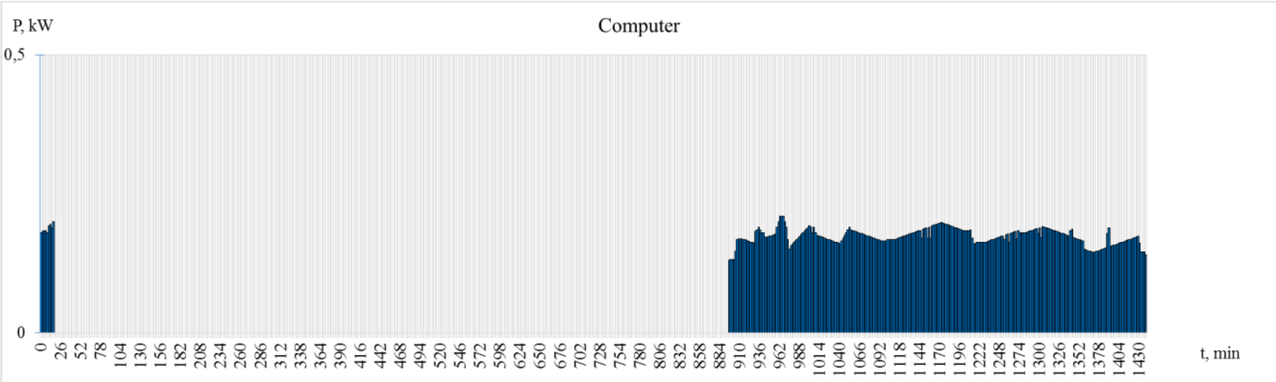


Figure 14 – Power consumption of the computer

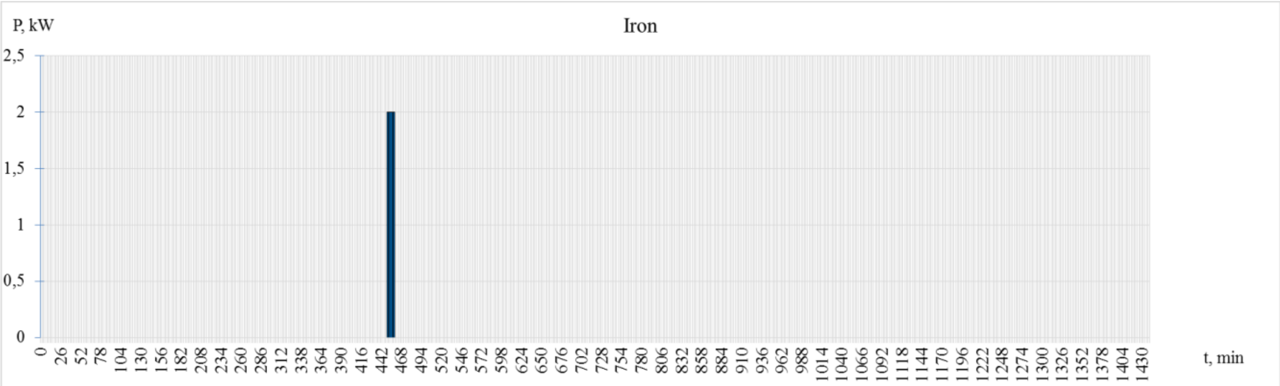


Figure 15 – Power consumption of the iron

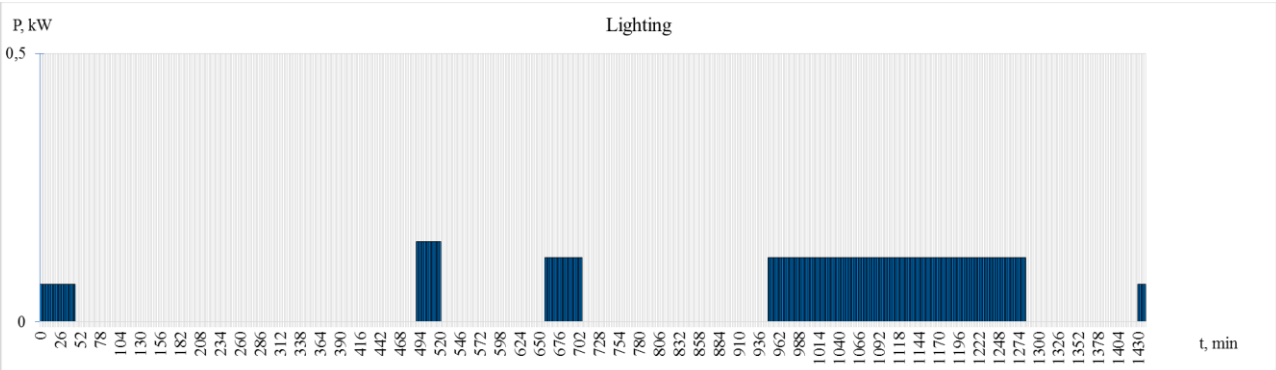


Figure 16 – Power consumption of the lighting

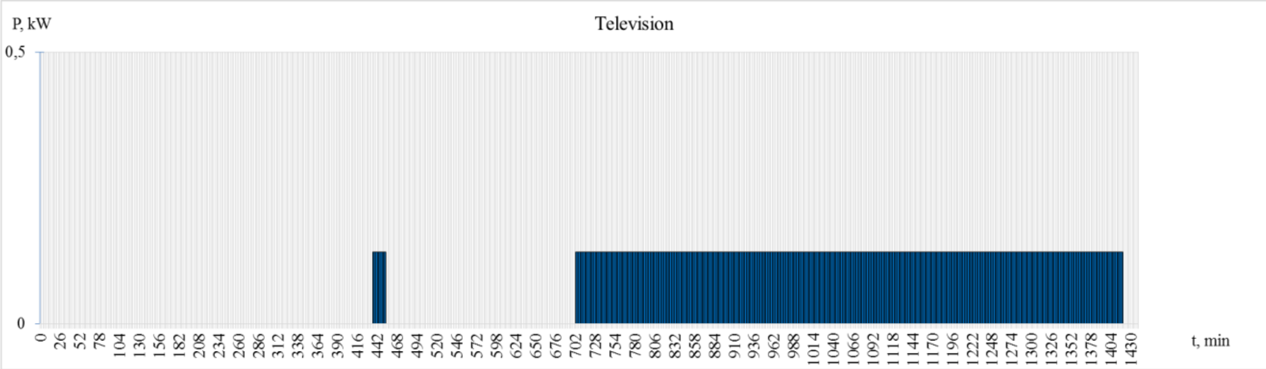


Figure 17 – Power consumption of the television

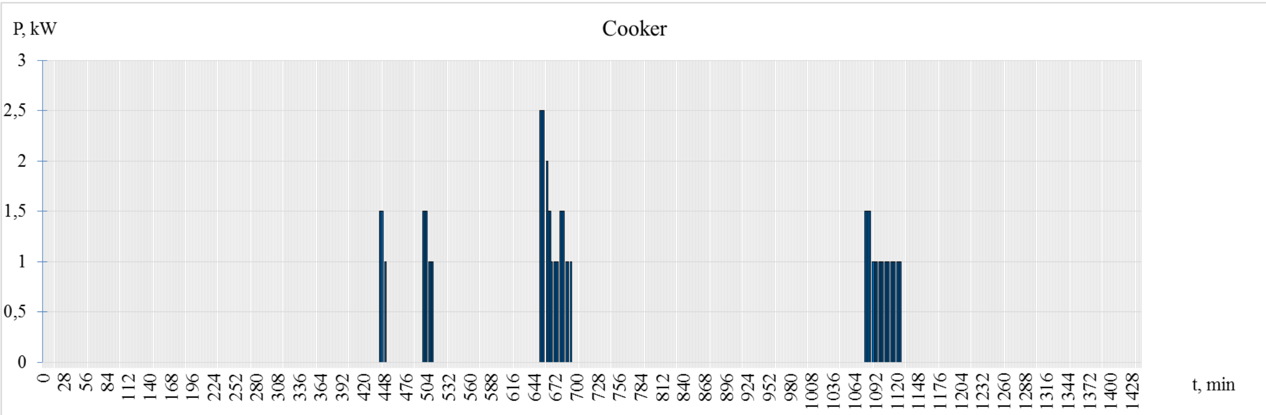


Figure 18 – Power consumption of the cooker

I will divide these 10 modeled houses into three approximately equal phases: A, B and C. According to my calculation, phase A has 27.16 kW·h per day, phase B has 27.87 kW·h per day and phase C has 29.79 kW·h per day. The total consumption is equal to sum of three phases and is 84.81 kW·h per day. This means that in average each house consumes 8.481 kW·h, which gives us the total of

$$8.481 \cdot 150 = 1272.15 \text{ kW} \cdot \text{h per day for the whole village},$$

The calculations for the total consumption have been performed by adding up all the values from each cell and dividing this sum by 24 hours, which has given us the correct total amount of consumed electric energy.

However, this value is not the final one, because the coefficient of simultaneity also has to be taken into account. According to [32],"The coefficient of simultaneity is the ratio of the calculated load of a group of electric receivers to the sum of their maximum loads". Coefficient of simultaneity takes into account the fact that all the devices are never turned on at full power at the same time for the investigated area. The coefficient of simultaneity in the network with a voltage of 0.38 kV, depending on the number of consumers for residential buildings with a load of more than 2 kW per 1 house is 0.24 for 100 houses and 0.20 for 200 houses. As the Sujga has about 150 houses, I have taken the coefficient of simultaneity equal to 0.22.

Applying this coefficient to the whole power consumption, I received the total consumption of Sujga, which is equal to 279.7 kW·h per day.

3.2 Load diagram

The final step would be to obtain a load diagram. I have plotted a load diagram in MS Excel using previously obtained data in each interval of 24 hours. In addition, I have multiplied each value by 15 as intended. The final step which has to be done is to take into account the simultaneity factor (multiply by 0.22).

The load diagram is presented in the Figure 19. The vertical axis represents consumed power in kW, the horizontal axis represents the time of the day in minutes. As we can see from the load graph, the morning peak occurs at about 7:00, while the evening peak occurs at about 18:30.

For the future use of the load diagram use, I have constructed an hourly version of the load diagram presented in Figure 20. It has been plotted by summing up the values at the specific hour of the day. It is important to use the values of consumed energy for the specific given time, for instance from 12:00 to 1:00, from 1:00 to 2:00, etc. As we can see from the graph, there are two main daily peeks of consumption, the morning peak at 7 am and the evening peek at 18 pm.

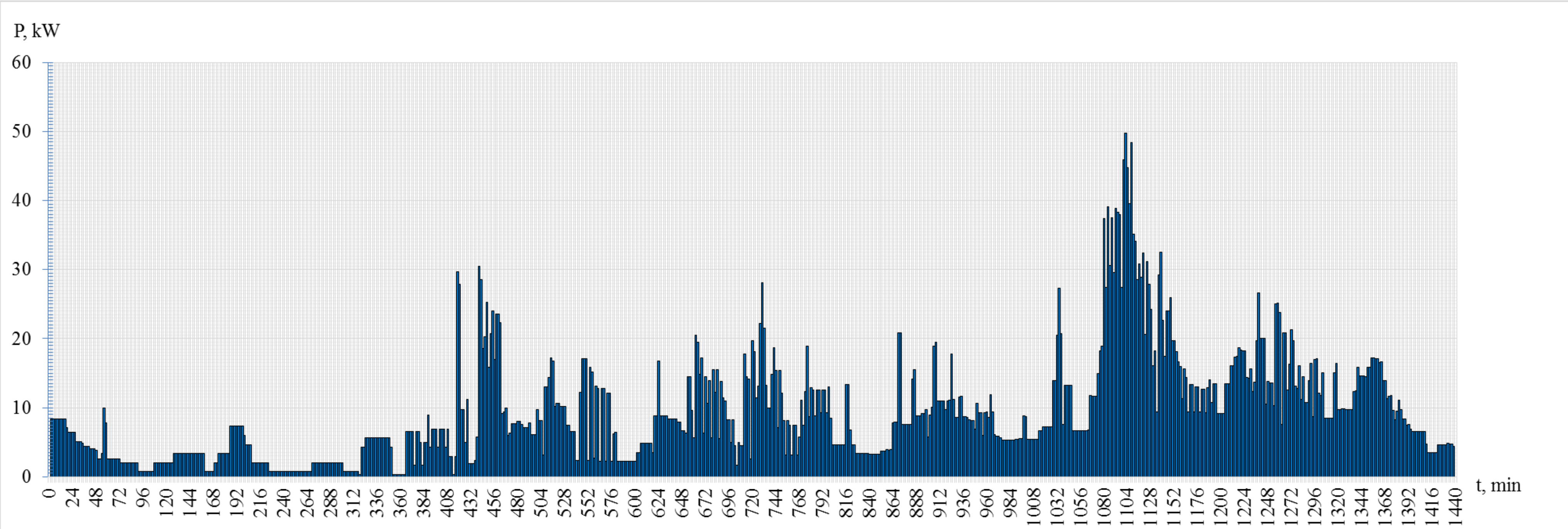


Figure 19 – Daily load diagram of the modeled village

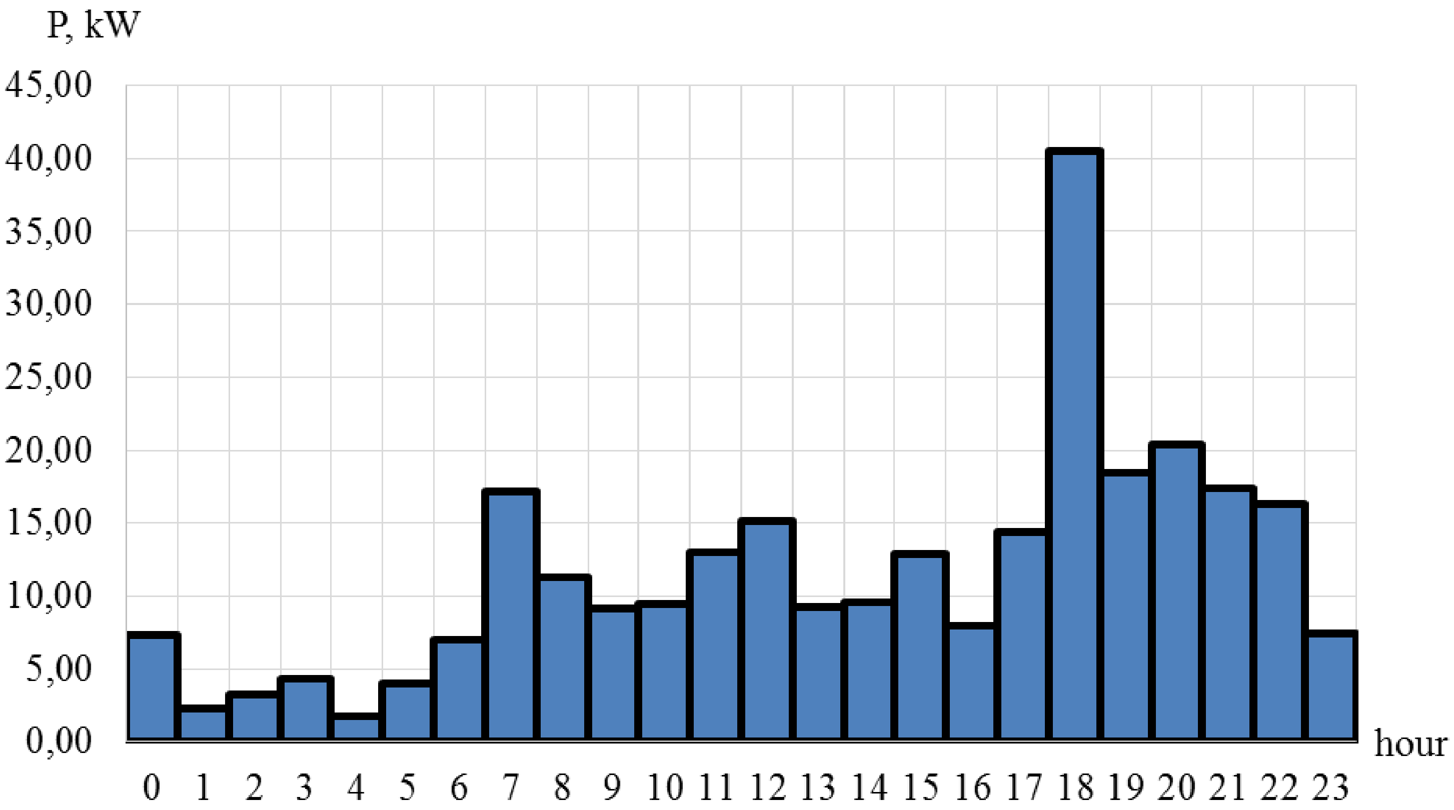


Figure 20 – Hourly load diagram of the village

4. Selection of electrical equipment

4.1 Structural diagram of the power supply system

A hybrid power supply consists of at least two independent energy sources. In my diploma thesis, it is a solar power plant (SPP) and a diesel generator (DG). The SPP is constantly in the mode of electric power generation, in case of lack of energy from solar radiation, the DG is connected, which fully covers the load.

Figure 21 shows the structural diagram of the power system, where SP – solar panels, C – controller, B – storage batteries, DG – diesel generator, I – inverter and L – load.

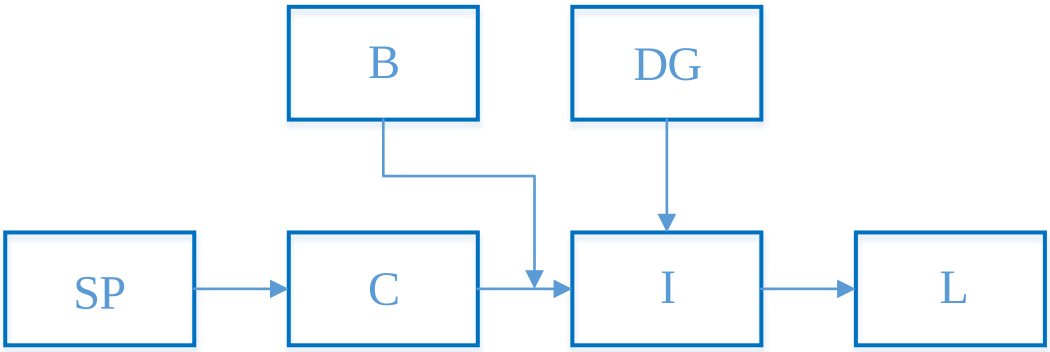


Figure 21 – Structural diagram of the power supply system

4.2 Selection of storage batteries

Operation of a solar, wind, hybrid power plant or other power plants with renewable energy have to have one of the main elements – electric energy storage device, a storage battery. The purchase of rechargeable batteries accounts for about 60% of the monetary investments, which makes their choice a highly responsible task [33].

In the next paragraph I will give a brief description of different kinds of storage batteries.

There are three main types of batteries [34]:

- lead acid;
- alkaline;
- lithium-ion.

When designing an isolated power supply system based on renewable energy sources, I will consider lithium-ion batteries. For the considered isolated power supply system, I chose lithium-iron-phosphate batteries ($LiFePO_4$) for a number of reasons.

Lithium batteries have recently become widely used in autonomous solar power plants, they were restrained by the instability of technology and a relatively high price. However, with the development of $LiFePO_4$ technology, they have become much more affordable, and most importantly, they are safe for widespread use. The main advantage of $LiFePO_4$ is the high number of charge-discharge cycles. This number of cycles is sufficient, the power plant has been operating without replacement of any components, repairs and expensive maintenance for 10-20 years. At the moment, batteries of this type allow you to store and store electrical energy with the lowest cost of one charge-discharge cycle [34].

They charge very quickly, can give up to 80% of the charge, do not lose capacity due to incomplete charging or long storage in a discharged state. They are quite expensive, but in comparison with, for example, acidic ones, they have twice the capacity per unit of weight [33].

$LiFePO_4$ also has some disadvantages, it works at subzero temperatures. The discharge is possible only up to a temperature not lower than -20C. It is also imperative to use balancing and leveling circuits for the cells. In this regard, when buying LiFePO4, it is worth taking the so-called "energy storage systems", which include the $LiFePO_4$ cells themselves, their control and balancing systems and a monitoring and alert system that allows you to warn of possible potential problems long before they arise. [33].

After considering some options of manufacturers of the necessary equipment for creating a working complex, I decided to choose the company "Microart" with their $LiFePO_4$ LT-LFP + BMS and WB-LYP100AHA + BMS [35].

Figure 22 – $LiFePO_4$ storage battery + BMS [35]

The main advantages are [35]:

1. Not much wires. Wires slow down and complicate installation, they increase the probability of installation errors, and reduce the overall reliability of the system.

2. Direct interaction of the BMS (Battery Management System) with the solar controller, which provides faster charging. No need for a central control board.

3. Affordable price.

Battery calculation

The basis for choosing the battery capacity is the daily consumption. I have chosen batteries with a constant voltage of 12 V, the discharge depth is 25%, because this is the maximum percentage, which will result in the highest number of cycles according to the manufacturer [35]. Given these initial data, lithium-ion elements show very good results. To calculate the battery capacity, I have used the following formula:

$$Q_{AB}^{nom} = \frac{E_{cons} \cdot t_{reserve}}{U_{AB}^{nom} \cdot k_{ab}}, \quad (1)$$

$$Q_{AB}^{nom} = \frac{279,7 \cdot 1000 \cdot \frac{17}{24}}{12 \cdot 0.25} = 66040 \text{ A} \cdot \text{h}$$

where k_{ab} – discharge depth, E_{cons} – daily consumption [kWh], $t_{reserve}$ – time of load reserve [days], U_{nom} – nominal voltage of the battery [V], Q_{AB} – nominal capacity of the battery pack [A·h].

As a result, the total capacity of the battery pack should be 66040 A·h in order to reserve a load of 17 hours (this is the maximum time, in which the energy is going to be stored in the batteries throughout the year – in winter). When the days are longer, there is no need in reserving for 17 hours, which means the depth discharge is going to be even less than 25%, which will result in a higher number of work cycles of storage batteries. This will help the storage batteries to work effectively so they do not require additional investments and maintenance.

I have chosen a model of batteries of the Russian manufacturer "Liotech". The presented variants of lithium iron-phosphate batteries start from 170 A·h and end with 770 A·h. I have chosen the model LT-LYP770 with nominal voltage 12 V in the amount of:

$$N_{bat} = \frac{66040}{770} = 86 \text{ pcs} \quad (2)$$

4.3 Selection of solar panels

There are several types of solar panels [36]:

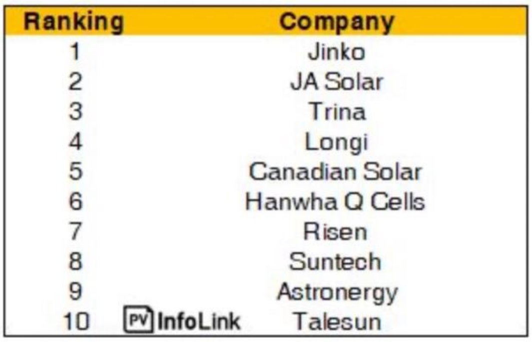
1. Silicon: monocrystalline, polycrystalline, amorphous
2. Tellurium-cadmium
3. Based on indium-copper-gallium selenide
4. Polymer materials
5. Organic
6. Based on gallium arsenide
7. Combined and multi-layer

A general customer is only interested in the first two crystal subspecies. Some other panels, although they may have a slightly higher efficiency, but due to the high cost, they are not widely used. The main types of solar panels used in solar power plants are silicon monocrystalline and polycrystalline [36].

In single-crystal panels, the grains of the crystals are oriented in one direction, since in fact, the plates are cut from a single cylindrical crystal. Batteries based on monocrystalline modules have the highest efficiency — up to 22%. In polycrystalline panels, the modules of silicon crystals are arranged and oriented randomly, which affects the performance of the module, which is 10-15% lower than the performance of single-crystal modules. However, the production of batteries on such modules is less expensive, and therefore the batteries have the lowest price [37].

Since the reduced efficiency and relative big size are quite significant disadvantages, I have chosen single-crystal panels.

I have chosen the solar panels JA Solar-410W, which came in second place in the PV InfoLink 2019 rating, as one of the largest suppliers of solar modules.



Ranking	Company
1	Jinko
2	JA Solar
3	Trina
4	Longi
5	Canadian Solar
6	Hanwha Q Cells
7	Risen
8	Suntech
9	Astronergy
10	Talesun

PV InfoLink

Figure 23 – PV InfoLink 2019 Rating

JA Solar Solar modules are high-quality premium modules. The company JA Solar Holdings Co., Ltd, is among the top 10 best manufacturers of PV panels in the world. The high quality of the products is confirmed by the international certificates of TÜV. The Percium series is a high-tech single-crystal solar module from JA Solar [38]. The solar panel is shown in the Figure 24.

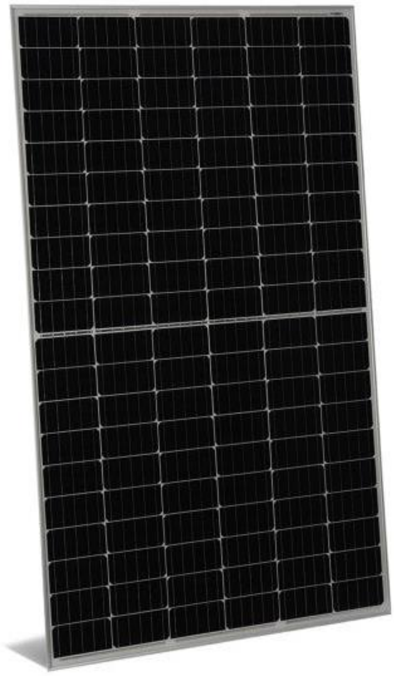


Figure 24 – JA Solar 410W PV panel [38]

Main technical characteristics [38]:

- Rated power - 410 W;
- Crystal type-single crystal
- No-load voltage-50.08 V;
- Maximum voltage-42.54 V;
- Closed circuit current - 10.26 A;
- Current at maximum power - 9.64 A;
- Maximum efficiency – 20.6%;
- Width 1005 mm; Height 2037 mm.

The main advantages of Percium solar cells [38]:

1. In the manufacture of solar cells, double-layer printing technology is used, which eliminates defects on the structure.

2. Excellent performance in ambient light

3. Complete, fully automated production cycle

4. Special solar cell structure, increasing the average efficiency to 20.6%

5. Before shipping, the solar panels pass the EL test twice

4.4 Selection of controller

MPPT – Maximum Power Point Tracking. The principle is based on the constant measurement of the current and voltage generated by the panels and ensuring their optimal ratio, which depends on the time of day and on the current weather conditions. This will allow you to achieve the most efficient use of battery power in almost all operating modes [39].

For MPPT controllers that convert excess voltage into additional current, the required reserve for rated current must be even greater and the total battery current can be limited to up to 75%, and sometimes up to 60% of the current given by the controller to the load. In some conditions, the output of the photo panels itself may exceed the nominal one, for example, on a clear winter day, when there is white snow that perfectly reflects light, contributes to the over-illumination of the photo cells compared to the calculated one, and a moderate frost slightly increases their efficiency, and the controller must withstand such excessive output [39].

I have chosen the MPPT controller for the power plant for the following reasons.

The main advantages of MPPT controllers compared to Pulse Width Modulation (PWM) controllers [1]:

- high efficiency;
- optimal performance when an area of the solar panel is shaded;
- increased efficiency in low light conditions and cloudy weather;
- increased return when the temperature of the solar module increases (which leads to a decrease in its power), and at negative air temperatures (which, accordingly, leads to an increase in power);
- using a higher input voltage, allows you to reduce the cable cross-section;
- allows you to increase the distance from the panels to the controller.

I have chosen a solar controller of the company "MicroART" KES DOMINATOR MPPT 250/60.

The chosen controller is presented in the Figure 25 below.

Figure 25 – Solar controller DOMINATOR MPPT 250/60 [39]

Main technical specifications [40]**:**

Maximum current: 60 A;

Voltage of the storage batteries: 12/24/36/48/96;

Type of the storage batteries: $LiFePO_4$;

Maximum voltage from solar panels: 250 V;

Efficiency: 98%.

4.5 Selection of inverter

For a load of more than 1500 W, it is recommended to choose a 48 Volt inverter [1].

I have selected the MAP SINE DOMINATOR inverter.

The latest development, the MAP DOMINATOR inverter not only has all the functions of the best European brand inverters, but also surpasses them in some ways. MAP DOMINATOR is able to synchronize not only with the 220V network (or with an electric generator), but also in parallel between other MAP DOMINATOR inverters (up to 10 pieces in parallel). This can be useful for gradually increasing the capacity and improving the system's fault tolerance [41].

The price of the MAP DOMINATOR inverter is 3-5 times lower than for similar power and functionality branded inverters from the best European manufacturers [41].

The inverter is selected based on the peak power consumption during a day with a 20% reserve, as the inverter cannot operate at full capacity [6]:

$$P_{Inverter} = 1.2 \cdot P_{MAX} = 1.2 \cdot 49.76 = 59.7 \text{ kW} \quad (3)$$

where P_{max} is the peak load of the village [kW], $P_{inverter}$ – power of the inverters [kW].

I will select three 20 kW inverters.

Technical specifications are shown in the Table 3.

Table 3. Technical specifications of MAP DOMINATOR inverter [41]

Name	20 kW DOMINATOR inverter
Power, kW	20.00
Efficiency, %	96
Voltage, V	48.0
U_{output}, V	220
~Frequency, Hz	50
Peak power, kW	25.00

The following inverter is shown in the Figure 26.

Figure 26 – Inverter MAP DOMINATOR [41]

Advantages of the chosen inverter:

1. The chosen inverter can provide high charging currents, which allows the use of external batteries even with a very high capacity.

2. Safe battery assembly voltages (12 V, 24 V or 48 V) and easy access to the batteries.

3. The inverter has a microcomputer board that allows controlling the inverter, claiming statistics, and utilizing functions. The software is suitable for all MS Windows.

4. The inverter can be connected in parallel or combined into 3 phases

5. Low-frequency technology used provides a minimum level of electromagnetic emissions and higher reliability.

4.6 Selection of diesel generator

Based on the need to provide consumers with electricity in all situations, the choice of the number and power of diesel generators (DG) should be carried out taking into account the following requirements. The following values can be considered as recommendations for the efficient use of the diesel generator in the hybrid power supply system according to [1]:

1. The total capacity of the units must be 25% higher than the daily maximum load.

2. For ease of maintenance, it is advisable to choose a DG of the same size.

3. The load of diesel generators should be within 25-80% of the nominal load.

4. The number of diesel generators must be excessive to ensure that the units can be taken out of operation for maintenance and major repairs.

5. The operating conditions of diesel power plants must correspond to the climatic characteristics of the area.

According to the schedule of daily electricity consumption, I will calculate the power for the selection of the DG.

Taking into account the 4^{th} requirement for the selection of the DG, I will choose two of them. One is for the backup, just to insure the unit can be taken out of the operation for major repairs and maintenance.

Calculation of power of one diesel generator [1]:

$$P_{DG} = 1.25 \cdot P_{MAX} = 1.25 \cdot 49.76 = 62.2 \text{ kW} \quad (4)$$

where P_{MAX} is the peak load of the village [kW], P_{DG} – power of the DG [kW].

According to the obtained data, I will choose the model of the AD-70 YAMZ 70 kW diesel generator of the Yaroslavl company "Diesel" [42].

Diesel generator 70 kW YaMZ / DGU AD-70-T400 is designed to generate three-phase alternating electric current with a frequency of 50 Hz, a voltage of 400 V, the main (nominal) power of 70 kW, reserve power 80 kW. The 70 kW YaMZ diesel generator is equipped with a V-shaped 11-liter turbocharged diesel engine with intercooling of the charge air, a mechanical fuel injection regulator and liquid cooling [42].

There are several key advantages of the chosen diesel generator:

- Reliable starting in cold conditions – reliable operation even in harsh northern conditions, soft start in sub-zero temperatures
- Extended engine life: 10,000 to 18,000 hours before overhaul
- Modesty to the quality of fuel: unlike most imported diesel generators not adapted to Russian fuel the classic YMZ engines with a very simple fuel system and a mechanical fuel injection regulator are very unpretentious towards fuel quality.
- Extended service interval
- The widest availability of spare parts: is No1 in Russia in terms of production and sales of diesel engines that are used in a wide variety of industrial and commercial equipment. This provides the widest availability of YAMZ spare parts in any region of Russia.

Technical specifications of the AD-70 YAMZ 70 kW diesel generator are shown in Table 4 [42].

Table 4. Technical specifications of the AD-70 YAMZ 70 kW diesel generator

Name	AD-70-T400	Power factor	0.8
Power, kW	70	Fuel consumption at 100% power, liters/hour	21.8
Type of current	Alternating, three-phase	Fuel consumption at 75% power, liters/hour	16.7
Nominal frequency, Hz	50	Fuel consumption at 50% power, liters/hour	11.6
Nominal voltage, V	400	Fuel efficiency - the cost for the production of 1000 kW·h of electric energy, liters	318.3
Nominal current, A	129.6	Fuel tank, liters	200

The chosen diesel generator is presented in the Figure 27

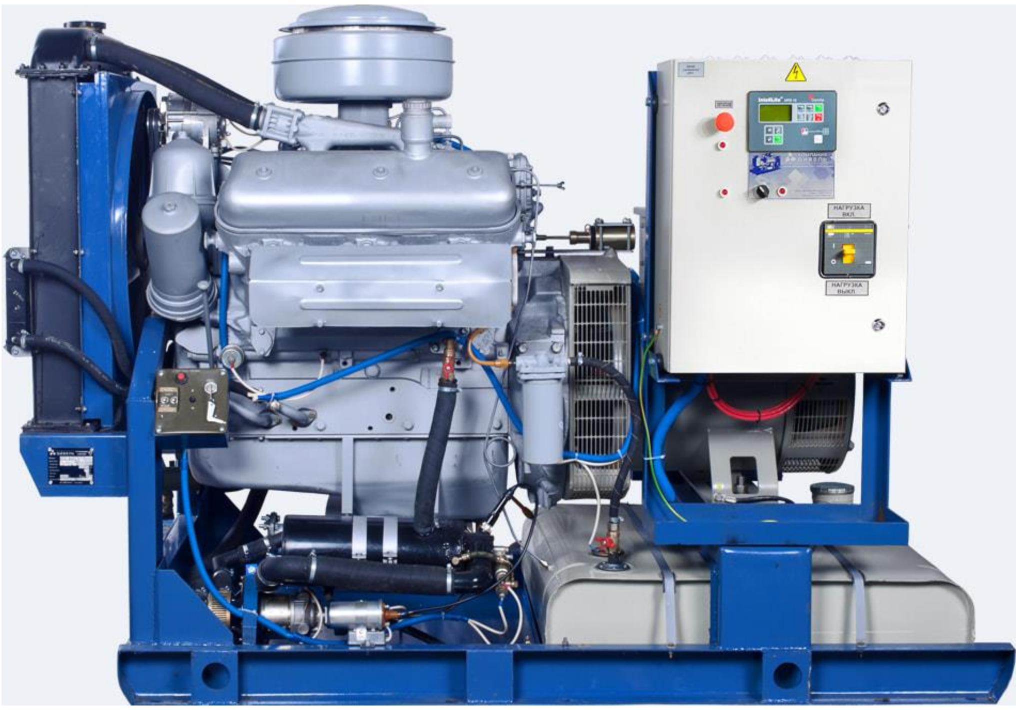


Figure 27 – Diesel generator AD-70 YAMZ 70 kW [42]

5. Solar-diesel power supply system

5.1 Preliminary calculations

For the calculation of solar generation, I have to calculate the amount of solar panels installed in the village. Firstly, the calculation of area of the PV panel is going to be made.

$$S_{PV1} = 1.005 \cdot 2.037 = 2.05 \text{ m}^2 \quad (5)$$

For the increase of efficiency of solar panels I will consider the optimum angle of inclination of PV panels. According to [6], most often, the angle of inclination of solar panels is oriented to the south and is assumed to be equal to the latitude of the area. This angle is considered optimal and the most technically feasible. In the case of village Sujga, the latitude is 57° [24].

The next step is going to be the calculation of number of solar panels. Monthly irradiance is going to be found by taking the month with the highest generation of solar energy – June because, when the monthly irradiance is taken using a month with low or average solar irradiance, the power supply system requires too much PV investment, which is going to be economically unprofitable. This data has been found using the Photovoltaic Geographical Information System [43].

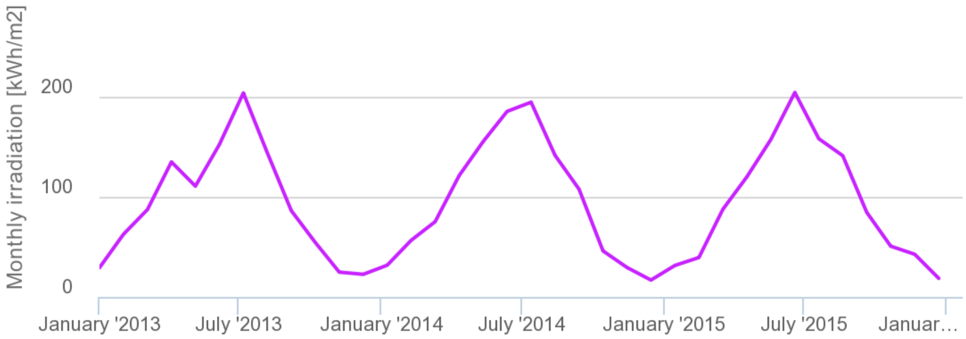


Figure 28 – Monthly solar irradiation estimates (2013-2015) [43]

The average irradiation in June from 2013 to 2015 is 200.82 kW·h/m^2

$$S_{req} = \frac{W}{\eta \cdot Q_s} = \frac{30 \cdot 279.7}{0.206 \cdot 200.82} = 203 \text{ m}^2 \quad (6)$$

where W – monthly consumption [kWh], η – efficiency of the solar panel, Qs – monthly solar irradiation [kW·h/m2].

Taking into account previously calculated area of the PV panel and required area, I have found the required number of PV panels.

$$N_{SP} = \frac{S_{req}}{S_{PV(1)}} = \frac{203}{2.05} = 100 \text{ pcs} \quad (7)$$

It is better to choose 108 solar panels: 6 parallel branches of 6 solar panels each connected in series. There are three such packs located on the territory of the village. The installed power of PV is calculated below, where P_{ins} – installed power [kW], P_{SP} – power of one solar panel [kW], N_{SP} – number of solar panels.

$$P_{ins} = P_{SP} \cdot N_{SP} = 0.41 \cdot 108 = 44.28 \text{ kW} \quad (8)$$

After finding the number of PV panels, I have found the time where the irradiance of the sun occur during the day for every season. In winter, the daytime is from 10 am to 5 pm. In spring and fall, the daytime is from 7 am to 8 pm. In summer, the daytime is from 6 am to 9 pm [43]. According to the previous load diagram in the Figure 20 the amount of energy consumed during time with no sun is presented in the Table 5.

Table 5. Amount of energy consumed during time with no sun (no irradiance)

Season	Winter	Spring	Summer	Fall
Daytime	10 am – 5 pm	7 am – 8 pm	6 am – 9 pm	7 am – 8 pm
Energy consumed daily at zero irradiance, kW·h	202.3	91.38	64.04	91.38

Table 6 shows the amount of consumed energy monthly, depending on the month of the year.

Table 6. Consumption of energy by month

Consumption	Total	Night	Day
Month	kWh	kWh	kWh
January	8 671	6 271	2 399
February	7 832	5 664	2 167
March	8 671	2 833	5 838
April	8 391	2 741	5 650
May	8 671	2 833	5 838
June	8 391	1 921	6 470
July	8 671	1 985	6 686
August	8 671	1 985	6 686
September	8 391	2 741	5 650
October	8 671	2 833	5 838
November	8 391	2 741	5 650
December	8 671	6 271	2 399
Total, kWh	102 091		

The total amount of consumption is 102091 kW·h a year.

As was noted earlier in the assumptions for load diagram modeling (5.3) the power consumption does not depend on the month. The power consumption stays more or less the same every day throughout the year, which means the monthly consumption depends only on the number of days in a specific month.

The Figure 29 below shows the monthly consumption of energy by each month of the year.

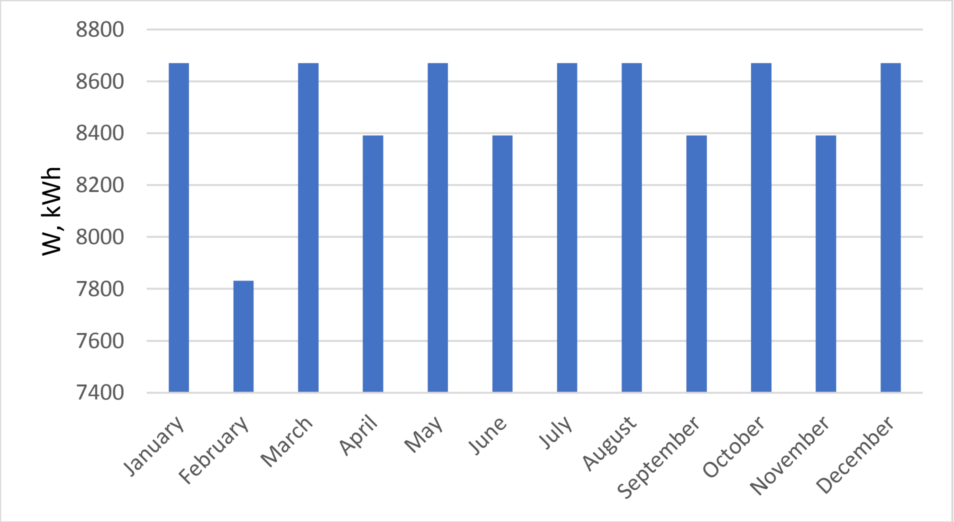


Figure 29 – Monthly consumption of electric energy

5.2 Scenarios

For analyzing different scenarios, I will take solar power supply system with and without using storage batteries, and a diesel generator. Moreover, I will increase the installed power of the solar power supply system by 20% with each scenario till +80% (there is no need in going further, because the PV investment becomes too big and the differences in fuel consumption reduction are not that high). And finally, I will model a scenario, where only the DG is supplying customers with electricity.

In this project, I have considered 11 scenarios:

1. 108 solar panels + batteries + diesel generators
2. 108 solar panels + diesel generators
3. 130 solar panels + batteries + diesel generators
4. 130 solar panels + diesel generators
5. 152 solar panels + batteries + diesel generators
6. 152 solar panels + diesel generators
7. 172 solar panels + batteries + diesel generators
8. 172 solar panels + diesel generators
9. 194 solar panels + batteries + diesel generators
10. 194 solar panels + diesel generators
11. Diesel generators

I will provide the calculation for the scenarios 5 and 6. The calculation for the rest of the scenarios can be found at the end of the diploma thesis, in the Appendices part.

1. Scenario 5 (152 solar panels + batteries + DG) and Scenario 6 (152 solar panels + DG).

   The consumption of electricity by month, as well as the PV generation for the Scenario 5, 6 is shown in the Figure 30.

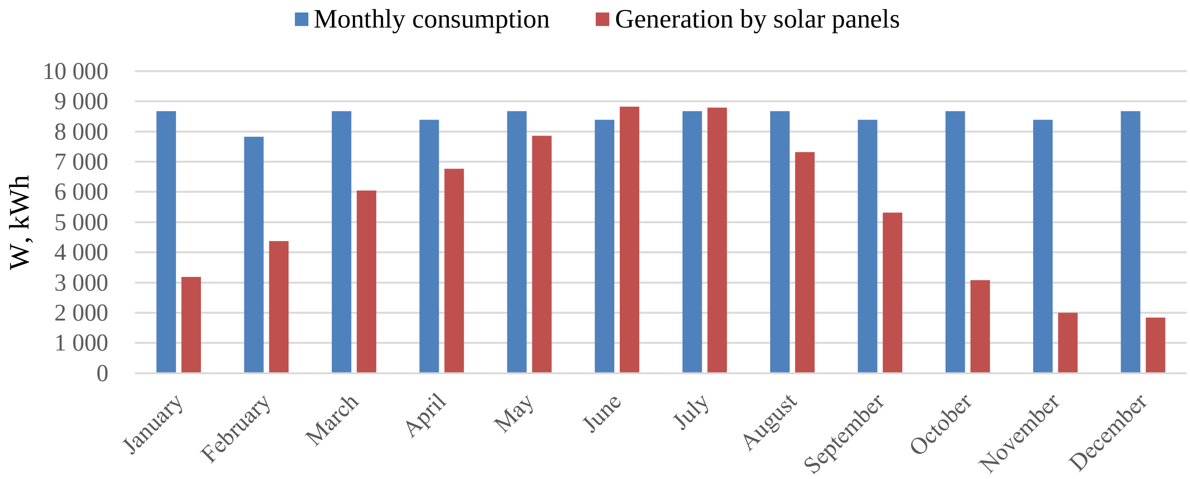


Figure 30 – Monthly consumption and generation (Scenario 1 and 2)

As can be seen from the Figure 30, the solar generation fully covers June and July.

The calculation for the Scenario 5 and 6 is presented in the Table 7 below.

Table 7. Scenario 5 and 6

					w/o storage batteries		
+40%			with batteries		For DPP supply		
152 PV panels	Generation, kWh	Consum-n, kWh	Delta 1, kWh	Diesel, kWh	Delta 2, kWh	Day, kWh	Night, kWh
January	3 182	8 671	-5 489	5 489	783	0	6 271
February	4 377	7 832	-3 455	3 455	2 209	0	5 664
March	6 043	8 671	-2 628	2 628	205	0	2 833
April	6 772	8 391	-1 619	1 619	1 122	0	2 741
May	7 859	8 671	-811	811	2 021	0	2 833
June	8 826	8 391	435	0	2 356	0	1 921
July	8 794	8 671	124	0	2 109	0	1 985
August	7 320	8 671	-1 351	1 351	634	0	1 985
September	5 313	8 391	-3 078	3 078	-336	336	2 741
October	3 076	8 671	-5 595	5 595	-2 762	2 762	2 833
November	2 002	8 391	-6 389	6 389	-3 648	3 648	2 741
December	1 844	8 671	-6 827	6 827	-555	555	6 271
Total for DG with batteries, kWh				37 241	total without batteries, kWh		48 122

Generation column in the Table 7 represents the generated energy during the month in kW·h. The consumption column shows the monthly consumption of the village in kW·h.

Delta 1 is the difference between the generation of solar panels and consumption by the village. The negative sign of the values depicts that the consumption overweighs the generation from PV panels. The diesel column represents the amount of energy in kW·h that has to be supplied by the DG, when the solar energy is not sufficient to cover the needs. For instance, for June we can see the zero diesel consumption, because generation of June is bigger than the consumption at the same month.

Delta 2 in the column with no storage batteries is calculated by subtracting the consumption during the day (sun irradiance is present) from the generation of solar panels, which means if delta is >0, the DG does not have to be working throughout the day, because the energy from the solar panels is enough to supply the load, however, the night use of energy has to be supplied by a DG since there are no batteries for storing energy for night utilization.

The total amount of required energy from the DG with and without the storage batteries is calculated in the last bottom row by summing up all the values of the column "Diesel" in the Scenario 1 and the column "Day" and "Night" in the Scenario 2, since the DG has to work during the night and during specific hours during the day.

As you can see from the Table 7 the amount of energy that is supplied by a DG in Scenario 5 is 37 241 kW·h, while the amount of energy supplied by a DG in Scenario 6 is 48 122 kW·h, which is more than in the previous scenario by 29%.

The consumption of electricity by month, as well as the PV generation for the Scenarios 1-10 is shown in the Figure 31.

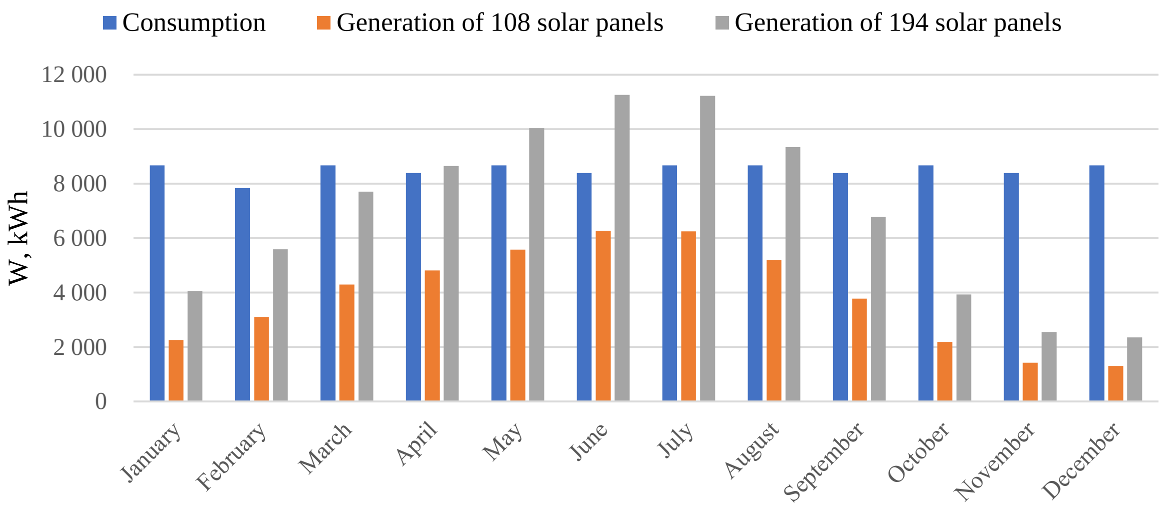


Figure 31 – Monthly consumption and generation (108-192 PV panels)

As it can be seen from the Figure 31, using 108 PV panels, the consumption cannot be covered even in the sunniest month, in June. However, when the number of PV panels increase by 84, we can see that from April until August, the generation of PV panels overlap the consumption of the village.

The calculations for the Scenarios 1-11 can be found at the end of the diploma thesis in the Appendices section (Appendix 1-7). Finally, I have obtained the values of energy supplied by a DG for each of the 11 scenarios. The data for the mentioned cases is presented in the Table 8.

Table 8. Annual generation by the DG in different scenarios

No	Scenario	Total annual generation by DG, kWh
1	DG + 108 PV panels + batteries	55 617
2	DG + 108 PV panels	56 559
3	DG + 130 PV panels + batteries	46 147
4	DG + 130 PV panels	50 988
5	DG + 152 PV panels + batteries	37 241
6	DG + 152 PV panels	48 122
7	DG + 172 PV panels + batteries	31 176
8	DG + 172 PV panels	46 875
9	DG + 194 PV panels + batteries	26 321
10	DG + 194 PV panels	45 873
11	DG	102 091

As can be seen from the Table 8, the maximum amount of energy generated by a DG in a year is 102091 kW·h. The most efficient scenario in terms of fuel consumption reduction is Scenario 9 (DG, 194 PV panels and storage batteries). However, this variant requires the most investment. Therefore, in the chapter 6, I am going to perform an economic evaluation of the proposed variants in order to find the most economically efficient one, taking into account many economic parameters: such as discount rate, inflation, maintenance, fuel cost, etc.

5.3 Calculation of diesel fuel consumption

The installation of a PV power supply system is economically efficient only if the costs of renewable energy source are comparable with the cost of saved diesel fuel. The efficiency of renewable energy installations depends mostly on the potential of the energy resource. The bigger savings from the fuel correspond to the more hours of operation of the SPP.

The absolute fuel consumption of the DG is determined by the formula below [6]:

$$G_1 = K_i \cdot G_r + (1 - K_i) G_r \frac{P_1}{P_r} \tag{9}$$

Where G_1 – real fuel consumption [g/kW·h];

G_r – rated fuel consumption [g/kW·h]; For the chosen DG, I have assumed G_r = 230 g/kW·h [6]

K_i – no load fuel consumption coefficient (Ki=0.3);

P_1 – load on the generator [kW];

P_r – rated capacity of the generator [kW].

After the calculation of real fuel consumption for each interval, we can calculate amount of consumed fuel for the period of time using the following formula [6]:

$$Q_{fuel} = G_1 \cdot W \tag{10}$$

Where Q_{fuel} – real fuel consumption [g];

G_1 – real fuel consumption [g/kW·h];

W – energy, generated a given time period [kWh].

The price of the diesel fuel, according to [44] at the start of 2021, is 53225 ₽ per one ton of diesel fuel.

Taking into account all the above mentioned data, I have calculated the consumption of diesel fuel in each of the scenarios. The information about the consumption of the diesel fuel is shown in the Table 9.

Table 9 – Annual consumption of diesel fuel by DG in different scenarios

No	Scenario	Annual cons-n of diesel by DG, tons
1	DG + 108 PV panels + batteries	8,315
2	DG + 108 PV panels	8,456
3	DG + 130 PV panels + batteries	6,899
4	DG + 130 PV panels	7,623
5	DG + 152 PV panels + batteries	5,568
6	DG + 152 PV panels	7,194
7	DG + 172 PV panels + batteries	4,661
8	DG + 172 PV panels	7,008
9	DG + 194 PV panels + batteries	3,935
10	DG + 194 PV panels	6,858
11	DG	15,262

As it can be seen from the Table 9, the least amount of tons of diesel per year is depicted by the 9^{th} scenario, as it should be, since it has the least amount of energy generated by a DG. The maximum number of tons of diesel fuel corresponds to the last scenario, where only the DG is operating. In the next chapter, an economic analysis will be performed to find the most economically profitable variant according to the main economic parameters, such as: discount rate, inflation, maintenance, fuel cost, etc.

6. Economic evaluation

In this part, after calculating the main scenarios, I am going to perform an economic evaluation using the main economic criteria and the economic input parameters. At the end, I am going to calculate the NPV of the different variants and compare the options by the value of NPV. Moreover, there is going to be a sensitivity analysis performed using such parameters as discount rate, diesel fuel price, PV investment costs, escalation of fuel price.

6.1 Theoretical background

The main criterion that is going to be mentioned in the economic evaluation is:

Net Present Value

Net Present Value (NPV) is a sum of discounted cash flows throughout the lifetime of the project minus initial investment price. The final results of the NPV are going to be presented both in rubles and euros. The NPV is described by the formula below:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - INV, \tag{11}$$

Where CF_t – cash flows during the period t;
t – number of time periods;
r – discount rate;
INV – Total initial investment costs;
T – lifetime of the project;
NPV – net present value.

NPV shows the difference between the present value of cash inflows and the present value of cash outflows. However, there will be no cash inflows in the economic model. The NPV will include such economic factors as: initial investment cost, annual maintenance costs, fuel costs, escalation of fuel price, inflation and lifetime of the project. The project assessment will be based on the mentioned factors. Each option (out of 11) is going to be assessed by using the NPV of the project. Since there are no cash inflows, the NPV is going to be negative for all variants, therefore the comparison of the options will be performed by taking the variant with the highest NPV, comparing to the others [46].

6.2 Economic parameters

Inflation

Inflation is an average increase of prices of products and services over time (usually during the year). Inflation rate will be used for the future escalation of prices for the maintenance of the equipment and for the delivery of the diesel fuel. To estimate the future inflation rate, it is advised to analyze the inflation in the past years. The data for the past 10 years has been presented in the Table 10 [47]. The average inflation for the past 10 years is 6.57%. Despite the data being accurate, it does not represent the future changings of the inflation. Therefore, I will use more relevant data for the project, which is mentioned in the Table 11 below.

Table 10. Historical values of inflation (2010-2020) [47]

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Inflation, %	8.78	6.10	6.58	6.45	11.36	12.91	5.38	2.52	4.27	3.05	4.91
Average Inflation, %	6.57										

For the economic evaluation I am going to use the inflation forecast by the Central Bank of Russia and the Ministry of Economic Development. The forecast is shown in the Table 11 and corresponds to the 2021-2025 [48].

Table 11. Inflation forecast by the Central Bank of Russia and the Ministry of Economic Development [48]

Inflation / Year	2021	2022	2023	2024	2025	2026-2040
Inflation, %	4,2%	4,0%	3,8%	3,7%	3,5%	3,83%
Average Inflation, %	3,83%					

Table 11 shows the inflation rate for the lifetime of the project. The 2021-2025 have been forecasted by the Central Bank of Russia and the Ministry of Economic Development. The inflation for the years 2026-2040 has been found by using a geometric average of the values to assume the inflation for the 2026-2040 years. The inflation for these years is assumed to be 3.83%.

Discount rate

One of the most important factors that influence the whole economic model is the discount rate. Discount rate is used for determining the present values of future cash flows. I have assumed the discount rate to be equal to risk-free governmental bonds in Russia. Risk-free rate is taken as 7%, according to Russian governmental bonds [49]. The discount is assumed to be 7%.

Escalation rate

Cost of equipment, fuel and other products escalate each year. The average escalation can be taken as the inflation rate mentioned before. In this diploma thesis, escalation rate for 2025-2040 is taken as 3.83%. The escalation of the diesel fuel price is very difficult to predict and estimate. There are no accurate and valid sources of information about it on the internet; therefore I have also assumed the diesel fuel price to escalate at 3.83% each year.

6.3 Input for the economic model

It is important to take into account the main input parameters when creating an economic model. I am going to consider 11 scenarios with different equipment configurations. Since, the investigated power supply system is of an off-grid type, I cannot sell electricity to the grid, therefore, there will be no cash inflows in my economic model, which means that the NPV of the variants will be negative. I will compare scenarios based on cash flow and NPV. The main input parameters for the economic model are presented below.

Investment

The prices of the equipment have been taken from vendor websites. Besides the main electrical equipment such as solar panels, diesel generators, storage batteries, inverters, controllers, I have also selected a frame for the installation of solar panels. Moreover, I have taken into account the cost of installation as 20% [1] from the initial investment and the delivery of the equipment to the necessary location of 200000-250000 rubles (depending on the scenario) [1]. The investments are done by the funds of the company without taking any loans.

The Table 12 shows the investment costs of each scenario.

Table 12 – Investment costs for each scenario

No	Scenario	Total investment cost, RUB	Total investment cost, EUR
1	DG + 108 PV panels + batteries	8 995 720	99 952
2	DG + 108 PV panels	4 999 640	55 552
3	DG + 130 PV panels + batteries	9 378 520	104 206
4	DG + 130 PV panels	5 382 440	59 805
5	DG + 152 PV panels + batteries	9 761 320	108 459
6	DG + 152 PV panels	5 765 240	64 058
7	DG + 172 PV panels + batteries	10 109 320	112 326
8	DG + 172 PV panels	6 113 240	67 925
9	DG + 194 PV panels + batteries	10 492 120	116 579
10	DG + 194 PV panels	6 496 040	72 178
11	DG	2 203 000	24 478

Operational costs

The lifetime of the project is 20 years, since the selected equipment's (DG, Inverter, Controller, PV panels) service life is equal to 20 years in average. With a discharge depth of 5-25 %, the service life of storage batteries of the selected type is 15-25 years when stored and operated under normal conditions [35]. Since the discharge depth in this project is 25%, I will consider the service life of the storage batteries to be 20 years, which means there is no need of purchasing equipment throughout the whole lifetime of a project.

The maintenance cost for PV panels was taken as 2% each from solar panels investment per each year [6]. The maintenance of batteries throughout their lifetime is not required, according to the producer [35]. The annual maintenance for the diesel generators is estimated to the 5% of its cost in scenario 11, since it is the only source of energy. For the rest of the scenarios, annual maintenance for the diesel generators is taken as 2.5% [45].

The diesel fuel is coming from the nearest oil refinery (Molchanovo). Taking into account the prices of fuel transferring of different companies, I have assumed that it costs 15000 ₽ per shipping of one ton of fuel. The price of the diesel fuel was calculated in Fuel consumption calculation (5.3). The price of 1 ton of diesel fuel is 53225 rubles.

6.4 Calculation of the economic model

According to all the previously mentioned economic parameters and input data, I have created the economic model for each of the scenarios. The next step of economic evaluation is to calculate the NPV for each variant. Since there are no cash inflows, the NPV of every project is going to be less than zero, therefore the most economically profitable project has the highest NPV (closest to zero).

The NPVs of each scenario are shown in the Table 13. The economic calculations of each scenario in detail are presented at the end of the diploma thesis in the Appendices 15-25.

Table 13. The net present value of each scenario

No	Scenario	NPV, RUB	NPV, EUR
1	DG + 108 PV panels + batteries	-18 054 580	-200 606
2	DG + 108 PV panels	-14 195 642	-157 729
3	DG + 130 PV panels + batteries	-17 135 348	-190 393
4	DG + 130 PV panels	-13 843 462	-153 816
5	DG + 152 PV panels + batteries	-16 298 791	-181 098
6	DG + 152 PV panels	-13 884 230	-154 269
7	DG + 172 PV panels + batteries	-15 832 996	-175 922
8	DG + 172 PV panels	-14 119 711	-156 886
9	DG + 194 PV panels + batteries	-15 584 888	-173 165
10	DG + 194 PV panels	-14 431 847	-160 354
11	DG	-18 251 497	-202 794

I compared the variants according to their net present values. The calculation of the economic model shows the most economically profitable scenario, which is No 4 with the highest NPV equal to -153 816 euros. As we can see the DG-powered system has a lower NPV equal to -202 794 euros.

In the next subchapter I will perform a sensitivity analysis for three scenarios, the most profitable one (no 4), the most profitable one among the configurations with storage batteries (no 9) and the configuration that uses only the diesel generator for supplying the customers (no 11).

6.5 Sensitivity analysis

Sensitivity analysis is an evaluation of the impact of changes in the parameters of an investment project (expenses, discount rate, investment costs, etc.) on its final characteristics, which is NPV in this case. The sensitivity analysis will be calculated for three configurations: the most profitable one (no 4 – DG + 130 PV panels), the most profitable one among the configurations with storage batteries (no 9 – DG + 194 PV panels + storage batteries) and the configuration that uses only the diesel generators for supplying the customers (no 11 – DG).

The sensitivity analysis will be performed on the following 4 parameters, because these chosen parameters can easily affect the final decision:

1. Discount rate
2. Diesel fuel price
3. PV investment cost
4. Escalation of diesel fuel price

1. Discount rate

The Figure 32 shows the dependence of NPV on the discount rate of the project.

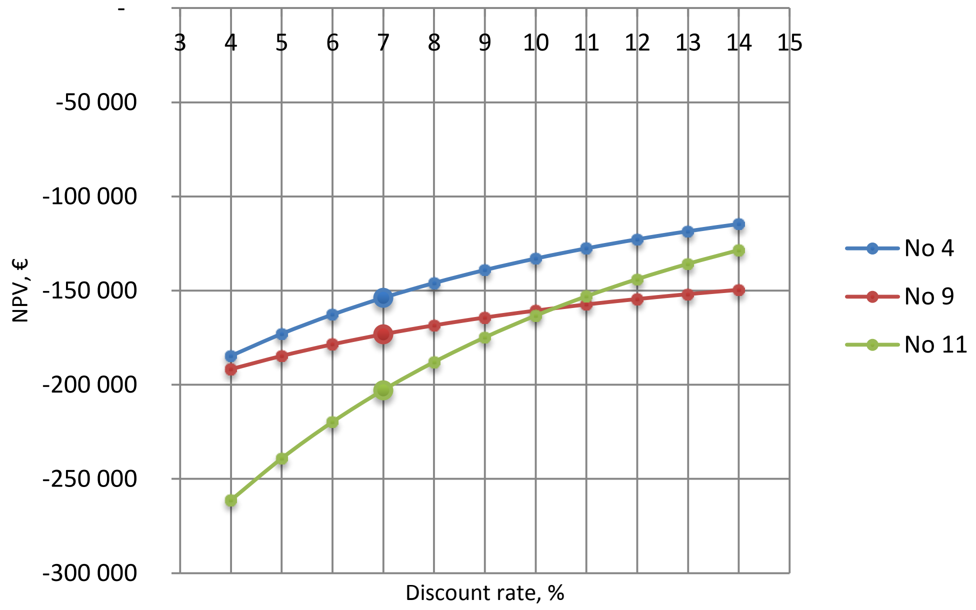


Figure 32 – Dependence of NPV on discount rate

The first analysis has been made on the discount rate. As we can see from the Figure 28, the NPV increases with the growth of discount rate. That is explained by the negative cash flows within each year. Figure 32 shows that with a discount rate greater than around 10.4%, scenario 11 is leading the scenario 9, unlike the case where discount rate is less than 10.4%. The scenario 4 is showing the best NPV throughout the whole change of discount rate. At some point in the future, scenario 11 will overlap the scenario 4, however this change is very unlikely due to a very big value of discount rate. The initial NPV is shown by the big dots, which correspond to the chosen 7% discount rate in the diploma thesis.

2. Diesel fuel price

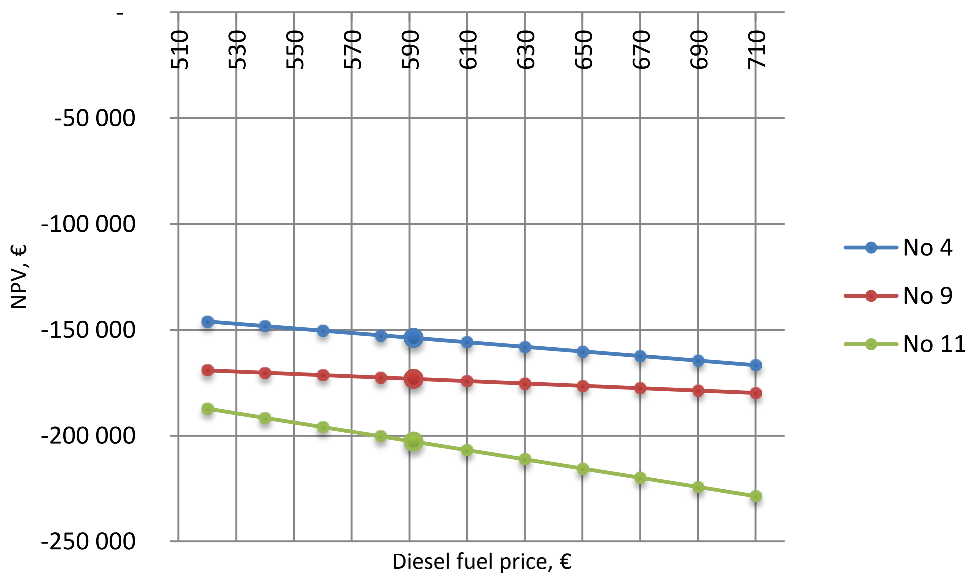


Figure 33 – Dependence of NPV on diesel fuel price

Figure 33 shows proportional decrease of NPV with the growth of diesel fuel price. The most dependent variant on the increase of price for diesel fuel is variant with only diesel generators (no 11). Scenario 9 is not very dependent on the price of the fuel. The scenario 11 will overlap the scenario 4 if the diesel price gets high, but this is very unlikely due the very high price of the diesel fuel, which cannot be set in the nearest future. The initial NPV is shown by the big dots, which correspond to the price of 591.4 euros per ton of diesel fuel.

3. PV investment cost.

The dependences of NPV on the PV investment costs are presented in the Figure 34 below.

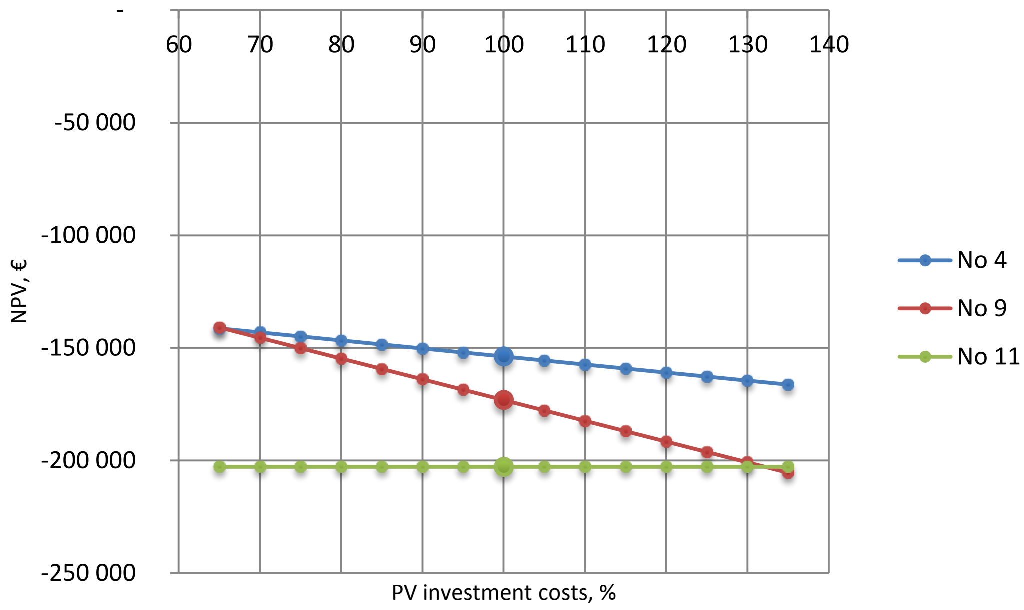


Figure 34 – Dependence of NPV on PV investment costs

The next parameter of the sensitivity analysis is the PV investment cost. I assumed the decrease of investment cost by 35% and increase of the cost by 35% to find the intersections of different scenarios. Figure 34 shows very distinct dependence on the PV investment cost. As can be seen from the graph, NPV of scenario 11 obviously does not depend on the changes of PV investment cost. However, I can make a clear conclusion judging the dependences. When the PV investment cost is greater than 132%, the scenario with a diesel generator is more economically profitable than scenario 9. However, the best one is the scenario 4. There is also a change around the 66% of the PV investment cost. If the PV investment cost is less than 66%, the scenario 9 is better than scenario 4. It means, if the considered investment is lower than 66%, then the most profitable variant is scenario 9 with the storage batteries. Otherwise, the scenario 4 is a clear winner. The initial NPV is shown by the big dots, which correspond to the price of 100% of the PV investment cost.

4. Escalation of price for the diesel fuel

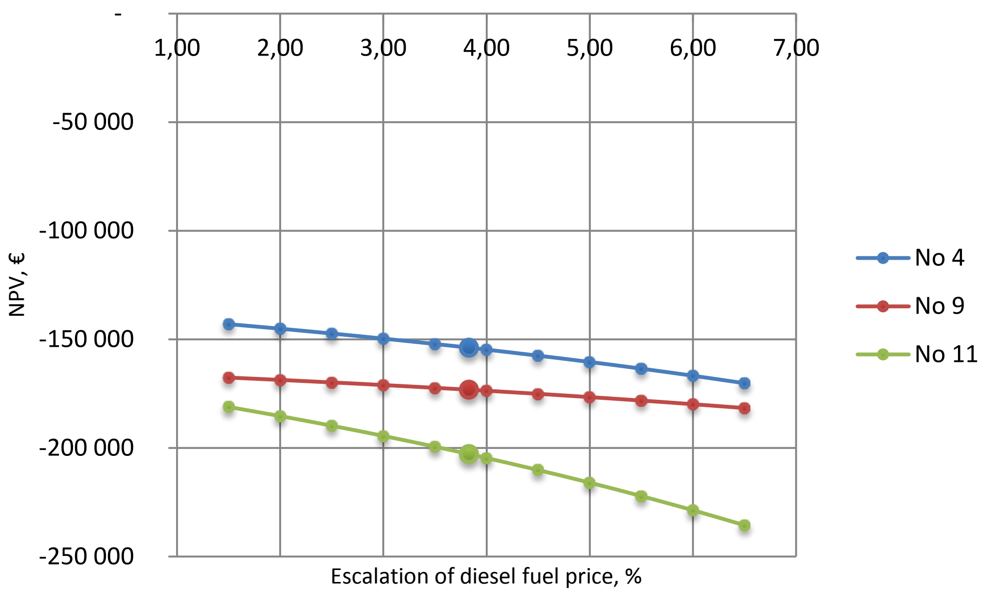


Figure 35 – Dependence of NPV on PV investment costs

The last parameter of the sensitivity analysis is the escalation of price for diesel fuel. The dependences are shown in the Figure 35. The configuration 4 can be considered the most profitable one, since it is not crossed by any of the projects throughout the investigated range of price escalation. The scenario 4 and 9 can overlap each other, however for it to happen the escalation of the diesel fuel price has to be very high, which is not expected in the nearest future. The initial NPV is shown by the big dots, which correspond to the 3.83% of escalation for the price of diesel fuel.

All NPV values for the sensitivity analysis can be found at the end of the diploma thesis in the Appendices 8, 9, 11, 12.

Conclusion

In this diploma thesis, I have solved the problem of power supply of a decentralized area of Sujga in Tomsk region. One of the biggest limitations was the remoteness of the village's territory, which means that it would take a huge amount of financial resources to connect the village to a centralized power supply system. Also, due to the geographical location of this territory, there are difficulties with the supply of diesel fuel due to poor roads. Thus, I considered the power supply for the village, using the available climatic resources to construct the hybrid power supply system for the village’s needs, which includes both renewable energy sources and traditional diesel generators.

The first step of the work was the investigation of the problem of decentralized areas in the world and specifically in Russia. Due the vast territory of the latter, the country is struggling with the reliable power supply, especially of the remote territories. I have proposed solutions for the issue and provided advantages and disadvantage of each variant.

The second part was based on a description of the village's territory and an assessment of its climatic conditions. All major climatic conditions were considered in terms of renewable energy sources. As the analysis showed, the most promising was the use of a solar power plant in combination with diesel generators to achieve maximum effect.

The third part was dedicated to the modeling of the power supply of the village taking into account many assumptions of the utilization of the electric appliances of the villagers. I have assumed that a common resident of the village has the following equipment at home: fridge, microwave oven, electric kettle, television, cooker, lighting and sometimes computer and iron. The process of modeling was performed using a large number of intervals within the day (each day was divided into many equal intervals of 2 minutes. The modeling was performed in the Microsoft Excel and it presented the modeling of the village’s daily consumption of electricity in a unique, diversified way. Each household has different habits regarding the use of the appliances, different power of the electric appliances, This realistic approach resulted in an accurate daily load diagram. I have also plotted an hourly version of the graph for the future work which is shown in the Figure 20.

The next step was the selection of the necessary equipment of the power supply system, taking into account the structure of the hybrid power plant. The main electric equipment has been selected including: storage batteries, solar panels, controller, inverter and diesel generators. The storage batteries accounts for around 50% of the whole investment, which is why I have chosen the best storage batteries for the purpose of storing energy with a 25% depth discharge. These are the LiFePO4 storage batteries that do not require any maintenance throughout their lifetime [35]. The parameters of the electric equipment were used to determine the number of pieces of equipment. In addition, the vendors’ websites were used to determine the maintenance of the equipment, the key points of operation and the prices.

The fifth part of the diploma thesis was based on the investigation of various scenarios of the solar-diesel power supply system. For comparison, 11 scenarios were defined, the differences of them included the installed power value, the presence of the storage batteries and the different configurations using different numbers of equipment. The scenarios were calculated taking into account the angle of inclination of the solar panels, the duration of the day in each of the seasons, the load diagram, which was previously constructed and several more parameters. The data of the solar irradiance was found using the Photovoltaic Geographical Information System [43]. Finally, the diesel fuel consumption was calculated based on the daily load diagram of the village. The results were made for each scenario.

For the economic analysis, I have constructed a model of each scenario, taking into account such parameters as discount rate, inflation, annual maintenance, escalation of prices, cost of installation, diesel fuel costs and investment costs of each configuration. The results of the economic analysis are presented in the Table 13 and shows the net present value of each scenario during the lifetime with a negative sign. That is explained by having only the cash outflows. Therefore the comparison of the options was performed by taking the variant with the highest NPV, comparing to the others. According to the results of the NPVs, the most profitable project is the scenario 4 with 130 PV panels, 2 diesel generators and no storage batteries. The NPV in this case is -153 816 euros. However, for making a final decision it is necessary to analyze different input parameters of the economic model, which can influence the NPV and make a big difference.

The final part of the project was the sensitivity analysis, which is an evaluation of the impact of changes in the parameters of an investment project (expenses, discount rate, investment costs, etc.) on its final characteristics, which in my case is NPV. The sensitivity analysis was performed for three configurations: the most profitable one (no 4 – DG + 130 PV panels), the most profitable one among the configurations with storage batteries (no 9 – DG + 194 PV panels + storage batteries) and the configuration that uses only the diesel generators for supplying the customers (no 11 – DG). The main parameters that were used in the analysis were: discount rate, diesel fuel price, PV investment cost and the escalation of the fuel price. According to the results, changing these parameters does not affect the final decision with one exception. If the PV investment cost is less than 66%, the scenario 9 (with storage batteries) is better than scenario 4. However, this change is quite drastic and is unlikely to happen in the nearest future.

To sum up, I would recommend investing into Scenario 4 which uses 130 solar panels and 2 diesel generators for power supply. This configuration is the most profitable one comparing with the rest of the configurations. This variant covers about 85% of the summer consumption and 32% of the winter consumption. The annual consumption of diesel fuel is relatively low and uses up to 7.623 ton/year comparing with the scenario 11 with 15,262 ton/year. The configurations with the storage batteries have relatively low NPV, due to high investment cost, because of the chosen $LiFePO_4$ storage batteries with the highest number of cycles. After performing the sensitivity analysis, it has been concluded that the scenario 4 remains the most profitable one in every case, apart from the very low PV investment costs (less than 66%).

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List of appendices

Appendices

Appendix 1 – Scenarios 1, 2

					w/o storage batteries		
			with batteries		For DPP supply		
108 PV panels	Generation, kWh	Consum-n, kWh	Delta 1, kWh	Diesel, kWh	Delta 2, kWh	Day, kWh	Night, kWh
January	2 261	8 671	-6 410	6 410	-138	138	6 271
February	3 110	7 832	-4 722	4 722	942	0	5 664
March	4 294	8 671	-4 377	4 377	-1 545	1 545	2 833
April	4 812	8 391	-3 579	3 579	-838	838	2 741
May	5 584	8 671	-3 086	3 086	-254	254	2 833
June	6 271	8 391	-2 120	2 120	-199	199	1 921
July	6 249	8 671	-2 422	2 422	-437	437	1 985
August	5 201	8 671	-3 470	3 470	-1 485	1 485	1 985
September	3 775	8 391	-4 616	4 616	-1 875	1 875	2 741
October	2 186	8 671	-6 485	6 485	-3 652	3 652	2 833
November	1 422	8 391	-6 969	6 969	-4 227	4 227	2 741
December	1 310	8 671	-7 360	7 360	-1 089	1 089	6 271
Total for DG with batteries, kWh				55 617	total without batteries, kWh		56 559

Appendix 2 – Scenarios 3, 4

					w/o storage batteries		
+20%			with batteries		For DPP supply		
130 PV panels	Generation, kWh	Consum-n, kWh	Delta 1, kWh	Diesel, kWh	Delta 2, kWh	Day, kWh	Night, kWh
January	2 722	8 671	-5 949	5 949	322	0	6 271
February	3 743	7 832	-4 088	4 088	1 576	0	5 664
March	5 168	8 671	-3 503	3 503	-670	670	2 833
April	5 792	8 391	-2 599	2 599	142	0	2 741
May	6 722	8 671	-1 949	1 949	884	0	2 833
June	7 548	8 391	-843	843	1 079	0	1 921
July	7 524	8 671	-1 146	1 146	839	0	1 985
August	6 260	8 671	-2 411	2 411	-425	425	1 985
September	4 544	8 391	-3 847	3 847	-1 105	1 105	2 741
October	2 631	8 671	-6 040	6 040	-3 207	3 207	2 833
November	1 712	8 391	-6 679	6 679	-3 938	3 938	2 741
December	1 577	8 671	-7 094	7 094	-822	822	6 271
Total for DG with batteries, kWh				46 147	total without batteries, kWh		50 988

Appendix 3 – Scenarios 5, 6

					w/o storage batteries		
+40%			with batteries		For DPP supply		
152 PV panels	Generation, kWh	Consum-n, kWh	Delta 1, kWh	Diesel, kWh	Delta 2, kWh	Day, kWh	Night, kWh
January	3 182	8 671	-5 489	5 489	783	0	6 271
February	4 377	7 832	-3 455	3 455	2 209	0	5 664
March	6 043	8 671	-2 628	2 628	205	0	2 833
April	6 772	8 391	-1 619	1 619	1 122	0	2 741
May	7 859	8 671	-811	811	2 021	0	2 833
June	8 826	8 391	435	0	2 356	0	1 921
July	8 794	8 671	124	0	2 109	0	1 985
August	7 320	8 671	-1 351	1 351	634	0	1 985
September	5 313	8 391	-3 078	3 078	-336	336	2 741
October	3 076	8 671	-5 595	5 595	-2 762	2 762	2 833
November	2 002	8 391	-6 389	6 389	-3 648	3 648	2 741
December	1 844	8 671	-6 827	6 827	-555	555	6 271
Total for DG with batteries, kWh				37 241	total without batteries, kWh		48 122

Appendix 4 – Scenarios 7, 8

					w/o storage batteries		
+60%			with batteries		For DPP supply		
172 PV panels	Generation, kWh	Consum-n, kWh	Delta 1, kWh	Diesel, kWh	Delta 2, kWh	Day, kWh	Night, kWh
January	3 601	8 671	-5 070	5 070	1 201	0	6 271
February	4 952	7 832	-2 879	2 879	2 785	0	5 664
March	6 838	8 671	-1 833	1 833	1 000	0	2 833
April	7 663	8 391	-728	728	2 013	0	2 741
May	8 894	8 671	223	0	3 055	0	2 833
June	9 987	8 391	1 596	0	3 517	0	1 921
July	9 951	8 671	1 281	0	3 266	0	1 985
August	8 283	8 671	-388	388	1 597	0	1 985
September	6 012	8 391	-2 379	2 379	363	0	2 741
October	3 481	8 671	-5 190	5 190	-2 357	2 357	2 833
November	2 265	8 391	-6 126	6 126	-3 385	3 385	2 741
December	2 087	8 671	-6 584	6 584	-313	313	6 271
Total for DG with batteries, kWh				31 176	total without batteries, kWh		46 875

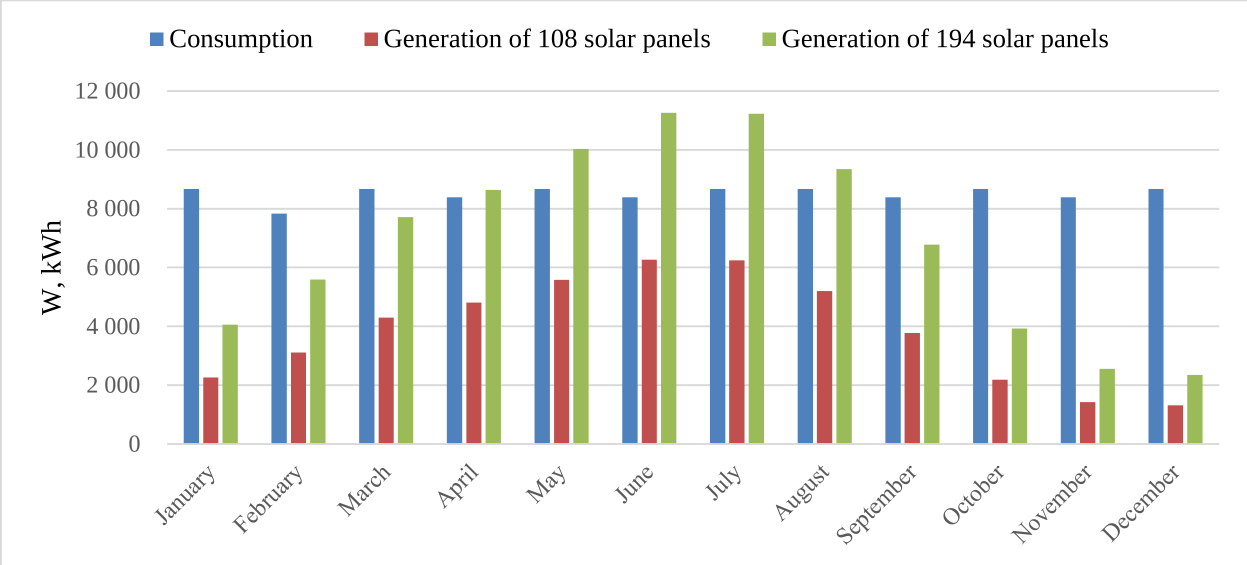
Appendix 5 – Scenarios 9, 10

					w/o storage batteries		
+80%			with batteries		For DPP supply		
194 PV panels	Generation, kWh	Consum-n, kWh	Delta 1, kWh	Diesel, kWh	Delta 2, kWh	Day, kWh	Night, kWh
January	4 061	8 671	-4 609	4 609	1 662	0	6 271
February	5 586	7 832	-2 246	2 246	3 419	0	5 664
March	7 712	8 671	-958	958	1 874	0	2 833
April	8 643	8 391	252	0	2 993	0	2 741
May	10 031	8 671	1 360	0	4 193	0	2 833
June	11 265	8 391	2 874	0	4 795	0	1 921
July	11 224	8 671	2 554	0	4 539	0	1 985
August	9 342	8 671	671	0	2 657	0	1 985
September	6 781	8 391	-1 610	1 610	1 132	0	2 741
October	3 926	8 671	-4 745	4 745	-1 912	1 912	2 833
November	2 555	8 391	-5 836	5 836	-3 095	3 095	2 741
December	2 354	8 671	-6 317	6 317	-46	46	6 271
Total for DG with batteries, kWh				26 321	total without batteries, kWh		45 873

Appendix 6 – Scenario 11

ONLY DG	For DG supply		
w/o batteries	Delta 2, kWh	Day, kWh	Night, kWh
January	-2 399	2 399	6 271
February	-2 167	2 167	5 664
March	-5 838	5 838	2 833
April	-5 650	5 650	2 741
May	-5 838	5 838	2 833
June	-6 470	6 470	1 921
July	-6 686	6 686	1 985
August	-6 686	6 686	1 985
September	-5 650	5 650	2 741
October	-5 838	5 838	2 833
November	-5 650	5 650	2 741
December	-2 399	2 399	6 271
	total without batteries, kWh		102 091

Appendix 7 – Monthly consumption and generation (108-194 solar panels)



Appendix 8 – Sensitivity analysis (discount rate)

Discount rate	NPV (no 4)	NPV (no 9)	NPV (no 11)
4	-184 655	-191 728	-261 286
5	-172 949	-184 682	-239 083
6	-162 744	-178 539	-219 727
7	-153 816	-173 165	-202 794
8	-145 980	-168 448	-187 931
9	-139 078	-164 294	-174 840
10	-132 979	-160 623	-163 271
11	-127 571	-157 368	-153 014
12	-122 761	-154 472	-143 891
13	-118 469	-151 889	-135 751
14	-114 628	-149 577	-128 464

Appendix 9 – Sensitivity analysis (diesel fuel price)

Fuel price per ton	NPV (no 4)	NPV (no 9)	NPV (no 11)
520,0	-146 057	-169 160	-187 259
540,0	-148 231	-170 282	-191 611
560,0	-150 404	-171 404	-195 964
580,0	-152 578	-172 526	-200 316
591,4	-153 816	-173 165	-202 794
610,0	-155 839	-174 210	-206 844
630,0	-158 013	-175 332	-211 197
650,0	-160 187	-176 454	-215 549
670,0	-162 361	-177 576	-219 901
690,0	-164 535	-178 698	-224 254
710,0	-166 709	-179 820	-228 606

Appendix 10 – Investment costs for each configuration

Equipment	Cost of 1 pcs, RUB	No 1	No 2	No 3	No 4	No 5	No 6	No 7	No 8	No 9	No 10	No 11
Solar panel JA-Solar 410W	12000	108	108	130	130	152	152	172	172	194	194	0
LiFePO4 battery	37600	86	0	86	0	86	0	86	0	86	0	0
Inverter MAP	247900	3	3	3	3	3	3	3	3	3	3	0
Controller	54800	1	0	1	0	1	0	1	0	1	0	0
Diesel generator YAMZ-70kW	845000	2	2	2	2	2	2	2	2	2	2	2
Frame for solar modules	2500	108	108	130	130	152	152	172	172	194	194	0
Delivery	250000	1	0,8	1	0,8	1	0,8	1	0,8	1	0,8	0,7
Cost of installation	20%	1 457 620	799 940	1 521 420	863 740	1 585 220	927 540	1 643 220	985 540	1 707 020	1 049 340	338 000
Total cost, RUB		8 995 720	4 999 640	9 378 520	5 382 440	9 761 320	5 765 240	10 109 320	6 113 240	10 492 120	6 496 040	2 203 000
Total cost, EUR		99 952	55 552	104 206	59 805	108 459	64 058	112 326	67 925	116 579	72 178	24 478

Appendix 11 – Sensitivity analysis (PV investment costs)

PV inves-t costs	NPV (no 4)	NPV (no 9)	NPV (no 11)
65	-141 337	-140 905	-202 794
70	-143 120	-145 514	-202 794
75	-144 902	-150 122	-202 794
80	-146 685	-154 731	-202 794
85	-148 468	-159 340	-202 794
90	-150 251	-163 948	-202 794
95	-152 033	-168 557	-202 794
100	-153 816	-173 165	-202 794
105	-155 599	-177 774	-202 794
110	-157 382	-182 383	-202 794
115	-159 165	-186 991	-202 794
120	-160 947	-191 600	-202 794
125	-162 730	-196 209	-202 794
130	-164 513	-200 817	-202 794
135	-166 296	-205 426	-202 794

Appendix 12 – Sensitivity analysis (fuel price escalation)

Fuel price esc-n	NPV (no 4)	NPV (no 9)	NPV (no 11)
1,50	-142 974	-167 569	-181 087
2,00	-145 077	-168 654	-185 297
2,50	-147 296	-169 799	-189 739
3,00	-149 637	-171 008	-194 428
3,50	-152 109	-172 284	-199 377
3,83	-153 816	-173 165	-202 794
4,00	-154 720	-173 632	-204 603
4,50	-157 477	-175 055	-210 124
5,00	-160 390	-176 559	-215 956
5,50	-163 469	-178 148	-222 119
6,00	-166 723	-179 828	-228 634
6,50	-170 163	-181 604	-235 522

Appendix 13 – Annual maintenance of PV panels and DGs for each configuration

Maintenance, annually	No 1	No 2	No 3	No 4	No 5	No 6	No 7	No 8	No 9	No 10	No 11
PV (2%), RUB	25 920	25 920	31 200	31 200	36 480	36 480	41 280	41 280	46 560	46 560	0
DG (5% or 2.5%), RUB	42 250	42 250	42 250	42 250	42 250	42 250	42 250	42 250	42 250	42 250	84 500

Appendix 14 – Fuel costs and delivery costs for each configuration

Fuel costs	No 1	No 2	No 3	No 4	No 5	No 6	No 7	No 8	No 9	No 10	No 11
Fuel cost, RUB	442 566	450 071	367 199	405 734	296 357	382 901	248 082	373 001	209 440	365 017	812 320
Delivery cost, RUB	124 725	126 840	103 485	114 345	83 520	107 910	69 915	105 120	59 025	102 870	228 930

Appendix 15 – Economic calculation of scenario 1

No 1																					
DG + 108 PV panels + batteries																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	8 995 720																				
Maintenance per year		68 170	70 897	73 449	76 020	78 227	82 273	85 426	88 700	92 099	95 629	99 294	103 099	107 051	111 153	115 413	119 836	124 429	129 197	134 149	139 290
Fuel costs		442 566	459 516	477 116	495 389	514 363	534 063	554 517	575 755	597 807	620 703	644 476	669 159	694 788	721 398	749 028	777 715	807 502	838 429	870 541	903 883
Delivery costs		124 725	129 714	134 384	139 088	143 125	150 528	156 297	162 287	168 507	174 965	181 670	188 632	195 861	203 368	211 162	219 254	227 657	236 382	245 441	254 847
Total expenses		635 461	660 127	684 949	710 497	735 714	766 864	796 241	826 742	858 413	891 296	925 439	960 891	997 700	1 035 919	1 075 602	1 116 806	1 159 588	1 204 008	1 250 131	1 298 020
CF	-8 995 720	-635 461	-660 127	-684 949	-710 497	-735 714	-766 864	-796 241	-826 742	-858 413	-891 296	-925 439	-960 891	-997 700	-1 035 919	-1 075 602	-1 116 806	-1 159 588	-1 204 008	-1 250 131	-1 298 020
NPV	-18 054 580																				

Appendix 16 – Economic calculation of scenario 2

No 2																					
DG + 108 PV panels																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	4 999 640																				
Maintenance per year		68 170	70 897	73 449	76 020	78 227	82 273	85 426	88 700	92 099	95 629	99 294	103 099	107 051	111 153	115 413	119 836	124 429	129 197	134 149	139 290
Fuel costs		450 071	467 308	485 206	503 790	523 085	543 119	563 920	585 519	607 944	631 228	655 404	680 506	706 570	733 631	761 729	790 903	821 195	852 647	885 303	919 210
Delivery costs		126 840	131 914	136 663	141 447	145 552	153 081	158 948	165 039	171 364	177 931	184 751	191 831	199 183	206 816	214 742	222 972	231 517	240 390	249 603	259 169
Total expenses		645 081	670 119	695 319	721 257	746 863	778 473	808 294	839 258	871 407	904 789	939 449	975 436	1 012 803	1 051 601	1 091 884	1 133 712	1 177 141	1 222 234	1 269 055	1 317 669
CF	-4 999 640	-645 081	-670 119	-695 319	-721 257	-746 863	-778 473	-808 294	-839 258	-871 407	-904 789	-939 449	-975 436	-1 012 803	-1 051 601	-1 091 884	-1 133 712	-1 177 141	-1 222 234	-1 269 055	-1 317 669
NPV	-14 195 642																				

Appendix 17 – Economic calculation of scenario 3

No 3																					
DG + 130 PV panels + batteries																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	9 378 520																				
Maintenance per year		73 450	76 388	79 138	81 908	84 286	88 645	92 043	95 570	99 233	103 036	106 985	111 085	115 342	119 762	124 352	129 118	134 066	139 204	144 539	150 078
Fuel costs		367 199	381 263	395 865	411 027	426 769	443 115	460 086	477 707	496 003	515 000	534 725	555 205	576 469	598 548	621 472	645 275	669 989	695 649	722 293	749 956
Delivery costs		103 485	107 624	111 499	115 402	118 751	124 894	129 681	134 651	139 811	145 169	150 733	156 509	162 507	168 735	175 202	181 916	188 888	196 127	203 644	211 448
Total expenses		544 134	565 275	586 503	608 337	629 806	656 654	681 809	707 928	735 047	763 205	792 442	822 799	854 318	887 045	921 026	956 309	992 943	1 030 980	1 070 475	1 111 483
CF	-9 378 520	-544 134	-565 275	-586 503	-608 337	-629 806	-656 654	-681 809	-707 928	-735 047	-763 205	-792 442	-822 799	-854 318	-887 045	-921 026	-956 309	-992 943	-1 030 980	-1 070 475	-1 111 483
NPV	-17 135 348																				

Appendix 18 – Economic calculation of scenario 4

No 4																					
DG + 130 PV panels																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	5 382 440																				
Maintenance per year		73 450	76 388	79 138	81 908	84 286	88 645	92 043	95 570	99 233	103 036	106 985	111 085	115 342	119 762	124 352	129 118	134 066	139 204	144 539	150 078
Fuel costs		405 734	421 274	437 409	454 161	471 556	489 616	508 369	527 839	548 055	569 046	590 840	613 470	636 965	661 361	686 691	712 992	740 299	768 653	798 092	828 659
Delivery costs		114 345	118 919	123 200	127 513	131 214	138 001	143 290	148 781	154 483	160 403	166 551	172 934	179 561	186 443	193 588	201 007	208 711	216 709	225 014	233 638
Total expenses		593 529	616 581	639 747	663 582	687 055	716 263	743 701	772 190	801 771	832 485	864 376	897 488	931 869	967 566	1 004 631	1 043 117	1 083 076	1 124 566	1 167 645	1 212 375
CF	-5 382 440	-593 529	-616 581	-639 747	-663 582	-687 055	-716 263	-743 701	-772 190	-801 771	-832 485	-864 376	-897 488	-931 869	-967 566	-1 004 631	-1 043 117	-1 083 076	-1 124 566	-1 167 645	-1 212 375
NPV	-13 843 462																				

Appendix 19 – Economic calculation of scenario 5

No 5																					
DG + 152 PV panels + batteries																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	9 761 320																				
Maintenance per year		78 730	81 879	84 827	87 796	90 344	95 018	98 659	102 440	106 366	110 443	114 675	119 070	123 633	128 372	133 291	138 400	143 704	149 211	154 929	160 867
Fuel costs		296 357	307 707	319 492	331 729	344 434	357 626	371 323	385 545	400 311	415 643	431 562	448 091	465 253	483 072	501 574	520 784	540 730	561 440	582 943	605 270
Delivery costs		83 520	86 861	89 988	93 138	95 841	100 799	104 662	108 673	112 838	117 162	121 652	126 314	131 155	136 182	141 401	146 820	152 447	158 289	164 355	170 654
Total expenses		458 607	476 447	494 308	512 663	530 620	553 443	574 644	596 658	619 515	643 248	667 890	693 476	720 042	747 625	776 266	806 003	836 880	868 940	902 228	936 791
CF	-9 761 320	-458 607	-476 447	-494 308	-512 663	-530 620	-553 443	-574 644	-596 658	-619 515	-643 248	-667 890	-693 476	-720 042	-747 625	-776 266	-806 003	-836 880	-868 940	-902 228	-936 791
NPV	-16 298 791																				

Appendix 20 – Economic calculation of scenario 6

No 6																					
DG + 152 PV panels																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	5 765 240																				
Maintenance per year		78 730	81 879	84 827	87 796	90 344	95 018	98 659	102 440	106 366	110 443	114 675	119 070	123 633	128 372	133 291	138 400	143 704	149 211	154 929	160 867
Fuel costs		382 901	397 566	412 793	428 602	445 018	462 062	479 759	498 134	517 212	537 022	557 590	578 945	601 119	624 142	648 046	672 867	698 637	725 395	753 178	782 024
Delivery costs		107 910	112 226	116 267	120 337	123 829	130 235	135 226	140 408	145 789	151 376	157 178	163 202	169 456	175 950	182 693	189 695	196 965	204 513	212 351	220 489
Total expenses		569 541	591 671	613 887	636 735	659 192	687 315	713 644	740 982	769 368	798 841	829 443	861 217	894 208	928 464	964 031	1 000 961	1 039 306	1 079 119	1 120 458	1 163 381
CF	-5 765 240	-569 541	-591 671	-613 887	-636 735	-659 192	-687 315	-713 644	-740 982	-769 368	-798 841	-829 443	-861 217	-894 208	-928 464	-964 031	-1 000 961	-1 039 306	-1 079 119	-1 120 458	-1 163 381
NPV	-13 884 230																				

Appendix 21 – Economic calculation of scenario 7

No 7																					
DG + 172 PV panels + batteries																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	10 109 320																				
Maintenance per year		83 530	86 871	89 999	93 149	95 853	100 811	104 674	108 686	112 851	117 176	121 667	126 330	131 171	136 198	141 418	146 837	152 465	158 308	164 375	170 674
Fuel costs		248 082	257 583	267 449	277 692	288 328	299 371	310 836	322 741	335 102	347 937	361 263	375 099	389 466	404 382	419 870	435 951	452 648	469 984	487 985	506 674
Delivery costs		69 915	72 712	75 329	77 966	80 229	84 379	87 613	90 971	94 457	98 077	101 836	105 738	109 791	113 998	118 367	122 904	127 614	132 504	137 583	142 855
Total expenses		401 527	417 166	432 777	448 807	464 409	484 561	503 124	522 398	542 411	563 190	584 765	607 167	630 427	654 579	679 655	705 692	732 726	760 797	789 942	820 204
CF	-10 109 320	-401 527	-417 166	-432 777	-448 807	-464 409	-484 561	-503 124	-522 398	-542 411	-563 190	-584 765	-607 167	-630 427	-654 579	-679 655	-705 692	-732 726	-760 797	-789 942	-820 204
NPV	-15 832 996																				

Appendix 22 – Economic calculation of scenario 8

No 8																					
DG + 172 PV panels																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	6 113 240																				
Maintenance per year		83 530	86 871	89 999	93 149	95 853	100 811	104 674	108 686	112 851	117 176	121 667	126 330	131 171	136 198	141 418	146 837	152 465	158 308	164 375	170 674
Fuel costs		373 001	387 287	402 120	417 521	433 512	450 116	467 355	485 255	503 840	523 137	543 173	563 977	585 577	608 005	631 291	655 470	680 574	706 640	733 704	761 805
Delivery costs		105 120	109 325	113 261	117 225	120 628	126 867	131 730	136 778	142 020	147 463	153 114	158 982	165 075	171 401	177 970	184 791	191 872	199 226	206 861	214 789
Total expenses		561 651	583 483	605 380	627 895	649 992	677 794	703 759	730 719	758 711	787 776	817 954	849 288	881 823	915 604	950 679	987 098	1 024 911	1 064 174	1 104 940	1 147 269
CF	-6 113 240	-561 651	-583 483	-605 380	-627 895	-649 992	-677 794	-703 759	-730 719	-758 711	-787 776	-817 954	-849 288	-881 823	-915 604	-950 679	-987 098	-1 024 911	-1 064 174	-1 104 940	-1 147 269
NPV	-14 119 711																				

Appendix 23 – Economic calculation of scenario 9

No 9																					
DG + 194 PV panels + batteries																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	10 492 120																				
Maintenance per year		88 810	92 362	95 688	99 037	101 912	107 183	111 291	115 556	119 985	124 583	129 357	134 315	139 462	144 807	150 357	156 119	162 102	168 315	174 765	181 463
Fuel costs		209 440	217 462	225 791	234 439	243 418	252 740	262 420	272 471	282 907	293 742	304 992	316 674	328 802	341 395	354 471	368 047	382 143	396 779	411 976	427 755
Delivery costs		59 025	61 386	63 596	65 822	67 733	71 236	73 966	76 801	79 744	82 800	85 974	89 269	92 690	96 242	99 930	103 760	107 737	111 866	116 153	120 604
Total expenses		357 275	371 210	385 075	399 298	413 062	431 160	447 678	464 828	482 636	501 125	520 323	540 257	560 954	582 444	604 758	627 926	651 982	676 959	702 894	729 822
CF	-10 492 120	-357 275	-371 210	-385 075	-399 298	-413 062	-431 160	-447 678	-464 828	-482 636	-501 125	-520 323	-540 257	-560 954	-582 444	-604 758	-627 926	-651 982	-676 959	-702 894	-729 822
NPV	-15 584 888																				

Appendix 24 – Economic calculation of scenario 10

No 10																					
DG + 194 PV panels																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	6 496 040																				
Maintenance per year		88 810	92 362	95 688	99 037	101 912	107 183	111 291	115 556	119 985	124 583	129 357	134 315	139 462	144 807	150 357	156 119	162 102	168 315	174 765	181 463
Fuel costs		365 017	378 997	393 513	408 584	424 233	440 481	457 352	474 868	493 056	511 940	531 547	551 905	573 043	594 991	617 779	641 440	666 007	691 515	718 000	745 500
Delivery costs		102 870	106 985	110 837	114 716	118 046	124 152	128 910	133 850	138 980	144 306	149 837	155 579	161 542	167 732	174 161	180 835	187 766	194 962	202 433	210 191
Total expenses		556 697	578 344	600 037	622 338	644 190	671 816	697 553	724 275	752 020	780 829	810 741	841 799	874 047	907 531	942 296	978 394	1 015 875	1 054 791	1 095 199	1 137 154
CF	-6 496 040	-556 697	-578 344	-600 037	-622 338	-644 190	-671 816	-697 553	-724 275	-752 020	-780 829	-810 741	-841 799	-874 047	-907 531	-942 296	-978 394	-1 015 875	-1 054 791	-1 095 199	-1 137 154
NPV	-14 431 847																				

Appendix 25 – Economic calculation of scenario 11

No 11																					
DG																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment	2 203 000																				
Maintenance per year		84 500	87 880	91 044	94 231	96 966	101 982	105 890	109 948	114 162	118 537	123 080	127 797	132 694	137 780	143 060	148 543	154 235	160 146	166 284	172 656
Fuel costs		812 320	843 432	875 735	909 276	944 101	980 260	1 017 804	1 056 786	1 097 261	1 139 286	1 182 921	1 228 227	1 275 268	1 324 110	1 374 824	1 427 480	1 482 152	1 538 919	1 597 859	1 659 057
Delivery costs		228 930	238 087	246 659	255 293	262 702	276 291	286 880	297 875	309 290	321 144	333 451	346 230	359 499	373 277	387 582	402 436	417 859	433 873	450 501	467 766
Total expenses		1 125 750	1 169 399	1 213 439	1 258 800	1 303 769	1 358 533	1 410 574	1 464 609	1 520 713	1 578 967	1 639 452	1 702 254	1 767 461	1 835 167	1 905 466	1 978 458	2 054 247	2 132 938	2 214 644	2 299 480
CF	-2 203 000	-1 125 750	-1 169 399	-1 213 439	-1 258 800	-1 303 769	-1 358 533	-1 410 574	-1 464 609	-1 520 713	-1 578 967	-1 639 452	-1 702 254	-1 767 461	-1 835 167	-1 905 466	-1 978 458	-2 054 247	-2 132 938	-2 214 644	-2 299 480
NPV	-18 251 497																				