Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management and Humanities

POWER SUPPLY OF REMOTE OFF-GRID RESIDENTIAL HOUSE

MASTER THESIS

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

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CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Master’s thesis title in Czech:

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Guidelines:

1) Describe and analyze the load diagram of given residential house
2) Identify and compare possible electricity sources in given area
3) Design technical solutions for power supply for given house
4) Evaluate proposed designs and perform economic evaluation

Bibliography / sources:

1) Eyad S. Hrayshat, Techno-economic analysis of autonomous hybrid photovoltaic-diesel-battery system, Published 8/2011. Energy for Sustainable Development.
2) LUKUTIN B. V. Vozobnovlyaemye istochniki energii: uchebnoe posobie (Renewable Energy Sources: Study Guide). Tomsk: Tomsk Polytechnic University, 2008.
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DECLARATION:

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ABSTRACT

Present Master thesis focuses on possibility to power supply a remote inhabited object by using the energy of alternative energy sources. The main purpose is to design the most technically efficient autonomous power supply system operating in the conditions of the limited energy potential of the Tomsk region and perform economic calculations. In the introduction I justified the relevance of the problem and in subsequent chapters I proceeded directly to the solution of the question.

The theoretical part is related to the analysis of problems related to the design and operation of remote systems and its components, where their functions in the system are described. The practical part is focused on load characteristics, production and optimal design of the power plant, which will be used to supply power to the house. In conclusion, I recommend the most economical configuration of the power plant.

KEYWORDS

Alternative energy sources, wind turbine, decentralized power supply, Solar panels hybrid power systems, off-grid, economic analysis

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AC	Alternating current
CH_2O	Formaldehyde
CO_2	Carbon dioxide
C_xH_y	Hydrocarbons
DPP	Diesel Power Plant
DC	Direct current
EE	Electrical energy
ES	Electrical supply
EMF	Electromotive force
IEA	International Energy Agency
LCOE	The levelized cost of electricity
NASA	The National Aeronautics and Space Administration
NO_x	Nitric oxide
RES	Renewable energy sources
SO_2	Sulfur dioxide
WEM	World Energy Model
DG	Diesel generator
PV	Photovoltaic panels
WT	Wind turbine
NPV	Net Present Value

INTRODUCTION

Nowadays, the problem of electrification will always exist due to the constant growth of the world's population, increase in production capacity and the development of society in general [1].

In 2017, a report was submitted by the International Energy Agency (IEA) according to which more than 1,1 billion people - 14% of the world's population - did not have access to electricity in 2016. About 84% of these people live in rural areas, where access to the central power supply system is more complicated [2]. Figure 1 shows the number of people who do not have access to electricity in different countries of the world. Most of these people - almost 95% live in sub-Saharan Africa and in developing Asia [3].

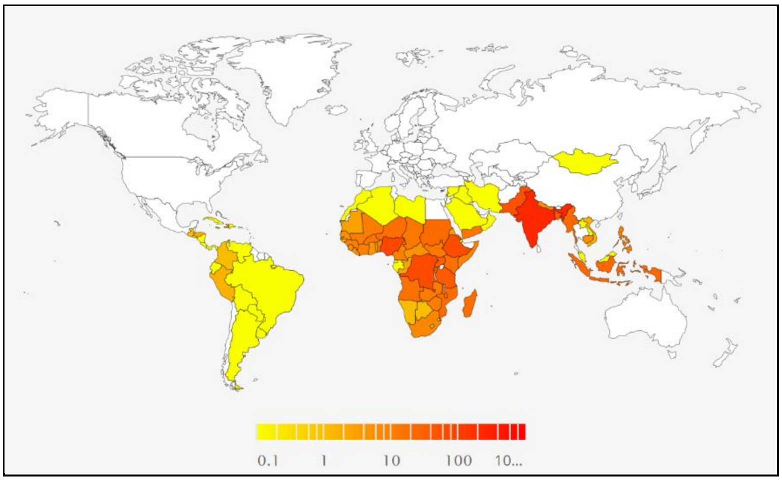

Figure 1 – Population without access to electricity in different countries of the world [3]

The problem of power supply to remote areas without access to electricity is also observed in countries or regions where a significant percentage of the population lives in regions with low population densities such as northern Canada, Mongolia, Kazakhstan or the Asian part of Russia [4].

Due to the fact that the territories of these countries have high energy potential - especially solar and wind, one of the strategies for solving the Energy Crisis in remote areas is the development of autonomous systems using renewables sources of energy [5].

Renewable energy can significantly improve the environmental situation by reducing emissions of pollutants arising from the burning of fossil fuels. In addition, there are opportunities to diversify sources of energy, and thereby create the prerequisites for improving energy security. For this reason, the issue of alternative energy development is increasingly being raised in many countries.

According to the Renewables 2016 Global Status Report, in 2014, about 19,2% of the world's energy needs were met through renewable energy sources [6]. In 2016, this indicator amounted to 19,3%. Moreover, in the last decade there has been a significant increase in energy production through alternative energy. From 2004 to 2016, the share of renewable energy produced in the European Union increased from 14% to 25%. Note that energy consumption from renewable sources is also growing [7].

Investments in renewable energy sources are unstable, nevertheless, there is a general positive trend (Figure 2). In 2017, global investments in clean energy amounted to $ 333,5 billion, which is 3% higher than in 2016, and which exceeded the investments of 2015, which were previously the highest ($ 330 billion). For the fifth consecutive year, investments in renewable energy (including hydropower plants of all capacities) were twice as high as investments in hydrocarbon generating capacities [7].

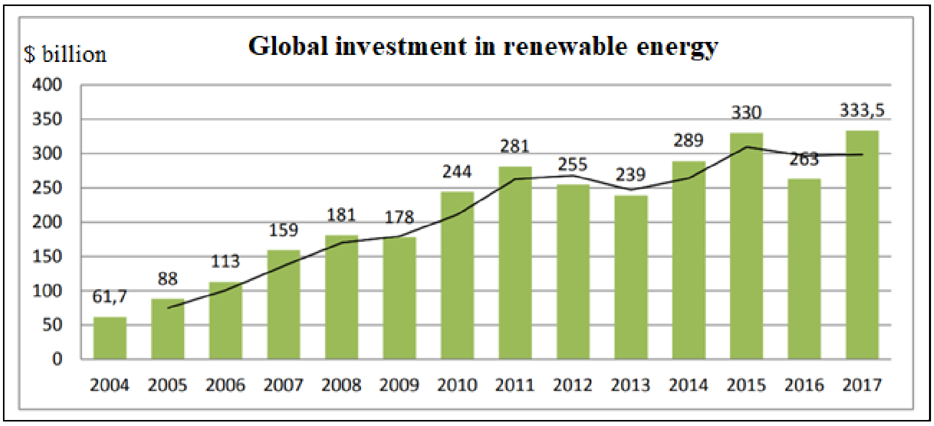

Figure 2 – Investments in renewable energy 2004–2017 (Based on data from [7])

In the Russian Federation, there is a centralized energy supply system and yet there is, at the same time, a need for decentralized energy sources since only a third of the territory of Russia is covered by the central energy system (Figure 3). Due to historical and geopolitical factors, the national economic activity of the Russian population is unevenly distributed throughout the state. A large proportion of Russia is characterized by a low population density and large distances between central sources and consumers of electric and thermal energy. Such areas include the Far East, northern territories and some other regions of the country. The population living in these areas is about 20 million people [8].

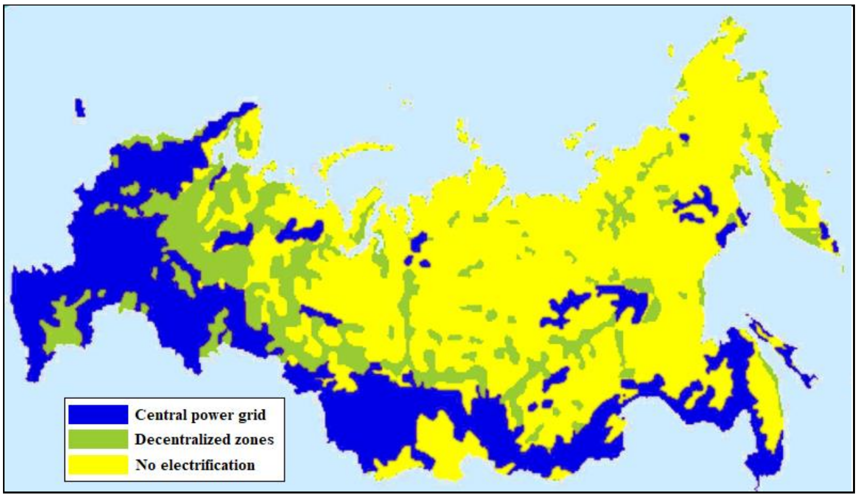

Figure 3 – The map showing type of electrification on the territory of Russian Federation [9]

The construction of power lines and the transportation of electric energy over long distances leads to electricity losses, and there are areas where construction is impossible, for example, swamps, permafrost, rocky soil, mountains, etc.

Currently, for the autonomous existence of consumers of this kind, a decision has been made based on the use of diesel and gasoline power plants. This method is characterized by high economic costs of fuel and low environmental performance, which is another important consideration in the modern world.

The cost of fossil fuels, and especially their delivery to these areas, has risen sharply in the last 2-3 years, since almost all liquid fuels are imported from the central regions of the country. Local budgets are often not enough to pay for fuel costs, which is one of the main causes of reduced reliability of energy supply. In addition, the functionality of such equipment does not allow optimizing its operation, taking into account the uneven distribution of the load over time, and, as a result, there is no way to improve the fuel and economic performance of such systems [10].

The most realistic option at the moment is the development and implementation of autonomous power supply systems using alternative energy sources. This can help reduce operating costs, and therefore the cost of electricity.

The main purpose of my Master thesis is to investigate the feasibility of small autonomous power supply system using the most suitable renewable energy sources in the Tomsk region. And carry out economic calculations proving the effectiveness of this project.

1. Off grid technologies

In order to solve the energy crisis in decentralized remote regions, it is necessary to consider and analyze various options for designing autonomous power supply systems.

The degree of participation of renewable energy installations in the electrification of an object depends on many factors, among which the most important are:

- The energy potential of renewable energy and its change over time;
- Needs of the facility for electrical power;
- Requirements for the reliability of power supply;
- Economic indicators of the power supply system.

Depending on these and other factors, it is possible to choose the composition and structure of the energy complex. Modern power plants for decentralized power supply can be built on the basis of liquid-fuel stand-alone systems, autonomous wind and solar power plants or on the basis of the joint use of renewable energy plants and diesel power plants. The option with diesel generation can be implemented using DPP as a backup power source or for working together with renewable energy installations for a common load.

The main goal with these systems is to reduce fuel consumption and, in this way, to reduce system operating costs and environmental impacts [11].

Based on the number of sources, there are two types of systems: a system using a single source and hybrid systems using multiple sources. Single source systems are also divided into traditional and renewable energy sources. A detailed classification of technologies and examples used in each category are shown in Figure 4.

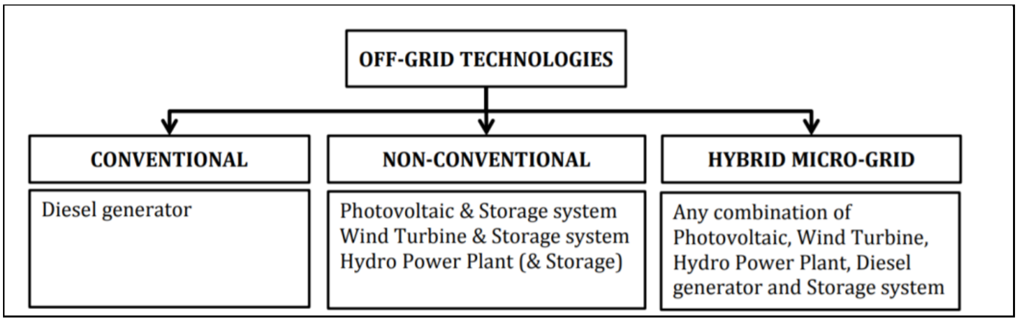

Figure 4 – Classification of technologies for autonomous systems [11].

1.1 Conventional energy systems

The generator is powered by an internal combustion engine that uses gasoline or diesel as fuel. The mechanical energy resulting from the ignition of liquid fuel is converted to EMF and voltage. This voltage is supplied to the consumer after stabilization using control devices [12].

These types of generators can be used as the main power source when the centralized power supply is completely absent, and as a backup source if the main power source is available. Installed sizes range from 8 to 30 kW for homes, small shops and offices and from 8 kW to 2000 kW (larger industrial generators) used for large office complexes and factories [13].

Diesel and petrol stand-alone systems usually consist of an engine, a fuel and air-cooling system, a synchronous or asynchronous generator, and automatic control systems. Plants designed to operate as a backup source of electricity are additionally equipped with an automatic load transfer.

Diesel autonomous systems have such advantages as high reliability and durability when used at full power and regular maintenance. In addition, such systems have a wide range of operating temperatures so that they can be installed almost everywhere. Despite the described advantages, generators have such disadvantages as high operating costs due to the need for constant energy supply. The fuel necessary for the operation of a diesel power plant is imported from remote centers by water and road transport, and sometimes even by helicopter, which makes its delivery more expensive [14]. In addition, fuel delivery depends on the weather and the time of year, so delivery is not always possible in remote areas. Another significant drawback of such systems is the adverse environmental impact - constant air pollution and greenhouse gas emissions into the atmosphere. Due to, these technologies are becoming less attractive because they do not correspond to modern attempts at sustainable development of the world.

1.2 Non-conventional energy systems

The combination of solar, wind and energy storage makes sustainable energy production possible for remote locations. Examples of such systems are: individual houses, autonomous commercial enterprises, agricultural and industrial facilities. The output power of such generators varies from 1kW to 50kW [15]. Low operating costs for renewable energy and high prices for fossil fuels mean that they are already competitive in many regions of the world compared to domestic prices for electricity or the generation of electricity using diesel generators. However, the main disadvantage of renewable autonomous systems, which consists in its variable output power, should be mentioned.

Electricity received from solar and wind sources is different - the amount of generated electricity varies depending on the time of day, season, and random factors. Thus, renewable energy sources in the absence of storage facilities present special problems for the electric power industry. To overcome these problems, energy storage devices are used.

Accumulative energy storage is a set of methods used for large-scale storage of electrical energy in an electrical network. Electric energy is accumulated during periods when production (using renewable energy sources such as wind and solar energy) exceeds consumption, and returns to the network when production falls below consumption [16]. Thus, in such systems there is a balancing of power and long-term energy management.

1.3 Hybrid micro-grid

A hybrid energy system consists of two or more energy systems, an energy storage system, energy conditioning equipment and a controller [17]. This technology combines renewable energy sources with a diesel or gasoline generator running on fossil fuels to provide electricity when electricity It is supplied either directly to the network or to batteries for storing energy. Examples of renewable energy sources commonly used in hybrid configurations are small wind turbines, photovoltaic systems, micro-hydro, biomass and fuel cells. Figure 5 presents a Principle Circuit of Hybrid Systems.

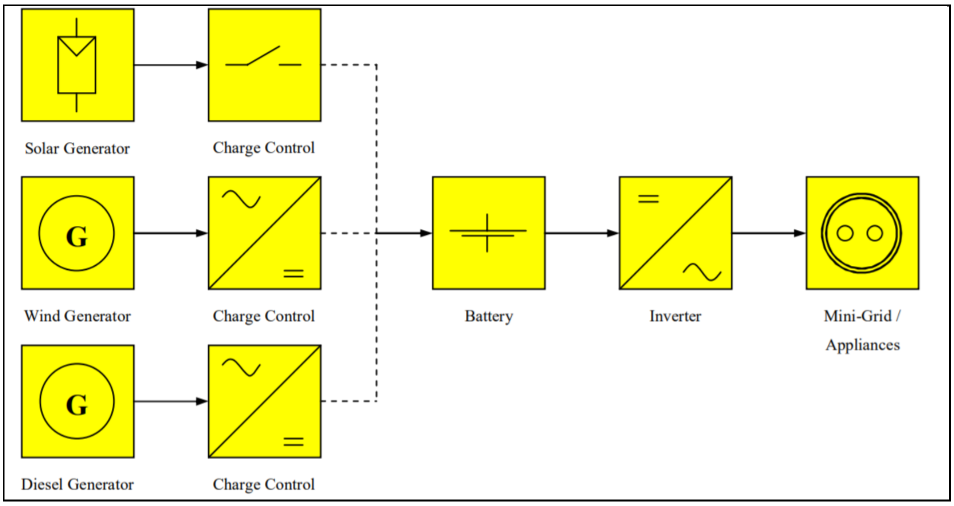

Figure 5 – Principle Circuit of Hybrid Systems [17].

The role of integrating renewable energy into a hybrid energy system is primarily to save diesel. The hybrid system uses advanced system control logic (scheduling strategy) to coordinate when energy should be generated from renewable energy and when - from sources like diesel generators. A feature of the algorithms is to precisely match the cheapest energy production to the load. Due to, cost savings are achieved not by using the most powerful solar panels or the most efficient diesel engine, but by improving this “appropriate” process. By connecting and coordinating sources, the system provides more reliable and better electricity at a lower cost [18].

Each type of renewable energy has its own disadvantage. Solar panels are very expensive and have higher maintenance costs than traditional methods of generating electricity. They also do not work in cloudy weather and at night. Similarly, windmills do not work at low and high wind speeds, and biomass technology does not work at low temperature. Therefore, if all these technologies are combined into a common hybrid system, these shortcomings can be partially or completely eliminated depending on the control devices [19].

Photovoltaic-diesel hybrid system

Combining Photovoltaic arrays and a diesel genset provides a rather simple solution and is feasible for regions with good solar resources. PV-Diesel hybrid systems require a DC/AC-inverter if appliances need alternating current, since PV modules provide direct current.

Compared to the common solution for rural off-grid electrification using diesel gensets alone, the hybrid solution using photovoltaic offers great potential in saving fuel. Experiences show annual fuel savings of more than 80% compared to stand-alone mini-grids on diesel genset basis, depending on the regional conditions and the design of the system. The CO_2 emissions decrease correspondingly.

Naturally, the observed fuel saving varies over the year. The solar generator can provide about 100% of the electricity during summertime, while in winter this figure is less [20].

Wind-diesel hybrid system

A wind-diesel hybrid system is any autonomous electricity generating system using wind turbines with diesel generators to obtain a maximum contribution by the intermittent wind resource to the total power produced, while providing continuous high-quality electric power [21]. Figure 6 presents a schematic diagram of a generalized wind-diesel system.

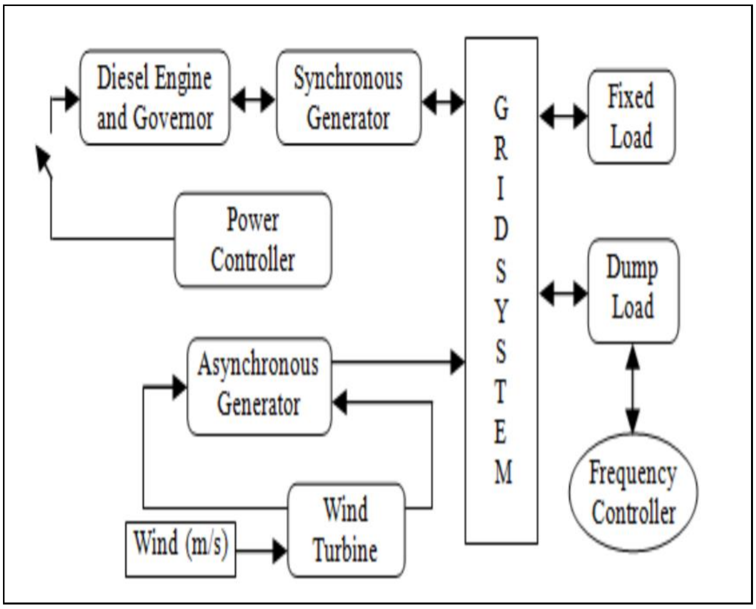

Figure 6 – Isolated Hybrid Wind-Diesel system [22].

Hybrid systems offer different penetration levels, with a large choice of technical solutions. The wind power allows a reduction of the diesel generator rating. Both for reasons of network compatibility and to reduce mechanical loads, many large wind turbines (installed either offshore or onshore) can be operated at variable speed and use doubly fed induction generators [23].

In low wind penetration, the diesel generator will run at full time with the wind power reducing the net load on the diesel generator. All the wind energy generated will be supplying the primary load.

In medium wind penetration, the diesel generator will operate at full time. During high wind power levels, the secondary loads will be dispatched to ensure sufficient diesel loading and alternatively, wind turbines are curtailed during high winds and low loads.

In high wind penetration, the diesel generator can be shut down during high wind availability and auxiliary components are required so as to regulate voltage and frequency [24].

PV/Wind-diesel hybrid system

In some regions, exploitation of both wind and solar resources may be favorable (coastal or mountainous areas). The peculiarity of this solution is that wind energy and solar energy complement each other, so that energy can be provided throughout the year. To ensure reliable power supply, this technology is supported by an additional diesel generator unit during periods of extremely adverse weather conditions.

Hybrid systems consist of PV and a wind turbine. Storage Batteries are used to store the generated energy with a renewable energy source during excess generation. To ensure reliable power supply, this technology is supported by an additional diesel generator unit during periods of extremely adverse weather conditions [25].

1.4 Technical and economic comparison of off grid technologies

In the previous sections, an overview of the options for constructing autonomous power supply systems for remote consumers was carried out. In order to choose the most suitable type of power plant for this project, it is necessary to compare the technical and economic criteria:

1) Current output

Depending on the type of electric energy source - a diesel generator, solar panels or wind turbines, it can produce alternating or direct current. In the case of direct current, it is necessary to additionally use an inverter to convert to alternating current for supply to the electrical network [17].

2) Technical Lifetime

Technical Lifetime is the time during which use of the equipment is considered beneficial. The service life of solar cells is determined by the degradation coefficient of solar PV modules, which depends on its products. Most manufacturers take into account about one percent annual solar cell loss. This ensures that in 20-25 years the solar installation will produce 80-85% of the rated installed capacity for the year of production. After a 25-year service life, the solar panel will not fail, it will continue to work, but with slightly worse performance [25].

3) Operating temperature range

For reliable and trouble-free operation of electrical equipment, it is necessary to observe the operating temperature range. Modern electrical installations have a wide temperature range. Autonomous technology works both in extremely cold northern regions and in hot southern regions. In each specific situation, it is necessary to mount thermal insulation. In the case of DPP, it is required to install an automatic oil heating system during cold start to preserve the life of the generator [13].

4) External factor

The effectiveness of power equipment depends on a number of external factors. Renewable energy sources are affected by weather factors such as long daylight hours and wind speed. DPP is not so susceptible to weather conditions and can be operated at air temperatures from -50 to +50 ºC. However, at low temperatures, the viscosity of the fuel changes, which affects the process of formation of the air-fuel mixture. Because of this, part of the fuel does not burn in the engine cylinders. This leads to a decrease in the power of the power plant and a decrease in efficiency [14].

5) Power stability

Each object has its own requirements for the reliability of power supply. One indicator of reliability is energy constancy. If we consider DPP, the constancy of energy depends mainly on the availability of energy carrier in the system - diesel fuel [14].

Renewable energy sources - wind and sun depend on weather conditions. The energy potential can vary not only from season to season, but also during the day. Energy storage makes it possible to make better use of renewable energy sources, reducing carbon emissions and making electricity more sustainable. They also improve network stability and reliability, which can be vital to the health of renewable energy technologies [16].

6) Environment Impact

Energy and environmental issues are closely related, since it is practically impossible to produce, transport or consume energy without significant environmental impact. These include air pollution, water pollution, thermal pollution, and solid waste management.

All energy production facilities, including PV and a wind turbine, create pollutants when their entire life cycle is taken into account. Emissions during the life cycle are the result of the use of energy based on fossil fuels for the production of materials for solar cells, modules and systems, as well as directly from the smelting and production facilities [27].

In this project, I will take into account the emissions emitted by DPP during the combustion of diesel fuel. Data can be obtained from the standard specific diesel consumption required for individual activities. Used Russian standards for diesel consumption [28]. Table 1 specifies specific emissions per tonne of diesel consumed from DPP.

Table 1 – Amount of Emission per kg of diesel fuel (Based on data from [28])

Rated power	Ejection of component, kg						
	CO_2	NO_x	C_xH_y	SO_2	Soot	CH_2O	Total
Up to 73,6 kW	30	43	15	4,5	3	0,6	96,1
From 74 to 736 kW	26	40	12	5	2	0,5	85,5

The use of renewable energy sources leads to a decrease in the operating time of the diesel generator and, as a consequence, to a reduction in the emission of pollutants into the atmosphere.

The integration of RES in the Off-grid system does not affect the reduction of the environmental tax in the economic model. Since in the Russian Federation there are no laws regulating the amount of pollutants released into the atmosphere. But the adoption of such laws is possible in the future as a result of Russia's new strategy in the energy sector, which was mentioned earlier. Therefore, this factor cannot be underestimated and it is necessary to comply with more environmentally friendly standards in the energy sector.

7) The levelized cost of electricity (LCOE)

The levelized cost of electricity (LCOE) in electrical energy production can be defined as the present value of the price of the produced electrical energy (expressed in units of dollars per kilowatt hour), considering the economic life of the plant and the costs incurred in the construction, operation and maintenance, and the fuel costs. For comparison, I used data from the report of The International Renewable Energy Agency 2018 [27] and data on electricity in Russia in the Tomsk region [29].

The cost per kilowatt-hour for DPP ranges from 0,08 to 0,16 USD/ kWh. The main factors affecting pricing are the installed capacity of the system, the price of diesel fuel and its transportation. For Non-conventional systems, the cost of a kilowatt hour is 0,08 - 0.38 USD/ kWh and depends on factors such as system configuration, government support, climate and solar energy. Hybrid systems combine the factors of the previous two types. The cost per kilowatt hour for hybrid power plants is 0,172 - 0,26 USD/ kWh.

8) Operating cost

Operating and maintenance costs vary widely between different forms of power generation, but are an important economic indicator of a power plant. Operating costs for power plants include fuel, labor and maintenance costs. Fuel costs prevail in the total cost of operating diesel-powered power plants, so they will depend on the capacity of the installation and fuel consumption and the difficulty of transporting it to the power plant. For renewable energy sources are almost equal to zero. Hybrid power plants consume less fuel due to the integration of RES. There are also labor and maintenance costs that depend on the complexity of the micro-grid system configuration.

9) Installation cost

The estimated costs of building new power plants are very uncertain and depend on the type of technology and location. In order to conduct a quantitative comparison, it is necessary to request accurate information from companies involved in transportation and installation in each case. A qualitative comparison of this criterion considers the technological aspects of power supply systems and shows the result in general. For evaluation, consider the information that was presented in the previous chapters. Autonomous power plants, including renewable energy sources, are a more complex technology compared to DPP. They include automation systems, controllers, inverters, batteries, the installation and configuration of which is the main part of the cost of construction.

To sum up, it may be said that every available technology for off-grid power supply has its own pros and cons. Table 2 shows a comparison of technical and economic parameters depending on the type of technology.

Table 2 – Comparison of technologies used in decentralized power supply by different parameters (Based on data from [14, 25, 27, 29])

	Type of off grid system		
Technical parameters	Conventional	Non-conventional	Hybrid micro grid
Current output	DC	AC/DC	DC
Technical Lifetime	15-20 years [25]	15-25 years [14]	25-30 years [27]
Operating temperature range	-50 /+50 °C [29]	-40 /+50 °C [25]	-40 /+40 °C [25]
External factor	Ambient temperature	Daylight length Solar power Wind flow speed	Daylight length Solar power Wind flow speed
Power stability	Constant	Inconstant	Constant
Environment Impact	High	Very small	Small
Economic parameters			
LCOE	0,08-0,16 USD/kWh [28]	0,08-0,38 USD/kWh [27]	0,172-0,26 USD/kWh [27]
Operating cost	High	Almost Zero	Low
Installation cost	Low	High	High

1.5 Summary

In the past, Diesel Power Plants are preferred in the field of autonomous systems. Compared with the construction of electric transmission lines, they significantly reduced investment costs, on the other hand, their use entailed high operating costs, mainly associated with fuel consumption and its transportation to remote areas. Currently, this type of electricity production, according to world statistics, is used less and less.

Thanks to the global development of alternative energy sources, their integration into the autonomous power supply system comes to the fore. Hybrid systems, combining production from several energy sources, a compromise solution to decentralized electrification. They reduce operating costs due to the operation of RES and at the same time provide the power required by end consumers. The disadvantage is the more expensive installation compared to DPP, as well as the need for detailed technical and economic analysis.

To use renewable sources, it is necessary to take into account the influence of external factors that do not allow a generalization of the solution and require the study of a specific case for each deployment of the system.

The next stage of design is to assess the energy potential of the region in which the power plant will be installed. As well as the calculation of consumption and the construction of a load diagram for the power supply object in order to choose the final version of the hybrid power supply system.

2. General project information

The aim of this work is to develop a hybrid power plant for the village of Bogashevo, Tomsk Region, which is located in Western Siberia (Figure 7).

The Tomsk region occupies the southeastern part of the West Siberian Plain and has an area of 316,9 km^2, exceeding in size such large European states as Great Britain, Poland or Italy. The maximum length of the Tomsk region from north to south is 600 km, from west to east is 780 km. More than half of the region's territory is covered with cedar, pine and birch forests. There are 573 rivers in the region. All of them belong to the Ob basin. The population of the region is more than one million people, more than half (53,1%) live in rural areas. The average population density of the region is 3,41 people per 1 km^2 [30].

Figure 7 – Tomsk region on the map of the Russian Federation [31].

The area in which the village is located is characterized as an area with extreme climatic conditions, long winters and short summers. The average annual temperature is minus 2 ° C, the average annual rainfall is between 45-60 centimeters of rain and 60-100 centimeters of snow. It is maintained in the region of 190-195 days a year.

The north-eastern territories of the Tomsk region do not have a centralized power supply. With a low population density and poor industrial development, the inclusion of these territories in a centralized energy supply system is impractical. Remote areas are electrified using 42 local diesel power plants with a total installed capacity of 44075 kW. 41 settlements, in which more than 24 thousand people live, receive electricity from them. The required annual diesel consumption is 15,930 tons [30].

Units of most diesel power plants have long exhausted their resources and require replacement. Frequent accidents in the power supply lead to significant material losses. This causes social damage to the population.

In the conditions of the Siberian winter, expenses on heat carriers make up 44% in the annual budget of the region. Annually it is necessary to freeze significant financial resources for the northern delivery of fuel, since in many areas of the Tomsk region its delivery is possible only on winter routes. The harsh climate of the Tomsk region, the poor development of the transport and energy infrastructure of the territory, low population density determine the critical situation in the energy supply of the northern regions of the region [30].

2.1 Description of the case study

For the design of the power supply system I chose a two-story cottage which is located in the suburban settlement “Bogashevo” located 30 kilometers from the city of Tomsk. According to the received information, there is no constant power supply in this place due to the fact that the agricultural season in the Siberian climate is limited to four months - from May to August. In the summer, houses are powered by a low-power transmission line, which cannot fully provide the studied object with electric energy.

The main entrance is organized from the main facade of the cottage, on the opposite side, passing through the corridor of the first floor, there is another entrance (through), which opens onto the adjacent territory. The land area is 1500 m^2. There are two non-residential premises on the territory. The selected object is shown in the following Figure. The data was obtained from the Google Maps web mapping service.

Figure 8 – Selected Territory with Remote house [32]

The walls of the cottage are made of ceramic bricks with cladding. The outer layer of masonry is made of facing brick. The thickness of the external bearing walls, taking into account the thermal insulation, is 950 mm and the internal 380 mm. Partitions in the premises of the first floor were initially made nonbearing, from gypsum concrete blocks 100 mm thick and 120 mm brick. The rigidity of the building is also provided by transverse self-supporting walls.

On the ground floor (kitchen area) and in transverse self-supporting walls are placed the bases of ventilation shafts with a thickness of 380 mm and risers of plumbing pipelines.

The rooms of the bathrooms are organized on the basis of ventilation units and risers of the plumbing pipelines of the building. The partition walls 120 mm thick are made of solid ceramic bricks. The walls and floors inside the bathrooms are tiled with ceramic tiles. Plumbing fixtures are connected according to a standard scheme.

2.2 Heating system

Since the object is located in a region where in winter the temperature drops below zero, the heating issue becomes extremely important. The task is complicated by the fact that in this village there is no gas supply, therefore, a search for alternative solutions is necessary.

After consulting with companies involved in the construction of similar projects in this region, we can conclude that the installed wall width will be enough to provide the necessary thermal insulation properties. Additional installation of modern double-glazed windows, which reduce heat loss, will contribute to energy saving of the facility.

In this house, thermal energy will be provided by two sources of heat supply - an electric underfloor heating with a capacity of 6,24 kW and a fireplace installed on the ground floor in the living room and running on combustible fuel.

The electric underfloor heating system is a cable heating system of increased reliability, which can be used not only as a comfortable floor heating system, but also as the main heating system, provided that all recommendations for thermal insulation of the object are observed. The heating sections of underfloor heating systems are shielded single-core and two-core cables having two layers of insulation, as well as reliable couplings.

To control and regulate the temperature of the floor, it is planned to use the climate control system, which consists of thermostats and sensors that will monitor the set temperature. Such a solution will ensure rational energy consumption and will reduce, if necessary, consumption during peak hours.

The fireplace is an additional source of heat supply, which is a system that consists of ventilation ducts and radiators, which are installed in places of the greatest freezing of building envelopes. This solution is a system with natural air circulation due to the temperature difference. At different temperatures, a different density of air occurs, due to which there is a natural movement of air in the system. Warm air flows through the air ducts under the ceiling and, occupying a significant amount, displaces colder (for example, near windows and doors) down and toward the air intake, thereby creating air circulation in the heated room.

2.3 Water supply and sewage system

As mentioned before, in this settlement there is no centralized water supply and sewage system, therefore it is necessary to design a local system. The main source will be the well.

A well for water supply is drilled directly under the house in the basement. Above the well in the attic in a separate insulated room there is a water tank with a capacity of 300-400 l. An electric pump for supplying water and filtering equipment are installed in the basement, the electric motor is controlled from the utility room inside the house, using a manual starter or automatically. A 600 W pump will be used to pump water from the well. With a maximum pumping capacity of 1,400 l / s, it is capable of pumping 400 liters in 20 minutes, which is the expected water flow in the building [32].

In our case, we will primarily heat the water using a boiler, but since sometimes we will have excess electricity from the power plant, it will be advisable to use this electricity to heat the water. Combined water heaters are suitable for this purpose, which allow heating water from several sources.

Due to the lack of a central main sewage system, a local system has been built. In this case, the sewage system is built on the soil principle of treating fecal waters. Its essence is that first the wastewater from the house riser flows into the yard pipeline, then to the septic tank at around 3 m3, designed to remove precipitation from it twice a year, in which the fecal water is clarified and flows through the drainage network to the soil.

2.4 Power consumption

In this chapter, I analyze an object and concentrate on its electricity needs. The requirement of a potential investor is to be able to comfortably operate the facility in these climatic conditions.

The next step will be the selection of possible electricity consumers and the calculation of the daily energy consumption of the facility. The house plan is summarized by the numerical values in Table 3.

Installed capacity is selected from the passport data of electrical appliances. As a basis, I took the recommended data from the company Schneider Electric [33], which specializes in the design and manufacture of electrical equipment.

Table 3 – Installed electrical appliances with installed capacity (Based on data from [33])

Rooms	Area, m^2	Installed electrical appliances	Rated power, kW
Kitchen	25,9	Electric stove	3,5
		Refrigerator	0,6
		Teapot	1,5
		Microwave	0,9
		Electric coffee maker	0,65
		Dishwasher	2
		Electric Warm floor	2
		1 Socket x 16 A	0,8
		8 Sockets x 6 A	
Hall, Tambour, Terrace	66,5	Iron	0,9
		Drainage Pump	0,6
		7 Sockets x 6 A	0,7
Living room	26,3	Home cinema	0,8
		Electric vacuum cleaner	0,65
		Electric Warm floor	1,5
		7 Sockets x 6 A	0,7
Bedroom 1	12,2	Personal Computer	0,4
		Electric Warm floor	0,98
		4 Sockets x 6 A	0,4
Bedroom 2	12,7	Electric Warm floor	1,16
		4 Sockets x 6 A	0,4
Entrance hall	4,3	2 Sockets x 6 A	0,2
Bathroom	6	Washing machine	2
		Electric Warm floor	0,6
		2 Sockets x 6 A	0,2
		Water heater	2
Sauna	10,6	TV	0,2
		3 Sockets x 6 A	0,3
Balcony	14	4 Sockets x 6 A	0,4
Total:	**178,5**		**27**

To calculate the loads of apartments and cottages on the basis of data on the installed capacity of appliances and machines, the following indicators are determined:

- Daily electricity consumption;
- The possible operating time of each device and machine and the average probability of their inclusion in the period of maximum load (Demand coefficient).

The probability of a mismatch in the peak loads of buildings (apartments) and other household consumers in determining the estimated loads of network elements is taken into account using appropriate participation factors and maximum loads combined.

The illumination is calculated relative to the nominal or installed active power [33]:

$$P = S \cdot P_{rated} \cdot K_d \cdot K_u,$$

Where S – floor space, m^2,

P_{rated} – rated or installed power, W/m^2,

K_d – demand factor, r.u.

K_u – utilization rate, r.u.

Table 4 shows the recommended values of the demand factor, utilization rate and installed capacity for various premises. In this project will be used lamps with LED lights.

Table 4 – Lighting Parameters

Room	Rated or installed power, W/m^2	Demand factor	Utilization rate	Calculated power, kW
Living room	3,8	0,8	0,8	0,064
Bedroom	2,8	0,6	0,6	0,025
Kitchen	2,8	1,0	0,8	0,058
Sauna	0,8	0,8	0,8	0,054
Other	2,3	0,8	0,8	0,149
Total:				0,35

Calculation of total active power [33]:

$$P_{p\Sigma} = \sum P \cdot \cos\phi,$$

Where $cos\varphi$ – active power factor, is equal to 0,92.

The values of active power consumption are given in Appendix 1. Based on the results obtained, it can be concluded that the total active power consumption of the house is 16,5 kW. Most of the energy consumed is spent on the operation of an electric furnace - 2,8 kW and on the operation of heating equipment - Underfloor heating system and a Water heater - 4 kW.

2.5 Description and analyzing the load diagram of given residential house

The next step is to determine the daily and seasonal load diagrams. This process is an important part of the design of power supply systems, since energy consumption is not constant throughout the year and is constantly changing throughout the day. A daily chart will also help us determine how electricity is stored from renewable energy sources. If mains electricity is consumed during the day, it is preferable to store excess electricity in batteries that will be used during periods of shortage of electricity from natural sources. This can happen in case of uneven energy consumption and the batteries must have a large capacity to cover this consumption.

Weather changes throughout the year, causing changes in electricity consumption. Due to the consumption forecast, the consumption rate is divided into four parts during the year, namely: spring, summer, autumn and winter.

Dividing the year into four parts, I got four load schedules for each season. I calculated the hourly average to get a daily consumption estimate. Such an assessment will serve as the main tool for system design.

According to the obtained calculated active power, we determine the power consumed every hour during the day by the formula [33]:

$$P_h = P_p \cdot k$$

Where P_h - the load consumed in a certain hour, kW;

k - load factor of the installed capacity;

Values of hourly consumption of active power for seasons of the year are shown in Appendix 2.

According to the obtained results, we construct characteristic graphs of daily consumption of active power for each season (Figure 9).

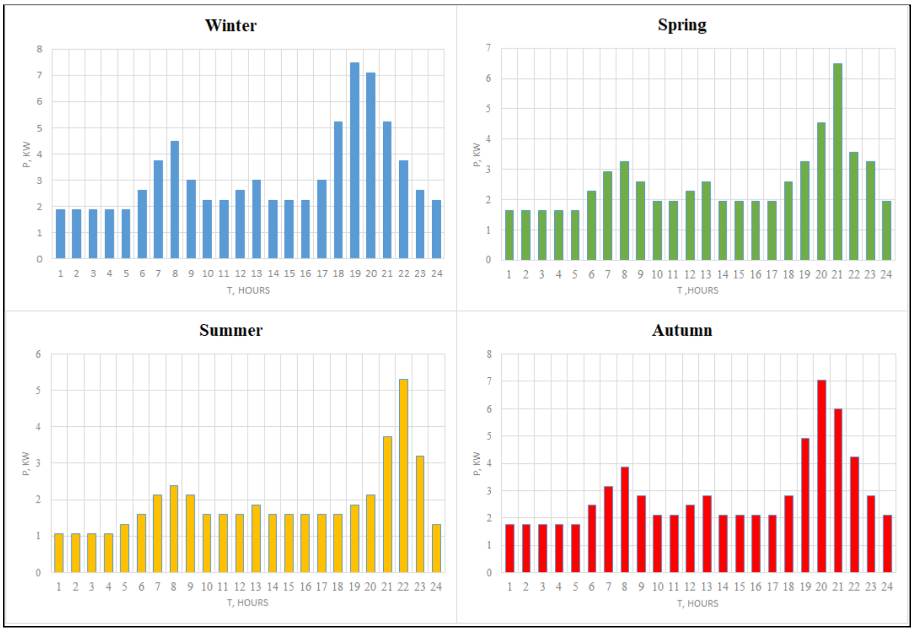

Figure 9 – Daily graph of active power consumption according to the season

In the previous figure, we can analyze the graph of the daily load of the object. There are averaged values for one hour, and short-term peaks will be much higher, up to 8 kW. However, these peaks are very difficult to convert to a graph, since some instruments do not consume constant power. In addition, some devices, such as a microwave oven, turn on only for a few minutes, and it is difficult to predict when exactly in an hour this will happen, so I decided to use the Schneider Electric company methodology, which uses coefficients for each season. Based on the constructed diagrams, it can be understood that the most consumed season is Winter, and the most non-consumed is Summer.

To obtain information on the average monthly and average annual electricity consumption, it is necessary to calculate the electricity depending on the season and the number of days in a month.

The electricity consumption of the Electrical supply, taking into account the seasonality factor:

$$W_{jan} = W_{day} \cdot k_s \cdot n,$$

Where W day is the daily consumption of energy efficiency, kWh;

k_s – seasonality factor;

n – number of days.

Results calculations are given in Table 5.

Table 5 – Electricity consumption by Electrical Supply by months

Month	k_s	W_{day}, kWh	Number of days	W_{month}, kWh
January	1	76,61	31	2 375
February	1	76,61	28	2 145
March	0,8	61,29	31	1 899
April	0,7	53,63	30	1 609
May	0,7	53,63	31	1 662
June	0,6	45,97	30	1 379
July	0,6	45,97	31	1 425
August	0,6	45,97	31	1 425
September	0,7	53,63	30	1 609
October	0,8	61,29	31	1 899
November	0,9	68,95	30	2 068
December	1	76,61	31	2 375
Total				**21 872**

Figure 10 shows the annual load schedule built on based on calculated data from [Appendix 2].

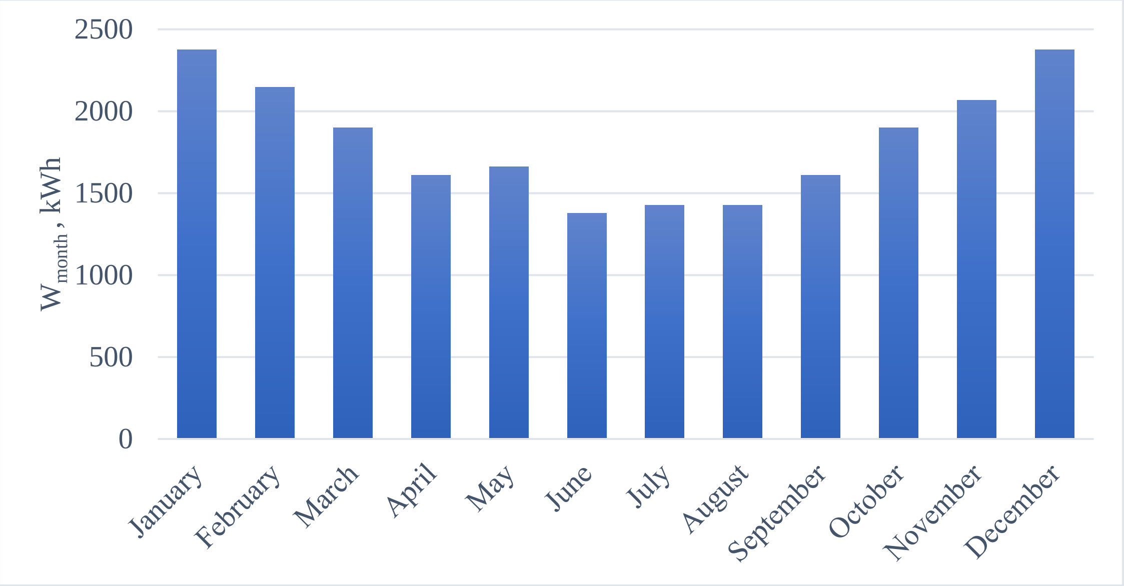

Figure 10 – Annual Electrical Energy consumption graph

As a result of calculations, daily load schedules of the seasons and the annual energy schedule of the cottage, the total annual consumption of electric energy by the cottage was W_{annual} = 21 872 kWh.

This is due to different daylight hours and climatic conditions of the region. In winter, the need for heating and lighting is higher than in summer.

2.6 Wind power potential of the region

The initial data for modeling a hybrid power plant are primarily statistical weather data obtained from meteorological stations.

Monthly and annual average wind speeds over long periods of time are the main and initial data for compiling characteristics of the general level of wind intensity. According to the characteristics, it is possible to preliminarily judge the prospects for placing wind energy equipment in the required area. When compiling the characteristics, it must be remembered that the wind speed strongly depends on the surface roughness and that the data of weather stations can change over time with the surrounding area. This should be taken into account when comparing average wind speeds and reducing them to equal conditions [10].

It is inconvenient to use large arrays of statistical data obtained from sources, in addition, the data contain only direct measurements, if necessary, additional calculations. Based on this, you should transform the source data for easy perception, as well as structure them for correct input into the model. I decided to automate this process using Microsoft Excel software.

To obtain data on the wind potential, a resource [34] is used, the available statistics of which contain direct measurements of wind speed every day, every three hours, for a selected period of time (five years).

The average wind speed is determined as the average value obtained as a result of repeated measurements of wind speed for equal time intervals for a given time interval (day, month, year), calculated by the formula [10]:

$$V_{AV} = \frac{1}{n}\sum_{i=1}^{n} V_i,$$

Where V_{AV} – average wind speed, m/s;

n – the number of time periods;

V_i - wind speed in a certain period of time, m/s.

The calculated data is submitted in table 6.

Table 6 – Annual and Average monthly wind speed (Based on data from [34])

Year	2015	2016	2017	2018	2019	Average 2015-2019
	Wind speed, m/s					
January	5,11	2,21	4,6	4,27	4,47	4,14
February	4,41	3,33	4,82	2,94	4,35	3,94
March	4,17	3,75	4,031	4,55	4,39	4,11
April	3,89	3,09	4,95	4,94	4,37	4,18
May	3,54	3,51	4,82	4,13	4,37	4,15
June	2,98	2,9	3,05	3,62	3,2	3,19
July	3,05	2,98	2,34	3,03	2,9	2,79
August	3,66	2,74	2,54	2,71	2,69	2,81
September	3,04	2,55	3,25	3,45	3,82	3,31
October	4,65	2,64	3,58	4,99	4,57	4,01
November	3,73	3,76	4,12	5,25	4,49	4,27
December	5,12	4,70	3,97	3,26	4,6	4,34

According to the calculations, the average wind speed at an altitude of 10-12 meters above the earth's surface, averaged over a 10-minute period, is V_{AV} =3,77 m / s.

For a more accurate determination, it is necessary to take into account the height at which the wind turbine will work. The wind speed increases with distance from the underlying surface and the air flow becomes more stable. The degree of increase in wind speed with height is highly dependent on the roughness of the underlying surface. Approximately the wind speed at a height h can be calculated by the formula [10]:

$$V_H = V_M \cdot \left(\frac{h}{h_M}\right)^{\alpha},$$

Where V_H – wind speed on the height H, m/s;

V_M – wind speed on the height of the mast, m/s;

h_M – height of the mast, m;

α – coefficient related to the average wind speed at the height of the mast.

Table 7 – Dependence of α on wind speed V_M (Based on data from [10])

V_M, m/s	0…3	3,5…4	4,5…5	5,5	6…11,5	12…12,5	13…14
α	0,2	0,18	0,16	0,15	0,14	0,35	0,13

In this project, for the design of a wind turbine, a height H is equal to 20 meters. The results of the recalculation of wind speed taking into account the given height is presented in Table 8.

Table 8 – Recalculated wind speed at the height of 20 meters

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average wind speed, m/s	4,14	3,94	4,11	4,18	4,15	3,19	2,79	2,81	3,31	4,01	4,27	4,34
Wind speed at a height of 20m, m/s	4,69	4,53	4,66	4,74	4,71	3,66	3,21	3,23	3,81	4,54	4,84	4,92

For a visual representation and further analysis, the results of wind speed calculations are presented in Figure 11.

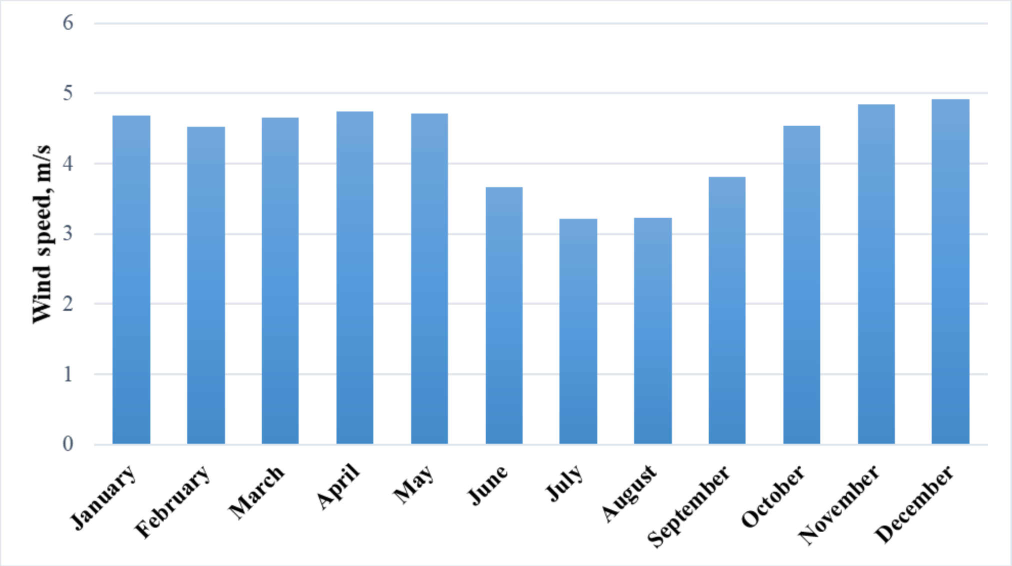

Figure 11 – Annual wind speed in the village of Bogashevo.

The next important indicator is the repeatability of various gradations of wind speed. It is considered as a percentage of the time during which one or another wind speed was observed. This characteristic is important for electric power calculations related to the assessment of the operating time intervals of a wind farm at various wind speeds. Due to noticeable seasonal changes in wind speeds, it is advisable to use the month as a sampling interval for the wind generator. Then, the average distribution of the monthly wind potential is determined by the processing of daily observation data. I processed the measurement data for every 30 minutes for 5 years and as a result I got the number of hours for each wind speed. The result is shown in Figure 12 below.

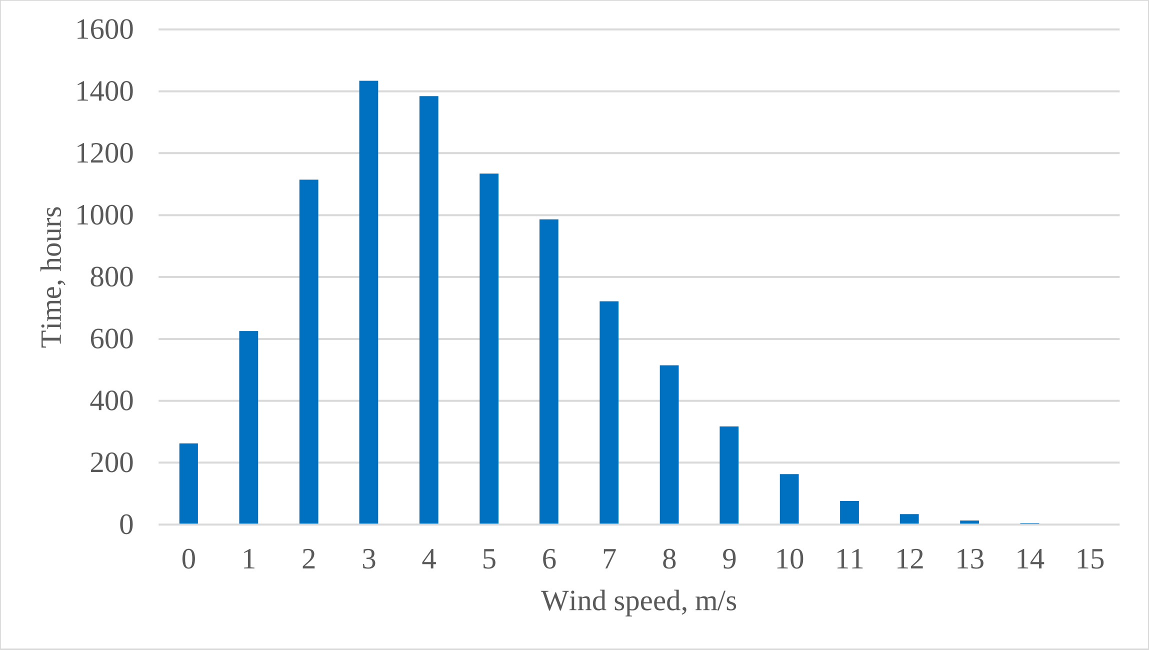

Figure 12 – Graph of the distribution of the duration of wind speed

The distribution of wind speed by gradation allows you to calculate the generation of wind power for each month. For this, the percentage of repeatability of the wind speed interval must be converted to the corresponding time interval. The graph shows that the main number of hours recorded wind speed of 3-7 m / s, which corresponds to the nominal speeds of modern wind turbines. This allows us to consider wind energy in this region as one of the alternative options for power supply to the consumer.

According to the obtained results, it can be concluded that in the village of Bogashevo, the maximum wind speeds correspond to the winter, autumn and spring seasons, and the minimum - in the summer. The average wind speed at an altitude of 10-12 meters above the earth's surface is V_{AV} =3,77 m /s and at altitude 18-20 meters above the earth’s surface is V_{AV} =4,29 m /s.

2.6 Solar power potential of the region

The sun constantly radiates a huge amount of energy. Due to absorption by atmospheric layers or reflection, only a part of it reaches the Earth [10]. The density of the flux of solar energy reaching the Earth's surface depends on the time of year and the latitude of the region, and the total amount of solar energy received in a particular area of the Earth depends on the duration of solar radiation.

Due to the inclination of the axis of rotation of the Earth relative to the orbit around the sun, there are seasons on our planet. In winter, the day is shorter and the sun moves closer to the horizon. In summer, the day is longer and the sun rises higher. And the farther the area is located from the equator, the stronger this dependence. Therefore, for regions that are remote from the equator towards the poles of the Earth, the seasonal dependence of solar radiation on the time of year should be taken into account.

To conduct an estimate of the Solar potential that is as close as possible to reality, the following indicators are usually used: the sum of the direct and total radiation, their variability at different time intervals in a clear and cloudy sky; duration of sunshine, its variability; continuous duration of sunshine above a specified level; the number of days without sun; cloud repeatability of different gradations. Based on these indicators, the maximum (Clear sky) and actual (Medium cloudiness) density of solar energy, optimal tilt angles that provide the maximum solar radiation flux to the receiving surface of the photo module are obtained [10].

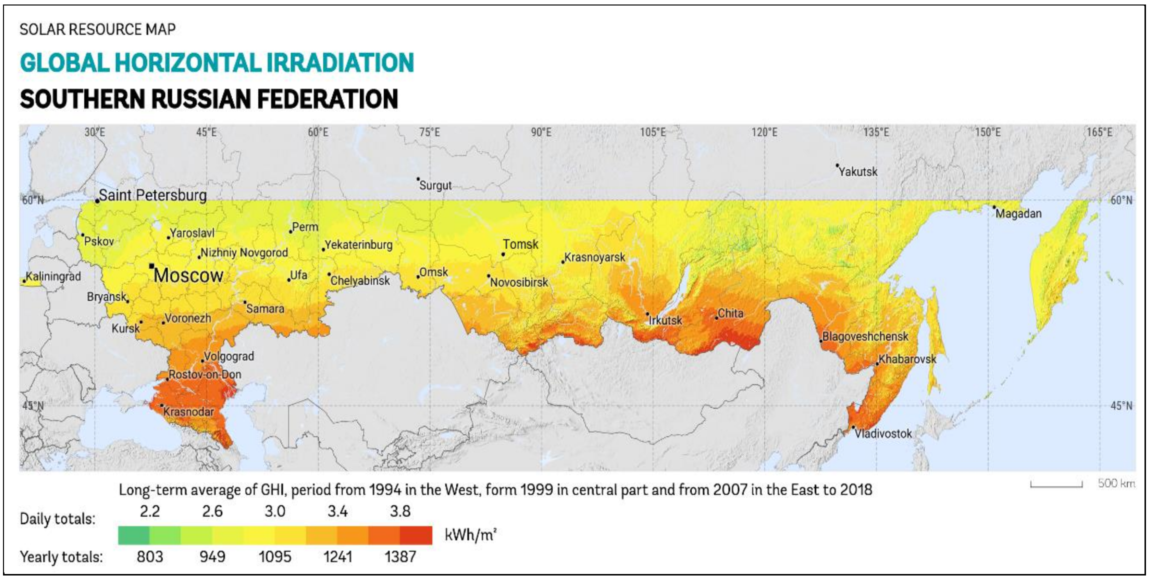

Figure 13 – Global horizontal Irradiation for Russia [35].

The duration of sunshine during the year is approximately the same in all regions and amounts to 4000 - 5000 hours. The total solar radiation in the Russian Federation varies from north to south within 1000 - 1400 kW/m^2 (Figure 13). The significant potential of solar energy makes it possible to use it economically in Western Siberia.

Since it is impossible to take into account the information obtained from the map shown in Figure 13 since the boundaries between the insolation zones are very arbitrary. Therefore, the next step will be to determine the average monthly solar radiation for each month.

The data provided by The National Aeronautics and Space Administration (NASA) are used to obtain data on solar potential (Table 9). For information processing, The RETScreen program was used.

Table 9 – Average Monthly Solar Radiation horizontal (Based on data from NASA)

Year	2015	2016	2017	2018	2019	Average 2015-2019
	Solar radiation, kWh/m^2/month					
January	16,77	14,02	14,09	14,63	17,21	15,34
February	40,46	37,17	31,81	33,58	28,6	34,32
March	73,92	63,1	67,11	72,16	74,6	70,18
April	110,66	100,38	118,55	96,93	109,55	107,21
May	150,17	119,86	143,96	142,77	145,05	140,36
June	198,11	165,99	186,6	195,03	190,15	187,18
July	172,67	172,48	172,25	169,99	158,9	169,26
August	124,36	126,32	132,36	124,39	131,41	127,77
September	81,46	78,7	83,63	72,13	85,59	80,3
October	35,84	34,44	27,52	32,5	33,58	32,78
November	16,28	15,16	14,01	16,28	17,92	15,93
December	12,24	7,93	9,33	6,22	8,8	8,9

For a visual representation and further analysis, the results of Monthly Solar Radiation for horizontal surface for each month are presented in Figure 14.

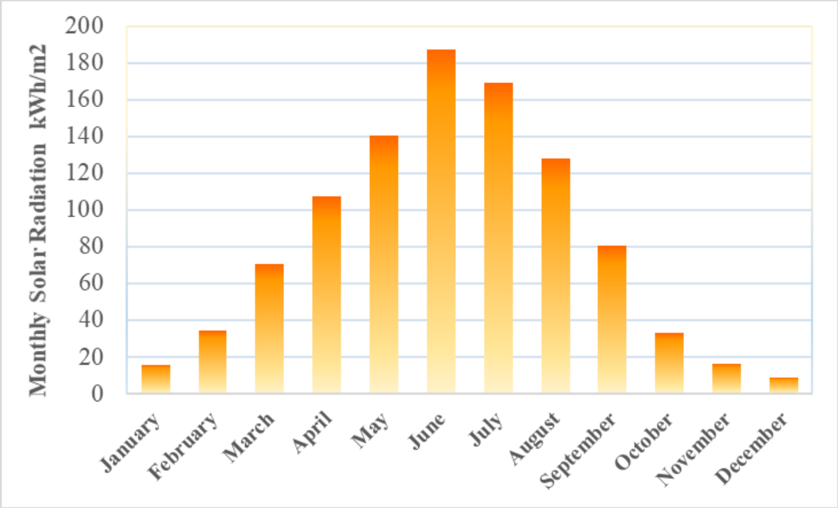

Figure 14 – The amount of solar radiation on horizontal surface.

The village of Bogashevo has a satisfactory potential for solar energy: for example, for a horizontal surface, the annual potential is 1040 kWh / m². For this reason, this energy source can be considered for further research.

The most rational use of solar energy occurs in the season from April to August, when the value of solar radiation is maximum. This creates a potential opportunity for the use of small installations designed to power small objects, in our case, a detached cottage.

However, an analysis of the change in the insolation value with an increase in the angle of inclination of the receiving surface from 0 ° to 45 ° showed that the specific reserve of the use of solar energy can be increased by different orientations of the receiving surface of power plants.

It should be taken into account that when installing power plants on flat roofs, it will be necessary to use additional mounting fittings to give the optimal angle of inclination of photographic panels or solar collectors. Thus, the use of panels or collectors with an inclination angle of the receiving surface of 30 °–45 °, at a constant value during the year, allows to increase the converted energy flux of solar radiation by 12 – 13,5% [10].

2.7 Biomass energy potential

For the production of electric and thermal energy, energy carriers of plant origin, formed during photosynthesis, are widely used. In order to have a complete picture of the energy situation in the region, I would like to consider the possibility of using biomass energy.

Biomass includes various raw materials of vegetable origin: wood, peat, agricultural waste. Currently, the decentralized zones of Russia have significant resources of forest and peat, many times exceeding other types of biomass. For this reason, it will be most rational to evaluate the energy potential of these types of natural energy sources.

In determining the energy potential of biomass, the following factors must be considered:

- The volume of bioresource, its distribution over the territory of the decentralized energy zone.
- The calorific value of various species, fractions and rocks of dry biomass.
- The absolute and relative humidity of the feedstock.

The Peat is one of the widespread solid fossil fuels. Tomsk region ranks second in peat reserves after the Tyumen region. 1340 peat deposits were found on its territory, which is approximately 32 billion tons [10].

The total area of the forest fund totals 26 722 thousand hectares, including the area occupied by coniferous species – 10 105 thousand hectares. The total wood stock of the main forest-forming species is 2 602 million m^3. Forests occupy about 60 % of the region. The total energy potential of the logging areas of the Tomsk region is 5,21 · 1012 J with a harvesting volume of 2 796 thousand m^3 / year [10].

To sum up, biofuels such as wood and peat can potentially be used in decentralized conditions to solve industrial and private problems. The main advantages of these energy resources are the independence of their potential from the time of year, proven technologies for energy conversion, and relative environmental friendliness in comparison with coal.

3. Design technical solution for power supply for given house

The content of this chapter is to determine the optimal design of the hybrid power plant and to develop an analysis of the cost of operating the plant for 20 years.

In the previous chapters, all the information needed to create a hybrid station model was obtained. In the first chapter, I made an analysis and comparison of existing solutions for the design of power systems for remote objects, where I chose the most suitable model of a hybrid power plant that consists of several energy sources. Also, I received electrical power load diagrams for each season.

The region's energy potential was also evaluated, which showed that wind can be considered the main year-round main source of energy. Solar energy may not be effective enough due to seasonality, which is determined by insufficient radiation. However, I will consider such a system as a power supply system:

1) Wind-diesel hybrid system

The principle of the scheme is the operation of a wind generator with the use of batteries to store excess energy and a diesel generator set for backup.

In case of excess energy, some of it goes to the batteries. Batteries store electrical energy, which turned out to be excessive during hours of maximum generated power and hours of minimum load of consumers. In the case when the generated power will prevail over the consumed and the batteries will be fully charged in the wind generator, ballast resistance is provided. To use energy more rationally, instead of ballast resistance, it is possible to use the payload (heating water or heating the room).

In the case when the wind generator does not produce the required amount of energy and the batteries are discharged, the diesel generator is turned on. It can cover both the missing part of the power and completely cover it.

2) PV-diesel hybrid system

As a next alternative, I'm going to consider installing solar panels to replace or replace part of the power generation from the diesel engine. A complete replacement of diesel generation by solar energy is not feasible due to the relatively low solar potential in the region. However, a combined solar / diesel system can prove to be very reliable and cost-effective if proper conditions are met (such as optimal sizing). A hybrid solar-diesel system can provide fuel savings over its entire life cycle while ensuring reliable power supply.

3) PV/Wind-diesel hybrid system

The combination of solar and wind energy in these systems allows to provide consumers with electricity during the calendar year in almost all-weather conditions.

- In cloudy weather or at night, when there is no sun, wind turbines are the main source of electricity.

- In sunny weather, when the wind is low, the share of electricity generated by photovoltaic panels is increasing.
- In the absence of favorable conditions (e.g. cloudy, windless weather, no wind at night), consumers are powered by batteries or a diesel generator that is part of a power plant. In case of sufficient wind-solar activity, when energy is supplied to consumers by wind generators and solar panels, the excess energy generated during this time is stored in the batteries and can be used to cover power shortages in adverse weather conditions [10].

4) Diesel power plant

For comparison, I will consider the option of power supply to the house using a diesel generator. Designing such a system does not require a large amount of expensive equipment, which reduces the cost of the initial investment. On the other hand, the regular use of diesel fuel leads to relatively high opportunity costs associated with the consumption, transportation and storage of fuel. Ultimately, in the course of technical analysis and economic calculation, it will be possible to decide on the use of renewable energy sources or a traditional energy source.

3.1 Wind turbine

The next step is to choose a wind turbine. Based on the analysis of the wind potential in the region, it can be concluded that the planned power plant will be located in the region with low wind potential, so it is necessary to choose wind generators with low starting speed and nominal speed. I have considered the models of wind generators which can be found on the Russian market and can be delivered to the region. Such models have relatively similar cost and technical characteristics, so the choice of producer will not affect the technical decision.

As the investigated wind generators, I consider the model range "Condor Air Max" consisting of three models with rated power of 10, 15 and 20 kW. Technical characteristics of the wind turbine generator are presented in Appendix 3-5. A low starting wind speed of 2,5 m/s and low nominal wind speed of 8 m/s, most fully corresponds to the wind potential in this region.

We need to calculate how much electricity the wind turbine produces and how much load the wind turbine can cover. To calculate this, we need wind velocity and loads of every month. The wind velocities are already calculated and the results are presented in previous chapter. All data are presented in Table 10.

Table 10 – Electricity produced by wind turbine “CONDOR AIR WT 10/15/20 kW”

Month	WT 1 kW	WT 10 kW		WT 15 kW		WT 20 kW	
	Produced, kWh	Produced, kWh	Coverage, %	Produced, KWh	Coverage, %	Produced, KWh	Coverage, %
January	174	1 745	73	2 374	99	2 724	115
February	144	1 439	67	1 988	92	2 245	104
March	164	1 646	86	2 256	118	2 612	137
April	145	1 451	90	2 035	126	2 266	140
May	157	1 570	94	2 176	130	2 503	150
June	83	832	60	1 175	85	1 307	95
July	52	519	36	803	56	863	60
August	72	724	50	1 067	74	1 169	82
September	83	833	51	1 228	76	1 340	83
October	150	1 503	79	2 096	110	2 367	124
November	199	1 993	96	2 686	129	3 156	152
December	196	1 967	82	2 651	111	3 032	127

To provide an uninterrupted power supply it is necessary to select a backup power source - in this case it is a diesel generator. Discussion of model and power selection will be presented below.

3.2 Solar panels

The next considered energy source will be photovoltaic panels located on the roof of the cottage.

In the previous chapter, it was determined that in this region, solar energy is a seasonal source of energy and cannot be the main source. This is confirmed by calculations of the optimal number of solar models to cover the entire load of the cottage (Table 10).

Solar panels in this case are a secondary source of power supply to the house. The main purpose of this installation will be to generate electricity on sunny, windless days to reduce electricity consumption from a diesel generator. Installation of the panels will be carried out on the south side of the roof with parallel connection of photovoltaic cells.

On the roof of the investigated house there is a limited area for installation of solar panels - 150 square meters. For this reason, when choosing the technology of solar modules, it is necessary to determine the option that allows for maximum power generation from the unit area.

The use of solar panels based on monocrystalline silicon allows to obtain the highest photovoltaic conversion efficiency among commercial modules due to the maximum possible purity of the original material. According to research [36], the efficiency of monocrystalline solar cells reaches 19-22%, and the efficiency of polycrystalline solar cells 14-16%. Due to the higher quality material, monocrystalline solar cells work more efficiently at low levels of illumination (in cloudy conditions), as well as at low temperatures. Such parameters allow to choose this technology.

I selected monocrystalline solar panels FSM-300M from the company Exmork. Technical characteristics of the solar module are presented in Appendix 6.

Table 11 – Electricity produced by solar panels “FSM-300M”

Month	PV 1 kW	PV 5 kW (17 panels)		PV 10 kW (34 panels)		PV 12,5 kW (42 panels)	
	Produced, kWh	Produced, kWh	Coverage, %	Produced, KWh	Coverage, %	Produced, KWh	Coverage, %
January	50	251	10	502	21	628	26
February	70	354	16	709	33	886	41
March	92	464	24	929	48	1 162	61
April	104	523	32	1 047	65	1 309	81
May	123	616	37	1 233	74	1 541	92
June	135	679	49	1 358	98	1 698	123
July	134	670	47	1 340	94	1 675	117
August	114	574	40	114	80	1 435	100
September	91	455	28	910	56	1 137	70
October	47	237	12	475	25	593	31
November	31	157	7	315	15	393	19
December	27	139	5	278	11	348	14

The range of the considered capacities I assumed (5 – 12,5) kW. Due to constructive restrictions, further increase in the number of solar panels is impossible. This number of solar panels allows to cover the load in summer periods up to 123 %.

3.3 Combination of solar panels and wind generator

The capacity of the wind turbine generator must be sufficient to power the house and to charge the batteries with enough capacity to power the receivers on windless days. It should be noted that during the calm period the batteries can be recharged by solar panels.

The optimization task, which will make it possible to decide on the composition of the power plant is to determine the optimal power and number of solar panels and wind generators required to provide uninterrupted power supply and minimize expenses.

To determine the most efficient source of renewable energy, it is necessary to make a comparison. For illustration it is feasible to calculate electricity generation using 1 kW of installed power from both sources (Figure 15).

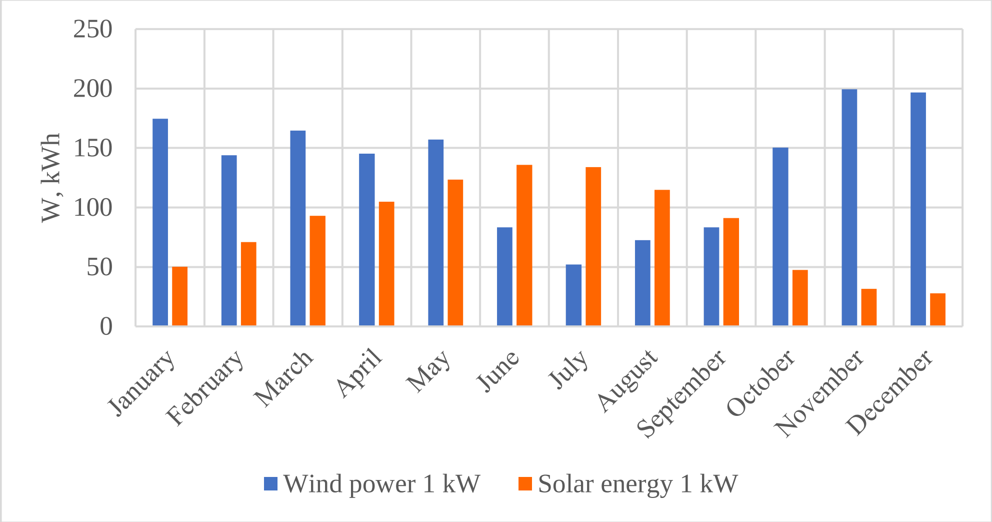

Figure 15 – Electricity production with 1 kW of solar and wind energy

The annual production of wind energy per year is 1 622 kWh and 1 024 kWh of solar energy. For this reason, I am going to consider the wind generator as the main source of energy and by changing the number of solar panels to regulate the total production of the power plant in order to achieve the maximum possible coverage. The range of the considered capacities I assumed (2,5 – 7,5) kW, which is the most complete coverage of the load. Further increase in the number of batteries is not rational as there is a large surplus (more than 50%) of electricity which will be spent on the balance load and is useless. Electricity generation by a combination of a wind generator and a different number of solar panels are presented below.

Table 12 – Electricity produced by combinations of wind turbine and photovoltaic modules

Month	WT 10 kW	+ PV 2,5 kW (9 panels)		+ PV 5 kW (17 panels)		+ PV 7,5 kW (25 panels)	
	Produced, kWh	Produced, kWh	Coverage, %	Produced, KWh	Coverage, %	Produced, KWh	Coverage, %
January	1 745	125	78	251	84	377	89
February	1 438	177	75	354	83	531	91
March	1 646	232	98	464	111	697	123
April	1 451	261	106	523	122	785	139
May	1 570	308	113	616	131	924	150
June	832	339	85	679	109	1 018	134
July	519	335	60	670	83	1 005	106
August	724	287	71	574	91	861	111
September	833	227	66	455	80	682	94
October	1 503	118	85	237	91	356	97
November	1 992	79	100	157	103	236	107
December	1 967	69	85	139	88	208	91

Each of the presented configurations should be equipped with batteries that will store surplus energy in order to use it during periods when there is a shortage of renewable energy sources. This will minimize the operating time of the diesel generator and will save fuel.

3.4 Batteries

Generation of electrical energy from renewable sources is characterized by power variability over time, and the schedule of changes in this power may not be the same as the schedule of its consumption. This problem is solved by installing batteries and a generator on non-renewable fuel. Batteries will store energy and produce it at the right time.

Since weather conditions are only statistically predictable and the calculated RES capacity is not always available, it is impossible to determine the exact number of batteries needed and sufficient for an uninterrupted power supply of the load.

Storage systems can be classified into short-term storage for hours or days to cover periods of bad weather and long-term storage for several months. Long-term storage is typically used in big photovoltaic power plants to compensate for seasonal variations in solar radiation in summer and winter. It is more rational for individual residential facilities to consider short-term storage of electricity for several hours.

I will use Delta GEL 12-200 batteries. Its rated capacity is 200 Ah, its cell voltage is 12 V and its lifetime is 10-12 years according to manufacturer and considered research [36,37]. Detailed specifications are provided in Appendix 7.

In my scenario, the capacity of the batteries is calculated in such a way that the object can receive electrical energy from the charging bases, in an economical mode, for at least 12 hours per day. To select the optimal number of batteries, the following configuration examples [36,37] were used. Energy that can be stored in one battery [36]:

$$W_{battary} = \frac{0,7 \cdot U \cdot C}{1000} = \frac{0,7 \cdot 12 \cdot 200}{1000} = 1,68 kWh,$$

Where,

U - battery voltage, V;

C - Rated Battery Capacity, Ah;

0,7 - Factor that takes into account the need to keep 30% of the battery charge level.

Daily consumption of the cottage in the winter period is W_{day} – 76,61 kWh.

The next step is to find the number of batteries:

$$N_{batteries} = \frac{W_{day}}{2 \cdot W_{battery}} = \frac{76,61}{2 \cdot 1,68} = 22,8 \approx 23$$

According to obtained results, in my calculations I will use 23 batteries, which ensure uninterrupted operation of the electrical equipment of the cottage for at least 12 hours. This number of batteries fulfils the technical recommendations of the wind generator and inverter manufacturer [38].

In order to prolong battery life, it is necessary to operate the batteries under optimal conditions and to keep the battery level within the permissible range. For this purpose, discharge controllers are used. For these systems, it is rational to use inverters with an integrated charging controller.

3.5 Inverter

The inverter converts the DC voltage to the AC voltage of the industrial frequency to power the electrical consumer. The shape of the received signal can be different: pure sinusoid, modified sinusoid, close to the sinusoid or rectangular. The form of the output signal of different types of inverters is shown in Figure 16. Currently, there are a large number of electrical receivers that cannot operate with a signal other than a pure sine, or the efficiency and life time is reduced [37].

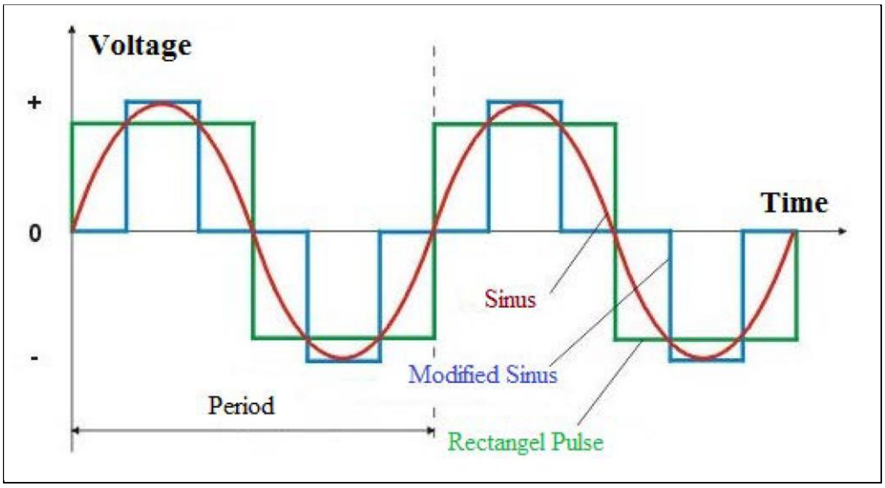

Figure 16 – Voltage in output of the inverter [37]

The configurations discussed in the previous sections of the systems include storage batteries. For this reason, it is necessary to consider stand-alone inverters capable of operating between several sources of energy, while recharging the storage batteries and monitoring the level of charge.

The solution to this problem is the use of hybrid inverters, which are a combination of a stand-alone inverter and a network inverter. That is, this device can supply electrical power to the load and recharge the batteries, both from wind turbines and solar panels.

The inverter will be selected based on the maximum power consumption per day during winter with a 20% reserve, as the inverter cannot operate at full capacity:

$$P_{inverter} = 1,2 \cdot P_{\max} = 1,2 \cdot 7,8 = 9,36kW$$

I choose the MAP HYBRID 24V 13,5 kW, which has a built-in charge controller that allows to control the battery charge and prevent the charge level below the set level. The technical characteristics are presented in Appendix 8.

3.6 Diesel generator

As it is already mentioned, diesel generators are a general option not only for stand-alone supply but also for a wide variety of other cases: emergency reserve, part of the hybrid systems. This leads to a big market with different suppliers, options for installed capacity and for attachable electronics. Diesel generators are produced in an open or closed container and can be installed to the different sites with different conditions of exploitation.

Depending on the configuration of the power supply system, the power of diesel generators and the algorithm for determining power will be different.

Diesel power plant

Based on the requirement to supply electricity to consumers in any situations, the number and power of diesel generators should be selected with the following requirements [36]:

1. The total power of the machine should be 20% more than the daily maximum load;
2. To be able to service the equipment, it is necessary to select machines of the same power;
3. Diesel generators should be loaded within 25-80% of their rated power.

In the previous chapters, I calculated the electricity consumption of the cottage and determined a daily maximum load of 8 kW, so the total power of the entire system should be equal to 10 kW. I choose two 5 kW diesel generators.

This solution allows to load both generators equally and, if necessary, switch off one of them during periods of low power consumption. I was in contact with “Diesel Machines”, a company that designs similar projects, and they advised me to choose the KOHLER-SDMO DIESEL 6500 TE. This model meets the requirements for reliability and is capable of operating in these climatic conditions. The technical characteristics of this generator are presented in Appendix 9.

Hybrid systems

Diesel generators in hybrid power supply system perform the functions of a guaranteed power source. In addition, depending on the structure of the energy complex, it can perform buffer functions, compensating for ripple power from renewable energy sources.

In the previous section, I defined three options for a hybrid power plant. The power range covers load from 6 to 9 months. For the rest of the time, an additional power source must be included. For hybrid systems it is enough to use one 5 kW generator KOHLER-SDMO DIESEL 6500 TE because most of the energy the cottage will receive from renewable energy sources.

3.7 Calculation of diesel fuel consumption

To analyze the technical and economic performance of the diesel power plant and the whole configuration, it is necessary to assess the dependence of diesel generator fuel consumption during the year. Except for rated fuel consumption there is real fuel consumption which depends on load and can be calculated with the following formula [36]:

$$G_1 = K_{nl} G_r + (1 - K_{nl}) G_r \frac{P_1}{P_r},$$

Where G_1 – real fuel consumption;

G_r – rated fuel consumption;

K_{nl} – no load fuel consumption coefficient (K_{nl}=0,3);

P_1 – load on the generator;

P_r – rated capacity of the generators (Pr =5 or 10 kW).

If we know rated fuel consumption for respective load mode and volume of generated energy, we can calculate volume of consumed fuel for the period of time with following formula [36]:

$$Q_f = G_1 W,$$

Where W – energy, generated in day, month or year.

According to previous formulas, we obtain that 5 249 liters of fuel the diesel generator consumes a year to satisfy consumer needs in case of Diesel power plant. For comparison, I calculated the annual diesel consumption for all the configurations of the schemes that I considered in the previous sections. Fuel consumption for other variants is presented in Table 13.

Table 13 – Annual diesel consumption

Configuration of power plant	Wind turbine and Diesel generator (10 kW+5 kW)	Wind turbine and Diesel generator (15 kW+5 kW)	Wind turbine and Diesel generator (20 kW+5 kW)
Fuel consumption, l/year	1 355	413	277
Configuration of power plant	PV panel and Diesel generator (5 kW+5 kW)	PV panel and Diesel generator (10 kW+5 kW)	PV panel and Diesel generator (12,5 kW+5 kW)
Fuel consumption, l/year	4 019	2 789	2 314
Configuration of power plant	WT+PV and Diesel generator (10 kW+2,5 kW+5 kW)	WT+PV and Diesel generator (10 kW+5 kW+5 kW)	WT+PV and Diesel generator (10 kW+7,5 kW+5 kW)
Fuel consumption, l/year	818	441	182

4. Evaluation proposed designs and performing economic evaluation

A comparison from the economical point of view offered above measures which will allow the saving of electrical energy consumption is represented in this chapter. The main point is not only to know how much energy would be possible to save by implementation of the definite measure but also to know the initial investments required for a definite measure. Moreover, I should take into account possible changes in the main inputs.

For the economic evaluation of the project, I will use the net present value (NPV) model. All calculations for the model will be performed in Microsoft Excel, as it is a reliable and widely used tool for such tasks.

Net Present Value (NPV) is a sum of discounted cash flows minus investment in the initial period. It may be written as a following formula [41]:

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

Where CF_t – cash flow in the period t;

r – discount rate;

INV – initial investment in the project;

t – number of time periods;

T – lifetime of the project.

NPV shows the difference between the present value of cash inflows and the present value of cash outflows. However, in the current project, there are no cash inflows. Thus, NPV for each possible measure will be calculated based on initial investments and annual expenses for fuel consumption and maintenance, taking into account every year's cost growth, inflation rate and lifetime period of the project. As in basis of NPV calculation are only expenses then NPV for all considered measures will be negative and a higher rate of NPV will represent a more profitable option.

The project's lifetime is equal to 20 years since this is the average lifetime of the main equipment in the system (Diesel generator, PV panels, Wind generator and Invertor). Because the typical lifetime of used batteries is about 10-12 years according to manufacturer data [35,39], I change batteries once during the project (on the 10th year of operation).

I will use the same economic model for calculating each design option by changing only capital input data of these calculations: analyzing different equipment and changing the installed capacity of energy source and operation costs.

4.1 Inputs for economic model

To create an economic model, it is necessary to determine all the input parameters. I am going to consider 10 Scenarios (Table 1) with different power system configurations.

For the economic evaluation of RES's design, a method usually works with stored energy that has not been taken from the grid and hence saves money or receives money from selling electricity to the grid. In my case, I cannot use this method because I am considering off-grid systems. Therefore, for comparison, I propose 1 Scenario (Table 1), where there is only a diesel generator without RES and batteries. I compare options based on Cash Flow costs. For this reason, I will only use NPV for comparison. The main components of the economic model of the project are described below.

Investments

Prices for equipment needed to construct the power supply system were taken from the vendor websites. After consulting with the delivery company PEK [42] and discussing the terms with the equipment manufacturers, I decided to assume a delivery cost of 1000 Euro. Geographical conditions do not complicate the construction of the power system, significant transport problems, or work at high altitudes - all equipment is installed inside the building and on the roof of the house. That is why the total cost of design and installation is taken equal to 2% of the investment costs. A brief description of each scenario and the values of the total investment are presented in the Table below.

Table 14 – Investment cost for each scenario

	Configuration of power plant	Total Investments, EUR
1 Scenario	Diesel generator	14 382
2 Scenario	Wind turbine 10 kW + Diesel generator	27 628
3 Scenario	Wind turbine 15 kW + Diesel generator	29 711
4 Scenario	Wind turbine 20 kW + Diesel generator	32 489
5 Scenario	PV 5 kW + Diesel generator	21 448
6 Scenario	PV 10 kW + Diesel generator	24 989
7 Scenario	PV 12,5 kW + Diesel generator	26 656
8 Scenario	WT 10 kW + PV 2,5 kW + Diesel generator	29 503
9 Scenario	WT 10 kW + PV 5 kW + Diesel generator	31 169
10 Scenario	WT 10 kW + PV 7,5 kW + Diesel generator	32 835

Operational costs

Yearly maintenance of RES includes: checking the state of equipment, contacts and insulation of cables connection, testing inverter, checking the efficiency of grounding, an inspection of fastening systems for corrosion or loose bolted connections. The maintenance and repairs cost for RES was taken as 2% from main equipment investment per each year [36]. The battery maintenance will be equal to 1,5% of the invested funds once a year [10]. For a diesel generator, annual maintenance is estimated at 5% of its cost [13] in the first scenario, where it is the main energy source. In other scenarios, the diesel generator maintenance is assumed to be 2,5% of its cost. I assumed that half of the cost of operating a diesel generator was due to the shorter operating time and, therefore the longer service life. Operating costs are increasing in the future due to inflation and escalation.

Fuel costs are calculated by using the value of average fuel consumption, current diesel price in the region and taking into account predicted fuel price growth in nominal values. The costs related to the transportation of diesel were neglected due to the small distance between supplier and customer. All costs have been calculated as a sum for 20 years of project's lifetime.

Inflation

To provide validity results in the economic model, it is necessary to define the rates. These rates are used to increase the cash flows over the project horizon period. Inflation shows an average increase of prices on products and services in the country during the year. In this project, the growth rate of such parameters as the cost of maintenance and repair of equipment will be correlated with the inflation rate. Historical data for the range 2010-2019 [43] are presented in Table 15.

However, to estimate the inflation rate for this project, I used the available projections for 2020-2024 [44] from the Central Bank of Russia and the Ministry of Economic Development. The inflation rate for this project is assumed to be 4%.

Table 15 – Yearly inflation rate in Russia (Based on data from [43])

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Inflation, %	8,78	6,10	6,58	6,45	11,36	12,91	5,38	2,52	4,27	3,05
Average Inflation, %	6,74									

Escalation and (de-) escalation

The cost of diesel fuel is relatively complex to predict in the future, as the price depends on many factors and the economic situation in the country and in the world. In the Tomsk region the price of a liter of diesel fuel at the time of the research was in the range of 0,55-0,6 [45] euros and further growth was expected. The price of 0,6 EUR/liter will be used for the economic evaluation of a diesel station and design of a hybrid system. In the future, this price will grow by 6,27% every year. This is the value of the escalation of the diesel fuel price I assumed based on expert projections from the Ministry of Energy and Rankhigs [46].

As mentioned earlier, a replacement of the batteries is planned for ten years. The cost of the investment will be determined based on the initial cost of the batteries and the rate of price change. According to the Research [47,48], the cost of batteries is expected to decline in the coming years due to lower development costs, improved technology and optimized supply. This applies to lead-acid battery technology. As a result, the de-escalation of the cost of batteries is assumed to be 2,47 % for this project.

Discount rate

In this research, all investments in the project will be done by the own funds. The most influencing factor in choosing the type of investment is the discount rate value. The discount rate refers to the interest rate used to determine the present value of future cash flows. It takes into account the time value of money and the risk or uncertainty of future cash flows. For this project, I assume discount rate as risk-free rate of Government bonds in Russia 7 % [49].

4.2 Economic model calculation

In the previous sections, I obtained all the necessary data for economic analysis. The next step is to calculate the NPV for each scenario. The summarized results are shown in the Table 16 below. As we can see from this Table, the traditional solution with diesel generators to our task is not rational. In the current conditions, more attractive solutions are RES projects. It is necessary to mention that all models of RES have been built as the most pessimistic scenarios: prices of equipment change with projected escalation rates, a lifetime for each kind of equipment is considered to be minimal.

Table 16 – Results of economic model calculation

	Configuration of power plant	NPV, EUR
1 Scenario	Diesel generator	-79 024
2 Scenario	Wind turbine 10 kW + Diesel generator	-53 319
3 Scenario	Wind turbine 15 kW + Diesel generator	-46 117
4 Scenario	Wind turbine 20 kW + Diesel generator	-48 268
5 Scenario	PV 5 kW + Diesel generator	-73 318
6 Scenario	PV 10 kW + Diesel generator	-64 973
7 Scenario	PV 12,5 kW + Diesel generator	-62 127
8 Scenario	WT 10 kW + PV 2,5 kW + Diesel generator	-50 097
9 Scenario	WT 10 kW + PV 5 kW + Diesel generator	-48 292
10 Scenario	WT 10 kW + PV 7,5 kW + Diesel generator	-47 716

The previous table shows all scenarios and highlights that are most profitable for each of the main configurations in green. I compared the options according to NPV, and since I included only CF costs in the calculations, it is negative for all NPV options. Finally, I chose the highest NPV. I recommend choosing 3rd scenarios where the NPV is the highest of the offered options. The NPV, in this case, is -46 117 Euro.

However, I would like to do sensitivity analysis for the three most profitable scenarios (Scenario 3,7 and Scenario 10) in order to consider convenient economic conditions in which the options may be more reasonable.

4.3 Sensitivity analysis

Sensitivity analysis is a method used to determine how different values of the independent variable will affect a certain dependent variable in a given set of assumptions. This method is used within specific boundaries that depend on one or more input variables. Sensitivity analysis is important for planning a long-term project. Some parameters may change significantly during the project's lifetime, and it is necessary to assess these changes and evaluate how important they will be to the profitability of the project. After sensitivity analysis, it is possible to make conclusions about which factors have more or less influence on NPV.

In this chapter sensitivity analysis will be done for:

- Dependence NPV on discount rate;
- Dependence NPV on fuel price;
- Dependence NPV on of PV investments changing;

Let us consider how changing the discount rate will influence on NPV for each scenario. The value of discount rate is introduced by user. With discount rate growth NPV increases (Figure 17). However, within considered case changing of discount rate does not influence on the made decision. For all options, NPV increases proportionally. This form of the graph is explained by negative cash flows.

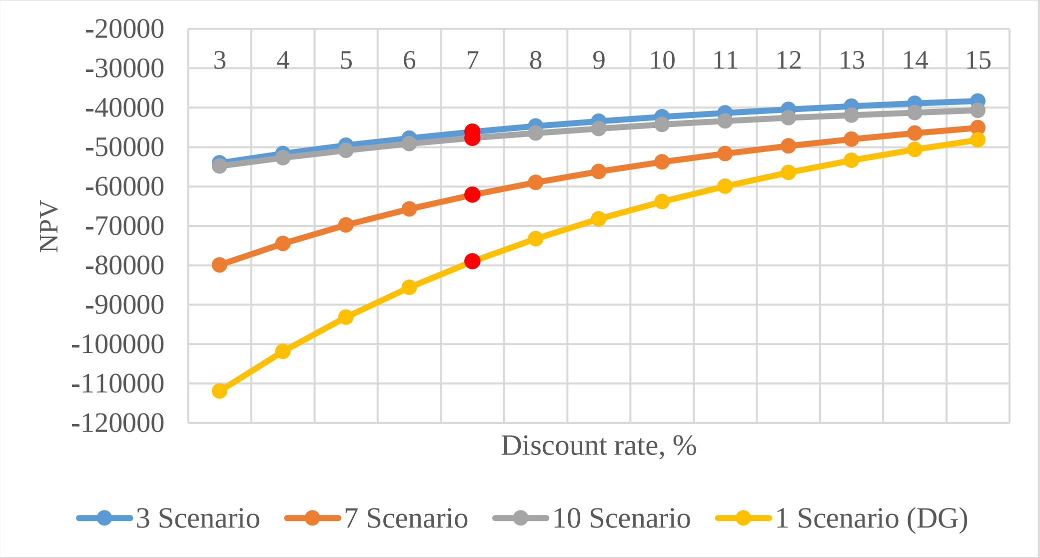

Figure 17 – Dependence NPV on discount rate

The cost of diesel fuel is one of the most relevant parameters in operating costs. There is a certain impact of the fuel price on the NPV (Figure 18).

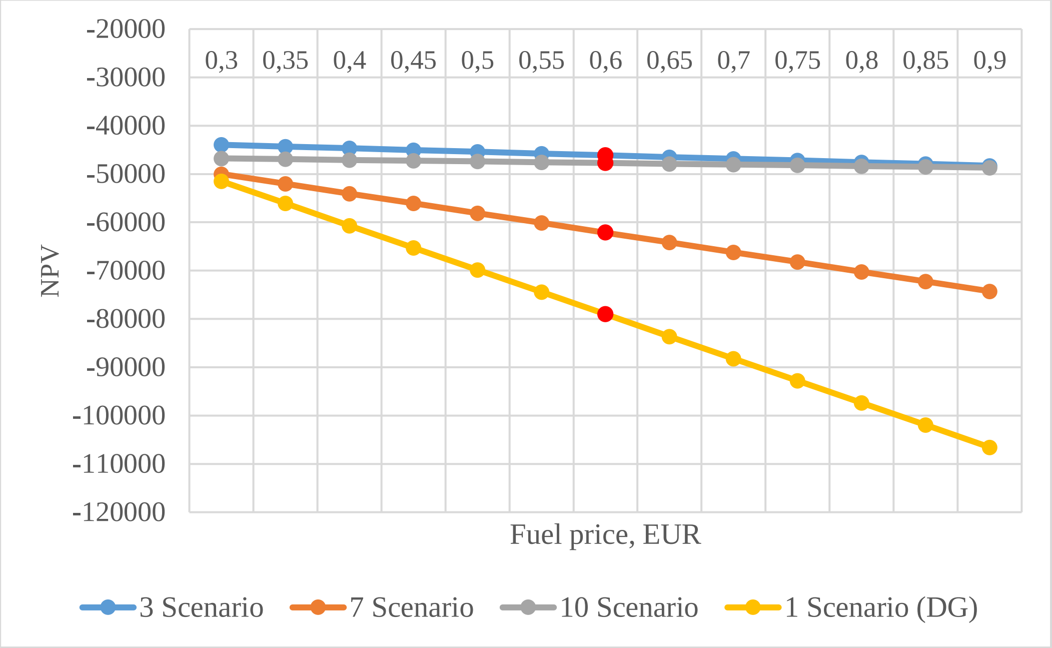

Figure 18 – Dependence NPV on fuel price

In this diagram, we may see that a significant increase in diesel fuel prices will affect operating profit and cash flow; therefore, the project will be more expensive. Changes in fuel prices affect more on 1st and 7th scenarios. This is due to the wide use of a diesel generator in the system.

Required investments for designing power plant differ depending on the cost of materials and price list of companies which provide construction work. In previous calculations, scenarios 3 and 10 show close NPV values for various parameters; therefore, I am going to consider a parameter that will be closely related to both options - the cost of solar panels. In my work, I used the average rate of investments. However, this value can be changed. Figure 19 shows how changing of investment rate influence on project NPV.

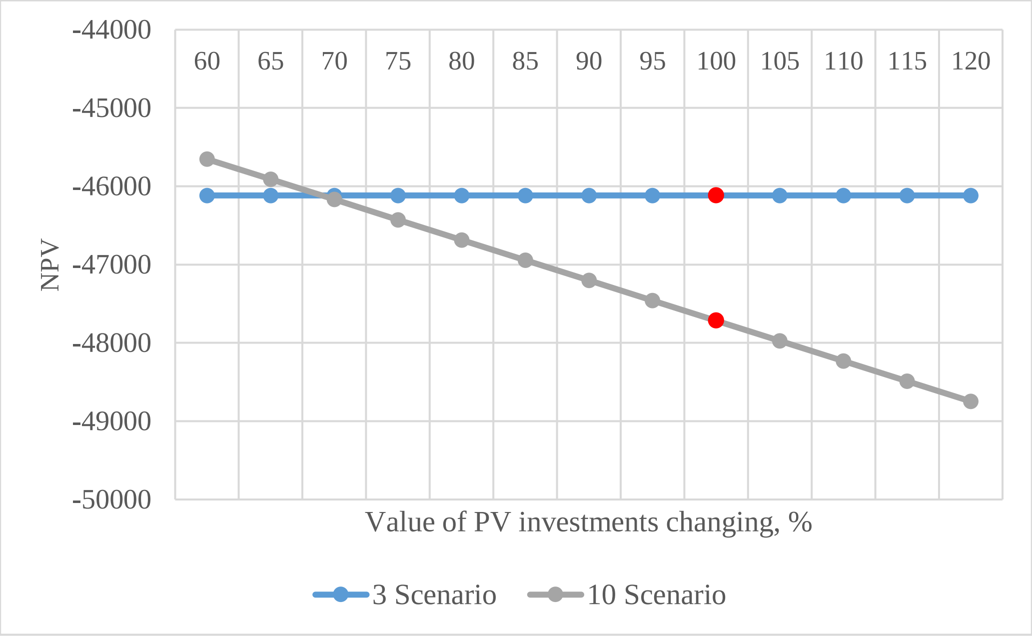

Figure 19 – Dependence NPV on of PV investments changing

The NPV of 3rd scenario remains at the same level because this configuration does not include solar panels. If the investment in solar panels decreases by 30%, the 10th scenario becomes more profitable and has a higher NPV. However, the 3rd scenario is preferable because it is quite complex to achieve such a significant reduction in capital costs and not to lose the quality and reliability of the entire system.

CONCLUSION

In the present master's thesis, I have solved problems connected with the decentralized power supply of an inhabited house in a village Bogashevo, the Siberian part of Russia. I was restricted by the fact that there is no gas pipeline or available electricity network in the chosen location that would provide electricity and heating to the investigated house. I, therefore, considered an autonomous power supply system for the design. In addition to traditional energy sources, such as diesel generators, I considered alternative energy sources that would be efficient in the Siberian climate.

At the beginning of my work, I reviewed trends in the development of alternative energy sources in the world and Russia. The price of fuel is constantly changing and depends on many geopolitical and economic factors. However, in recent years it has an apparent upward trend. This allowed to understand why renewable energy is interesting not only in terms of environmental impact, as it provides to reduce emissions of harmful substances into the atmosphere, but also in terms of economic profit, as it allows to significantly reduce operating costs as a result of reduced diesel fuel consumption.

My next step was to analyze existing technologies for designing autonomous power supply systems. I compared technical parameters related to reliability, stability, and efficiency, as well as economic parameters showing the value of an investment and annual maintenance, which eventually has an impact on the rationality of project realization.

Designing an autonomous power supply system is a complex optimization task. It usually involves many criteria and parameters that need to be considered. For this reason, I have made calculations to get all the necessary input data to create a technical model. At first, I evaluated the energy potential of the selected location. After this evaluation, I decided that wind and solar are the most optimal alternative energy sources for this project and can be considered the main or additional energy source in combination with a diesel generator. A load graph for each season was built to determine peak loads and the house's annual power consumption. For power generation, I have chosen a hybrid system that uses a combination of a wind turbine and solar panels with accumulation in batteries and a diesel generator.

For comparison, three basic configurations were defined - Diesel power plant, Wind-diesel hybrid system, PV-diesel hybrid system and PV/Wind-diesel hybrid system. For each configuration, a different set of equipment and installed power was considered. I decided to include batteries in hybrid systems that allow to improve reliability of power supply in periods of low wind and solar potential. This solution allows to significantly reduce operating costs by reducing diesel fuel consumption. At the end of the calculation, I had the following information for each scenario: the amount of equipment, information on power generation (how much each source produced), and information about diesel fuel consumption. Having collected all this information and selected the project evaluation methodology, I started the economic calculation of the project.

For economic analysis, I created a model that included the amount of initial investment and operating costs related to repair, maintenance, and consumption of diesel fuel. As a decision, I proposed ten scenarios. Based on the NPV results, the most advantageous scenario I chose configuration with Wind turbine and diesel generator (3rd Scenario).

The last part of the work was to perform a sensitivity analysis of individual input parameters. Sensitivity analysis related to the dependence of NPV on the price of diesel fuel, changes in the discount rate, and the price of solar panels for the three most profitable scenarios.

Changing these parameters does not affect the final decision. The configurations with a Diesel power plant (1st Scenario) and PV-diesel hybrid system (7th Scenario) are irrational for all considered parameter ranges. This is explained by high operating costs due to the significant consumption of diesel fuel and high annual maintenance costs.

To sum up, I would recommend the investor to choose the third scenario, where the installed capacity of the wind turbine is 15 kW and the backup power source is a 5 kW diesel generator. This configuration is the most profitable when compared to other options. To guarantee the reliability of power supply and reduce the diesel generator's operating time, it uses 23 batteries with a capacity of 200 Ah/12W. The operation of this system provides for annual maintenance of main equipment and replacement of batteries after ten years. This solution provides high load coverage due to the wind turbine in the summer season by more than 56% and by more than 90% in the winter season. Therefore, the annual consumption of diesel fuel is relatively low and is equal to 413 liters. The excess energy also utilizes to heat Hot Water Supply.

If it were possible to connect the house to the Public Electrical network, the economic evaluation would be different, and the question would be whether the construction of an autonomous power supply system would be economically feasible under these conditions.

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APPENDICES

Appendix 1 – Household consumers with specified and calculated characteristics

Electric consumer	Rated Power, кW	Demand factor, Kd	Use factor, Ku	Active Power, кW
Electric lighting	0.35	-	-	0.35
Household Electrical Network	4.1		0.7	2.87
Drainage Pump	0.6	0.9	0.7	0.378
Electric Warm floor	6.24	0.5	1	3.12
Kitchen				
Electric stove	3.5	0.8	1	2.8
Refrigerator	0.6	1	0.5	0.3
Teapot	1.5	0.3	1	0.45
Microwave	0.9	0.7	1	0.63
Electric coffee maker	0.65	0.3	1	0.195
Dishwasher	2	0.8	0.8	1.28
Hall. Tambour. Terrace				
Iron	0.9	0.3	1	0.27
Bedroom x 2				
Personal Computer	1	0.6	1	0.6
Living room				
Home cinema	0.8	0.6	1	0.48
Electric vacuum cleaner	0.65	0.7	1	0.455
Bathroom				
Washing machine	2	0.8	0.8	1.28
Water heater	2	0.6	0.8	0.96
Sauna				
TV	0.2	0.6	1	0.12
Total				16.5

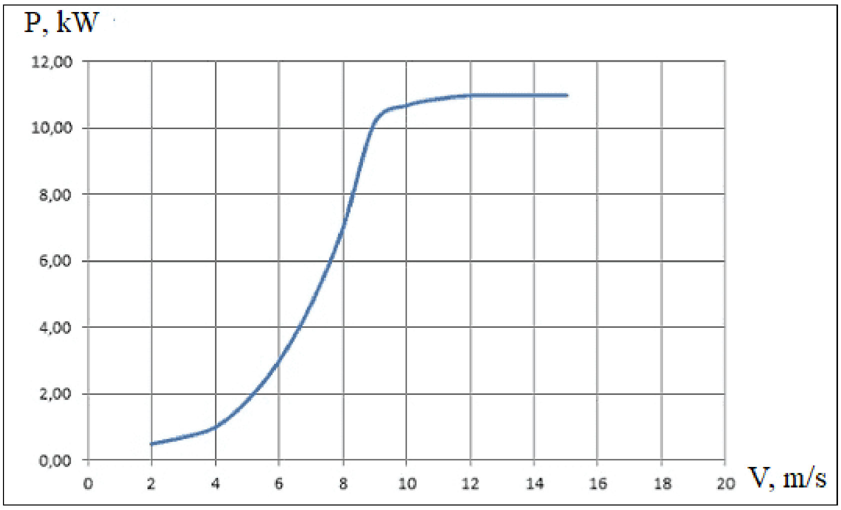
Appendix 2 – Daily power consumption

Electric consumer	Rated Power, кW	Working time per day, hours	W_{day}, kWh
Electric lighting	0,35	6	2,1
Household Electrical Network	4,1	1	4,1
Drainage Pump	0,6	1	0,6
Electric Warm floor	6,24	7	43,68
Electric stove	3,5	1,5	5,25
Refrigerator	0,6	4	2,4
Teapot	1,5	0,25	0,375
Microwave	0,9	0,2	0,18
Electric coffee maker	0,65	0,5	0,325
Dishwasher	2	1	2
Iron	0,9	0,15	0,135
Personal Computer	1	4	4
Home cinema	0,8	5	4
Electric vacuum cleaner	0,65	0,1	0,065
Washing machine	2	0,3	0,6
Water heater	2	3	6
TV	0,2	4	0,8
Total			76,61

Appendix 3 – Wind Turbine Specifications Condor Air 10 kW (Based on data from [38])

General information	
Rated power	10 kW
Rotor shaft location	Horizontal
Mast height	18 meters
Life time	20 – 25 years
Price	9 625 EUR
Performance indicators	
Starting speed	2,5 m/s
Nominal wind speed	3 – 20 m/s
Maximum wind speed	30 m/s
Wind energy utilization	More than 0,42
Conversion system efficiency	More than 0,85
Rotor	
Diameter	7,5 м
Number of blades	3
Blades	
Material	Fiberglass
Blade length	3,5 meters
Generator	
Type	Three-phase asynchronous
Voltage	220/380 V ± 10%
Frequency	50 Hz ± 5%
Recommended numbers of Batteries	20
Recommended battery capacity, A*h	150
Weight	
Rotor and Gondola	600 kg

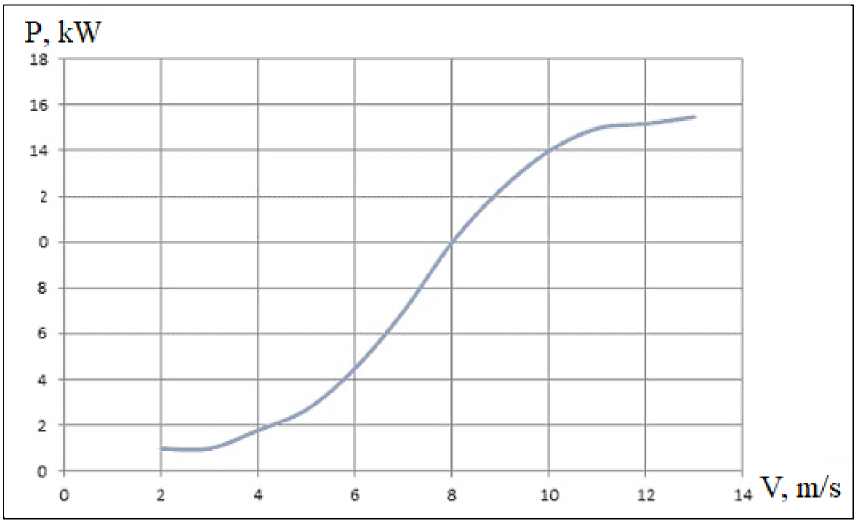
Dependence of power generation and wind speed



Appendix 4 – Wind Turbine Specifications Condor Air 15 kW (Based on data from [38])

General information	
Rated power	15 kW
Rotor shaft location	Horizontal
Mast height	18 meters
Life time	20 – 25 years
Price	11 688 EUR
Performance indicators	
Starting speed	2,5 m/c
Nominal wind speed	3 – 20 m/c
Maximum wind speed	30 m/c
Wind energy utilization	More than 0,42
Conversion system efficiency	More than 0,85
Rotor	
Diameter	9,5 м
Number of blades	3
Blades	
Material	Fiberglass
Blade length	4,5 meters
Generator	
Type	Three-phase asynchronous
Voltage	220/380 V ± 10%
Frequency	50 Hz ± 5%
Recommended numbers of Batteries	20
Recommended battery capacity, A*h	150
Weight	
Rotor and Gondola	850 kg

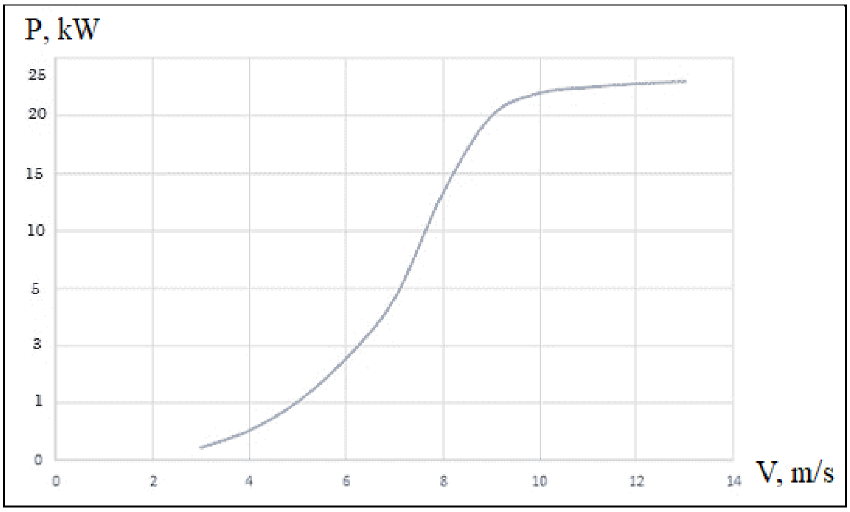
Dependence of power generation and wind speed



Appendix 5 – Wind Turbine Specifications Condor Air 20 kW (Based on data from [38])

General information	
Rated power	20 kW
Rotor shaft location	Horizontal
Mast height	18 meters
Life time	20 – 25 years
Price	14 437 EUR
Performance indicators	
Starting speed	2,5 m/c
Nominal wind speed	3 – 20 m/c
Maximum wind speed	30 m/c
Wind energy utilization	More than 0,42
Conversion system efficiency	More than 0,85
Rotor	
Diameter	13,5 м
Number of blades	3
Blades	
Material	Fiberglass
Blade length	6 meters
Generator	
Type	Three-phase asynchronous
Voltage	220/380 V ± 10%
Frequency	50 Hz ± 5%
Recommended numbers of Batteries	20
Recommended battery capacity, A * h	150
Weight	
Rotor and Gondola	1300 kg

Dependence of power generation and wind speed



Appendix 6 – Characteristics of the solar module FSM 300 [38]

General information	
Power P_{pan}	300 W
Area $S_{mod}(m^2)$	1,94
Price	207 EUR
Efficiency factor	16,5
Voltage (V)	24 V
Size	1956 × 992 × 50 mm

Appendix 7 –Technical characteristics of the storage battery Delta GEL 12-200 [35]

General information	
Voltage	12 V
Capacity	200 Ah
Electrolyte type	Lead-acid (AGM+GEL)
Price	440 EUR
Maximum charge current	1000 A
Size	522 ×239×222
Weight	64,7 Kg
Lifetime	10-12 years

Appendix 8 – Inverter Specifications MAP HYBRID 24V 13,5 kW (3 phase) [39]

General information	
Voltage input	24 V
Voltage output	220-380 V
Frequency	50 Hz
Price	2 035 EUR
Maximum power	13,5 kW
Size	63×37×51 cm
Weight	74,7 Kg
Lifetime	20 years

Appendix 9 – Diesel power plant Specifications KOHLER-SDMO DIESEL 6500 TE [40]

General information	
Rated power (P_{nom})	5 kW
Reserve power (P_{max})	5,2 kW
Generated current	3-phase/ 400 V/ 50 Hz
Fuel consumption	
Fuel consumption (100% of the load)	2,0 l/h
Fuel consumption (75% of the load)	1,2 l/h
Fuel consumption (50% of the load)	0,8 l/h
The volume of the fuel tank	200 l
Stand-alone mode of work (P 75%)	56,5 h
Other information	
Size	1810 x 1020 x 1550 mm
Weight	910 kg
Price	6 625 EUR