Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management, and Humanities

Stand-alone energy supply system with distributed photovoltaic generation

Study program: Electrical engineering, power engineering, and management

Field of study: Economy and management of power engineering

Scientific advisor: Sherzod Tashpulatov, Ph.D.

Dmitry Muravyev

Prague 2018

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Muravyev** Jméno: **Dmitry** Osobní číslo: **478929**
Fakulta/ústav: **Fakulta elektrotechnická**
Zadávající katedra/ústav: **Katedra ekonomiky, manažerství a humanitních věd**
Studijní program: **Elektrotechnika, energetika a management**
Studijní obor: **Ekonomika a řízení energetiky**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Stand-alone energy supply system with distributed photovoltaic generation

Název diplomové práce anglicky:

Pokyny pro vypracování:

1. Electrification issues in distant and small villages
2. Distributed generation of electricity based on integrating diesel with RES
3. Impact of distributed photovoltaic generation on the voltage magnitude in a stand-alone power supply system
4. Photovoltaic module modeling using Simulink/MatLab
5. Techno-economic analysis of stand-alone hybrid photovoltaic-diesel system

Seznam doporučené literatury:

LUKUTIN, B.V., MURAVLEV, I.O., PLOTNIKOV, I.A. Sistemi elektrosnabzheniya s vetrovimi i solnechnimi elektrostanciyami [Power supply systems with wind and solar power plants]. Tomsk: Tomsk Polytechnic University, 2015.
WOOD, J. Local Energy: Distributed generation of heat and power. London: The Institution of Engineering and Technology, 2008.
UDALOV, S.N. Vozobnovlyayemiye istochniki energii [Renewable energy sources]. Novosibirsk: Novosibirsk State Technical University, 2014. Available at: https://rucont.ru/efd/246609
EVANS, L.R. Fueling Our Future: An Introduction to Sustainable Energy. New York: The United States of America by Cambridge University Press, 2007.

Jméno a pracoviště vedoucí(ho) diplomové práce:

PhDr. Mgr. Sherzod Tashpulatov, Ph.D., katedra ekonomiky, manažerství a humanitních věd FEL

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

Datum zadání diplomové práce: **01.02.2018** Termín odevzdání diplomové práce: ____________

Platnost zadání diplomové práce: **30.09.2019**

PhDr. Mgr. Sherzod Tashpulatov, Ph.D.
podpis vedoucí(ho) práce

podpis vedoucí(ho) ústavu/katedry

prof. Ing. Pavel Ripka, CSc.
podpis děkana(ky)

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Declaration:

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

24.05.18 Dmitry Muravyev

ABSTRACT

The quality of electricity supply due to decreased voltage is becoming essential in countries with a vast territory and numerous settlements (for instance, China and Russia). This master thesis focuses on developing approaches to design a hybrid power supply for the needs of the rural settlement. I develop an algorithm for determining an optimal structure of a power supply system considering technical, economic, environmental, and local aspects. The aim of the thesis is to create a technical and financial model in order to evaluate the installation of the hybrid system and to analyze its effectiveness. In order to achieve this goal, I study the necessary generation capacity to analyze load coverage, and I also provide technical and economic analyses. One of my most important contributions is the analysis of investment and methods for reaching the maximum economic efficiency. I model the hybrid system, using the real data of the decentralized settlement in Russia’s Siberia area, which are analyzed in MS Excel, Homer Energy, and MatLab. For the economic part, I analyze the market of generating equipment as well as the investment, using discounted payback period, NPV, and IRR.

KEYWORDS

Renewable energy sources, photovoltaic generation, distributed energy, stand-alone power supply system

CONTENTS

LIST OF ABBREVIATIONS

AGM – Absorbent Glass Mat

CAPM – Capital Assets Pricing Model

CF – Cash Flow

CHPP – Combined Heat and Power Plant

DG – Distributed Generation

DPP – Diesel Power Plant

EMF – Electromotive Force

GDP – Gross Domestic Product

HPP – Hydro Power Plant

HPS – Hybrid Power Station

IRR – Internal Rate of Return

MOEX – Moscow Exchange

MPPT – Maximum Power Point Tracking

NASA – National Aeronautics and Space Administration

NPV – Net Present Value

NPP – Nuclear Power Plant

PLL – Phase Lock Loop

PV – Photovoltaic

RES – Renewable Energy Sources

SAPS – Stand-alone Power Systems

SCADA – Supervisory Control and Data Acquisition

SOC – State of Charge

SPP – Solar Power Plant

TPP – Thermal Power Plant

INTRODUCTION

Decentralized energy supply is one of the most important problems of modern power engineering. Electricity price for customers in the regions with decentralized power supply far exceeds the price for customers connected to the grid (approx. from 15 to 150 rubles in contrast to from 0.97 to 8.2 rubles per 1 kWh, respectively) [7]. The reasons for high electricity prices in the regions with decentralized power supply are high fuel transportation costs, poor maintenance of the generating equipme9nt and variable load leading to inefficient work conditions for generating equipment.

“Energy Strategy of Russia for the period until 2035” program defines the following two strategic objectives for the use of renewable energy sources (RES) [8]:

1. Integrate new generating capacities which are operating on the basis of RES, provided they are economically efficient.
2. Develop domestic scientific and technical base, advanced technologies in the field of using RES, increase production of basic generating and auxiliary equipment for RES in Russia.

Renewable energy can make a significant contribution in solving energy supply problem in decentralized regions of Russia, which account for up to 70% of the country's territory inhabited with about 14% of population.

The most promising option for building autonomous energy systems for such decentralized areas is the integration of wind and photovoltaic (PV) stations into the diesel power supply system. Reduction of the cost of photovoltaic panels in combination with the ease of their installation and operation increase the popularity of photo-diesel autonomous energy in Russia [1].

Solar distributed generators are the most promising technologies of renewable energy sources in networks with low voltage. Distributed generators are installed to satisfy local needs for load as an additional source with a constant percentage of power from the main diesel station.

Integration of solar power plant (SPP) into stand-alone power systems (SAPS) with diesel power plant (DPP) requires a solution of many problems, in particular:

1. Variable load in remote settlements of electrification and energy of solar radiation during the day.
2. The ratio of the capacities of the diesel and photovoltaic parts of the station, depending on the configuration of SAPS.
3. Quality and value of electric power losses in SAPS with distributed photovoltaic generation.
4. Optimal configuration depending on a single or multiple block structure considering customer load.
5. Technical and economic characteristics of the SAPS, where the main interest is focused on saving the diesel fuel in DPP.

In the first step, this integration project can be represented by mathematical modeling and subsequent analysis, as these mathematical models are flexible, and they can attach additional and independent sources of electricity.

In this thesis we analyze a stand-alone system of power supply of a radial type with a voltage of 0.4 kV in the Tokma village located in Irkutsk region.

Thus, the motivation of the study is to construct a mathematical model of a hybrid power supply system with distributed photovoltaic generation. The model should be capable of making the necessary calculations of the daily variation of electric power consumption and changing insolation. The calculation results will allow determining the optimal configuration of connection by RES into the transmission electricity network consistent with the power ratio between the SPP and DPP. The quality and value losses of electric power in the SAPS are also important indicators.

The power losses in the wire are the product of the square of the current (I) and the resistance (R) of the wire, described by the formula:

$$P_w = I^2 \cdot R \,. \tag{1}$$

This means that when transmitting fixed power on a given wire, if the current is halved (i.e. the voltage is doubled), the power loss will be four times less [9]. Therefore, higher voltage is associated with lower transmission losses. The mathematical model considered in this thesis allows to increase a voltage level by adding, for instance, PV system.

The novelty of this thesis is in the contents of the energy supply system, in the algorithm of its work, and in the economic evaluation taking into account the sensitivity analysis of the project. The research is based on data from the Tokma village located in Siberia, which has decentralized access to energy supply.

All research in the thesis is done by analyzing the technical and economic performance of power systems, statistical methods of information processing and the theory of mathematical modeling. Mathematical modeling is carried out in MatLab, Homer Energy and MS Excel.

1 DISTRIBUTED GENERATION OF ELECTRICITY BASED ON INTEGRATING DIESEL WITH RENEWABLE ENERGY SOURCES

In this chapter will provide a general description of meaning of distributed generation (DG), review of literature related to DG field, as well as an international experience on the examples of Germany, the USA, China, and the Czech Republic. In addition, it explains the state of DG in Russia.

1.1 Distributed generation

Traditionally, an established way of forming the structure of the fuel and energy complex in Russia for more than a century has shaped the national vision of distributed generation.

Distributed Generation System – facilities and equipment that make up a large number of energy production systems that are directly connected to the electrical network and work in parallel with the distribution system of energy [10]. Distributed generation can be considered by those objects that are near the final consumption, regardless of who owns them.

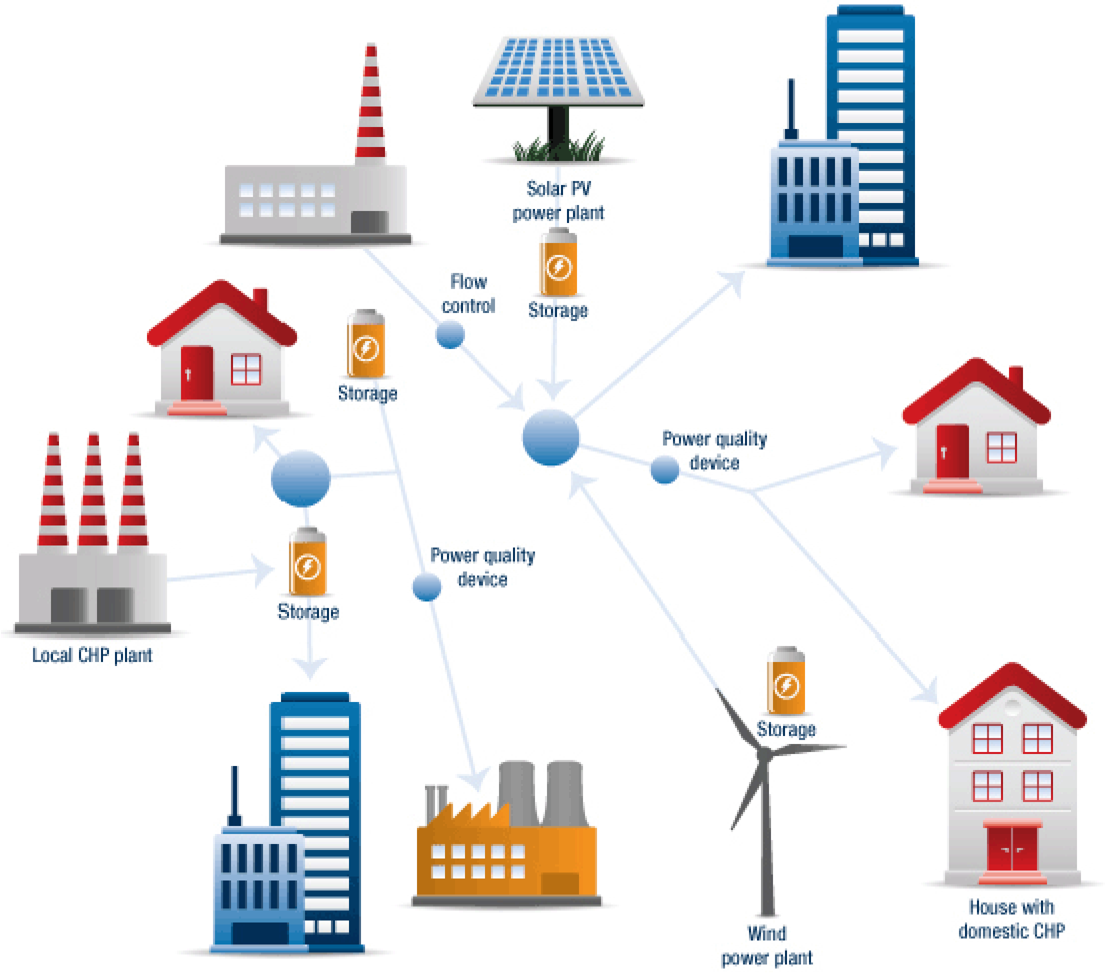
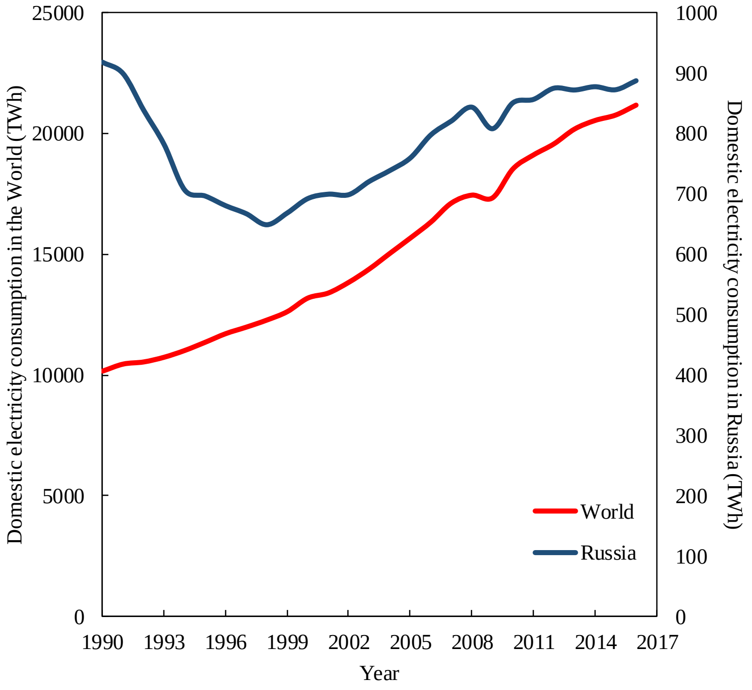


Figure 1 – Distributed generation scheme [11]

Energy consumption is growing all over the world, which is explained by the population growth, the ongoing process of industrialization, which causes an increase in the consumption of materials, an increase in energy consumption for transportation and extraction of natural resources and etc.

The DG has the ability to generate electricity from various sources from familiar sources to alternative energy sources. As a result, they have become an environmentally friendly alternative for electricity generation, and this trend is likely to continue over the next few years.



Source: Author’s calculations.

Figure 2 – Domestic electricity consumption in the World and Russia [12]

Globally, energy consumption was cut down by 1.5% during 2009, for the first time since World War II. Figure 2 clearly shows a drop in the level of electricity consumption. In 2008 there was a start of the financial and economic crisis began in the world, which appear in the form of a strong decline in the main economic indicators. The emergence of the crisis is associated with a number of factors: the general cyclical nature of economic development; overheating of the credit market and the resulting mortgage crisis; high prices for commodities (including oil); overheating of the stock market.

It is necessary to notice that the global electricity consumption is rising and consequently there is a demand to increase the power generation capacity. A significant percentage of the required capacity increase can be based on RES. Liberalization of the electric power industry has given a possibility of choice for consumers. Leaving the Unified Energy System of Russia (Edinaya Energeticheskaya Systema Rossii) to their own power supply can reduce their costs by 30–60% [44]. The need for a cleaner environment and the continuous increase in power demand makes renewable energy production, like solar and wind increasingly interesting approach for new solution.

Nowadays trends in the development of a distributed PV system show that countries, administrative and municipal governments are actively experimenting with policies aimed at encouraging a distributed PV system to compensate for a peak demand for electricity and stabilize the local network in terms of voltage levels. This paper gives a broad overview of the development of distributed PV energy not only in Russia, but also in other countries.

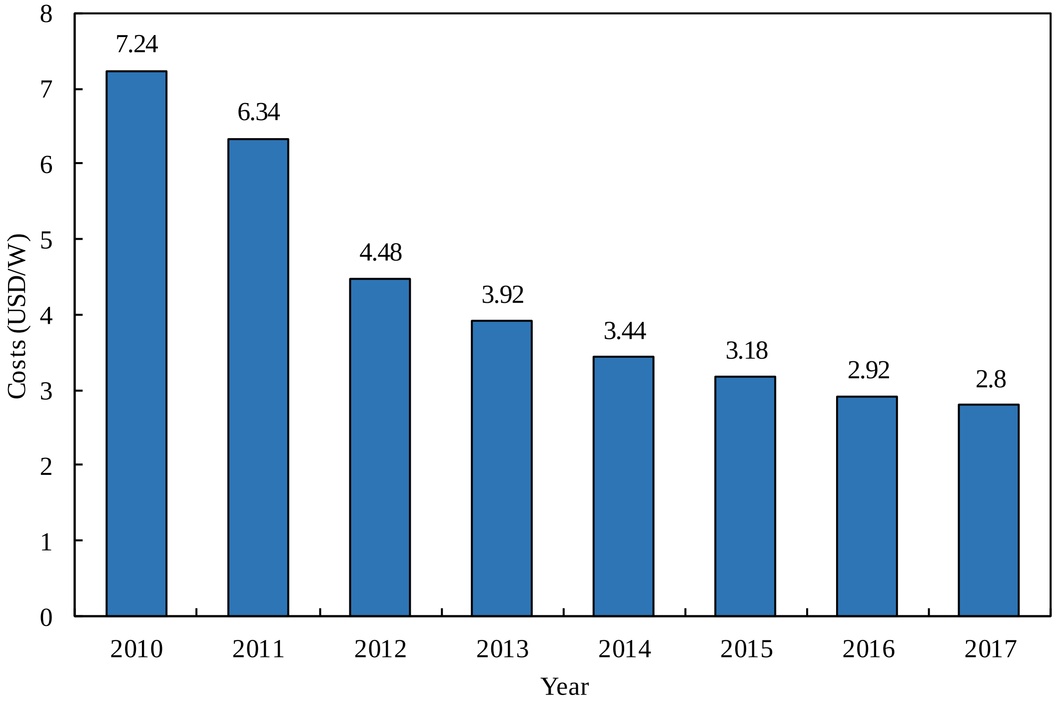


Figure 3 – World’s trend of the reduction in residential PV system cost between 2010 and 2017 [14]

As shown in Figure 3, from 2010 to 2017 there was a 61% reduction in the residential PV system cost. Approximately 61% of that reduction can be attributed to total hardware costs (module, inverter, and hardware of balance of system), as module prices dropped 86% over that time period. An additional 18% can be attributed to labor, which dropped 73% over that time period, with the final 21% attributable to other soft costs, including permitting, inspection, and interconnection, sales tax, overhead, and net profit. [14].

The active economic support provided by the leading countries such as United States of America, Germany and China in the field of the DG will stimulate the growth of electricity production from alternative sources such as solar energy, wind and geothermal energy. However, the high cost of DG installations will become a critical factor that adversely affects the growth. Therefore, this research should define DG’s economically efficient criteria for customer, suppliers and government.

1.2 Literature review

Over the past decade, the idea of integrating distributed PV generators into the existing SAPS became widespread. Distributed PV generators can provide many benefits, including the reduction of the cost of separating the power system, flexible operation and increased reliability.

According to the standards of European countries IEEE 1547 [13], distributed generators do not change the regulation of voltage or frequency. Moreover, they must operate at a fixed power factor or range between 0.95 a leading source of electrical energy and an auxiliary. The contribution to the active power, in general, is the only one condition for distributed generator plants. Many works qualitatively reflected the advantages of these requirements for distributed energy [15–18].

The problem of the connection rural areas to centralized system can be caused by technical barriers such as unsuitable geographical conditions or by economic barriers such as economically not-proved installation. In many cases the problems are the ones of funding, management and integration.

It is necessary to notice that Supervisory Control and Data Acquisition (SCADA) systems may not be available in decentralized areas with SAPS for remote control. The control of the generated power from the distributed resource must be carried out locally and automatically with the help of good power management, since it is impossible to set the equipment or to send a specialized engineer responsible for working with each generating unit [15].

There are several ways of decentralized energy supply. In many cases, diesel generators provide the necessary electricity in these areas and power individual facilities. Another possibility is to use renewables or joint hybrid energy system.

The main advantages of decentralized supply – reduced transmission and distribution costs, reduced fuel costs, reduced requirements for the capacity of central power stations to meet the peak load.

Table 1 – Share of population without access to electricity [19]

Regions	Population, M	Share lack of electricity, %
Asia	3.6	17.3
Africa	1.1	56.6
Middle East	0.215	7.9
Latin America	0.466	5

However, for the remote regions with difficult transportation conditions, which are not connected to the central power grid, the reliable operation of complex decentralized power facility is the only key to the energy security and safety. The load value in such areas is usually highly changeable, which calls for the simple, reliable, efficient generator. As the result of a high variety of installed capacity needed, natural and weather conditions and safety requirements, it is impossible to propose a universal solution, which will comprise technical and economic benefits.

Decentralized systems with DG have proven to be very cost-effective in many countries. Renewable and hybrid energy systems can replace or supplement existing traditional systems cost-effectively for areas not connected to the centralized electricity. The popularity of decentralized with DG projects has grown so much that it is now a niche-industry in itself – with customer systems being engineered for specific functions [20].

In addition, the optimal size and flexibility in the location of the SPP system have been high marked from a technical, economic and engineering perspective for both the consumer and the generation company [20].

1.3 International experience of using distributed generation

This part presents trends of using DG systems in Germany, the Czech Republic, the USA, Russia, and China. Here the focus is on particular programs and government supports in the field of RES. International experience could be a unique possibility for companies which specialize in DG systems for SAPS.

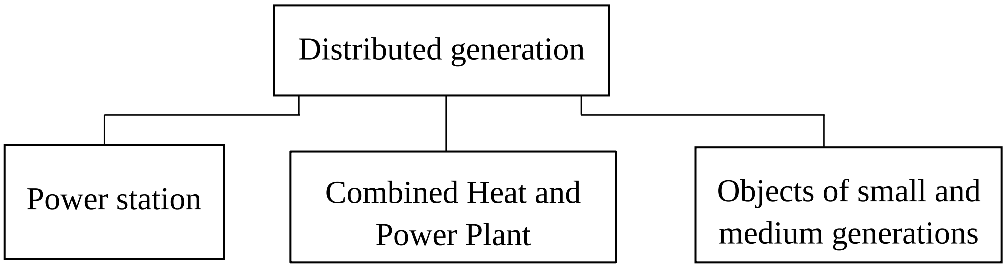
Table 2 – Grid facts and characteristics by countries [21–25]

Country	**Population, M**	**Length of power transmission lines, km**	**Area, km^2**
Russia	146.8	2 700 000	17 125 407
Czech Republic	10.5	210 000	78 866
USA	325	12 000 000	9 519 431
Germany	82.1	1 715 000	357 408
China	1380	10 500 000	9 598 962

There is no clear proportional relationship between length of power transmission lines and a count of population. It is necessary to notice that the USA and China are the leaders of the electricity production. Both of them produce 42.3% from the world electricity demand [25]. This high percent reflects dynamic economic growth and trend to improve manufacturing sector inside a country, which is supported by the development policy of the government.

Russia

Distributed generation can be considered as those objects that are near the final consumer, regardless of who owns them. As of today, in Russia it is possible to allocate three categories of generating capacities which fall under this definition [26]:



Source: Author’s illustration.

Figure 4 – Block diagram of the structure of the DG in Russia

Power stations, a source of electrical (sometimes thermal) energy located in the territory or near of an industrial enterprise and owned by the owners of this enterprise on the basis of ownership or another legal basis. Power stations, usually, are beneficial to their owners, since they can function at the expense of by-products of the main production (associated gas or blast furnace gas, etc.);

Cogeneration plants. Combined heat and power plant (CHPP) and centralized heating of settlements was the pride of Soviet Union energy sphere. Indeed, the combined production of electricity and heat increases the fuel utilization factor by an average of 30% [26]. According to the background of this effect, significant costs and inconveniences in the construction and exploitation of heating systems become acceptable nowadays. This is one of the reasons why cogeneration is widely promoted and encouraged now in the West;

Small and medium generation facilities, including gas turbine and gas piston stations, as well as small power plants based on RES which still not used widely.

In Russia, despite the growing temps of construction of DG facilities, the process of focusing government's forces does not find clear place in the long-term planning of the development of the system. There is still no understanding of the contribution that DG can make to improve development of the system and its modernization, and there is no developed state policy on this case. When developing such a policy, the most important part should be the requirement to analyze and, if necessary, revise the philosophy and technology of a long-term development planning of the system taking into account the spread of DG, the creation of micro networks and the integration of smart grid technologies [26].

Here are the main reasons of attractiveness by using DG:

1. The DG removes the requirements to build and reconstruct a new network infrastructure.
2. The availability of voltage sources in locations close to the load increases the reliability of power supply, helps necessary voltage levels in the network and reduces transmission losses.
3. Reduction of losses in transmission lines and flows of reactive power.
4. Financial risks associated for small and medium generation facilities are much lower than for facilities with a large installed capacity.
5. Predictability of energy costs.
6. Improving the reliability of power supply for the owner of its source of electricity, because most of interruptions in power supply are associated with accidental situations in the network economy.

DG is often a new equipment imported from abroad, with new dynamic characteristics and management capabilities. The influence of DG on the quality of electricity by voltage levels as well as on the generation of higher harmonics in the system is also unpredictable. Connection of sources of DG to the distribution network increases short-circuit currents, which may require replacement of switching devices, changes in protection settings, etc. The appearance of DG complicates operational dispatch control, as well as a relay protection and automation system, emergency control.

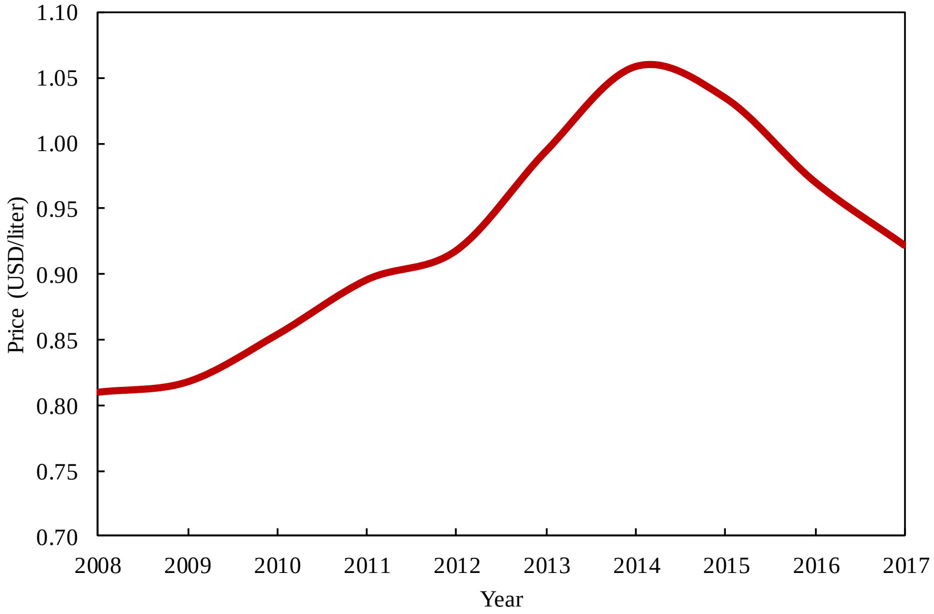
Russia is one of the countries in the world with the largest areas not covered with main grid power lines. The most common small-scale generation utilities in Russia are DPP. There are certain advantages of producing energy from diesel fuel, but the disadvantages are considerable, too: high consumption of fossil fuels in the production of one kWh of electricity, pollution.

According to Figures A1–A2, there is no doubt that the centralized electricity grid has correlation to areas of density of Russian population. South regions of Russia are more attractive for life and it has historical backgrounds: better possibilities for agriculture, proximity to other countries, better environmental conditions and etc.

It is clear that now in Russia there are specific areas – the Far East, the Arctic zone, the regions of the Far North, where distributed generation facilities have already been introduced, and they can be points of growth in the sphere of small energy.

The development of the Far East is one of the state's top priorities today. To solve this question, a federal target program for the development of the region has been set, and the Ministry for the Development of the Far East has been established.

In the northern part of the Far Eastern Federal District and the coastal areas of the Northern Sea Route, a large number of small DPP operate in the SAPS. As a consequence, the cost of electricity is extremely high, due to the large distance of these areas from the suppliers of diesel fuel [20]. In order to reduce the fuel dependence for local energy companies, alternative energy projects are being developed in the region, including distributed PV and wind generation.



Source: Author’s calculations.

Figure 5 – Dynamic of monthly prices of diesel fuel in Russia [27, 28]

The growth from October 2010 to November 2014 described in Figure 5 is explained by monopolistically high prices of diesel fuel. The leaders in the field of oil industry such as Rosneft, LUKOIL, GAZPROM Neft withdrew diesel fuel from the market, causing an artificial deficit, established and maintained higher prices, and created discriminatory conditions for deliveries of goods to the market [27, 28].

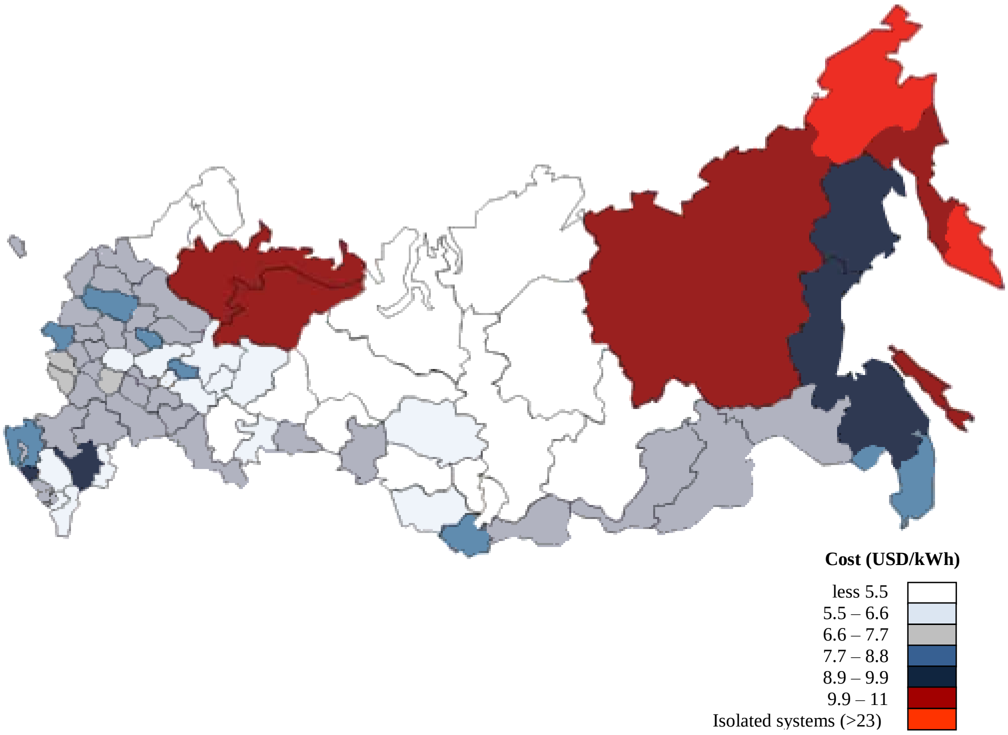


Figure 6 – Price of electricity production in diesel generation in stand-alone areas during 2011 [29]

The Northern Sea Route is the shortest sea route between the European part of Russia and the Far East, the historically established national unified transport communications of the Russian Federation in the Arctic. It passes through the seas of the Arctic Ocean (Barents, Kara, Laptev, East Siberian, Chukchi) and partly the Pacific (Beringovo). The distance from St. Petersburg to Vladivostok along the Northern Sea Route is over 14 thousand km (in contrast to 23 thousand km through the Suez Canal). The Northern Sea Route serves the ports of the Arctic and large rivers of Siberia (import of fuel, equipment, food, removal of timber, minerals). The overall route on Russia's side of the Arctic between North Cape and the Bering Strait has been called the Northeast Passage, analogous to the Northwest Passage on the Canada side.

Arctic attracts many countries with rich gas and oil reserves. Melting of ice and general warming could make the Arctic Ocean a busy transport route between Europe, Asia and America [30]. Also, the possibilities of pirate attacks on ships following the southern routes, increase the interest of ship-owners to the Arctic routes. However, the North Sea Route will be able to compete with the southern routes only if it is economically advantageous and its infrastructure will ensure the maximum reduction of additional costs when navigating in Arctic ice.

There are several main problems related to the energy infrastructure of the Northern Sea Route and the Far East, among which are the following:

1. Adaptation of the work of wind and PV plants in the Arctic climate.

The main obstacle of development, of wind energy, is the difficulty of working in the Arctic climate [31]. As a consequence, there is damage to the generating equipment.

2. Formation of infrastructure for the operation of hybrid complexes of three types of substitution [31].

For each category of hybrid power plant substitution schemes, there are a number of problems associated with the organization of automated complexes and control systems with the growth of installed capacity of installations.

3. Formation of own production of generators for wind turbines and PV in the territory of the Russian Federation.

Prospective is the large-scale use of RES power stations for electricity supply, oil and gas complex, railway and motor transport, and agriculture [32]. The need for the development of production and service infrastructure for wind energy and PV systems is one of the important vector. Currently, the enterprises of local production of energy based on RES are not enough in Russia.

4. The problem of using oil and gas production equipment on the basis of traditional technologies along the Northern Sea Route area.

Due to the fact that the Arctic Ocean is a specially protected object, the use of components containing radioactive elements is prohibited. It is about equipping virtually all oil producing wells with multi-phase VX-based flowmeters technology (radioactive measurement) [33].

The characteristic features of using RES in the northern and remote areas for wind power and PV power are the following [31]:

1. Reliable operation in extremely low temperatures (-40/-50°C).
2. Installation without construction machinery.
3. Simple and reliable design.
4. Availability of independent examination of the test results.

Distributed PV generation can provide support to the system in emergency situations and there prevent their occurrence or reduce the amount of damage. As a result, the tariff load on consumers served by the energy system is reduced because portion substitution of diesel fuel by solar energy. In addition, thanks to diversification into DPP and PV system, the financial risks associated with the objects of small and medium generation are much lower.

Irkutsk region is a federal subject of Russia. It lies in the south-eastern part of the Siberian Federal District. Its administrative center is the city of Irkutsk. As of 2017, population of Irkutsk region 2 408 901 (1.64% of the population of Russia) [34]. The Irkutsk region is a large subject of the Russian Federation, occupying an area of 774 846 km^2 (4.52% of the territory of Russia). Irkutsk region has some wide-spread sorts of resources such as hydropower, oil, gas, and coal. Hydro and coal are the most widely used in producing electrical and thermal energy for the central and south parts of the Irkutsk region. Usually in the remote north and isolated areas using expensive oil products is a simple way of getting electricity. For instance, reliable and high-cost power supply in isolated settlements is provided by small boiler-houses and DPP, which are relatively too old. These old technologies are very costly in terms of fuel supply and current operation of these energy sources. The necessary support is usually provided by regional budget [36].

Figure 7 – Irkutsk region (red) and the Tokma village (dark circle) in Russia [34]

The Tokma village with about 75 inhabitants is the one of the 361 settlements of Irkutsk region. There are some obstacles in electricity supply and daily life fields in this village. In the summer time, every two weeks, a helicopter flies and delivers units of needed goods, in winter – the transport goes by the winter road. Local residents are Russians and Evenks. The second one is a unique ethic group of the indigenous people of this area. They have original habitat, traditional crafts and customs, and the uniqueness of national character traits – it is important to save and support this group [35]. The main occupation of local residents is hunting and fishing.

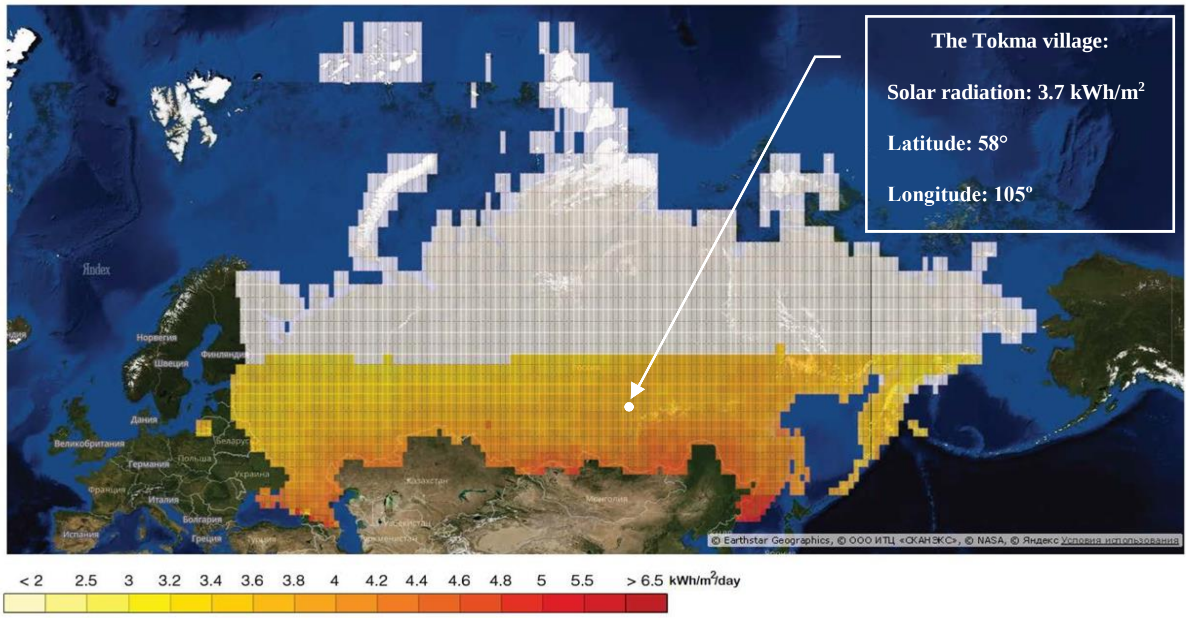
According to the program for the full development of the communal infrastructure systems of the Nepa Municipality for 2012–2015, the Tokma village has:

Table 3 – Description of the electricity system conditions in the Tokma village [38]

Diesel power plant, kW		**Length of transmissions lines, m**	
Unsatisfied condition	Satisfied condition	Unsatisfied condition	Satisfied condition
DPP – 1 (30)	DPP – 2 (60)	3000	1000

In 2010 there was a flooding which destroyed a one DPP, a village school, and a few houses [35]. Also, in the same year, the Irkutsk Oil Company (Irkutskaya Neftenaya Kompaniya) decided to create a new well near at the Tokma village [37]. Climatic difficulties, unsatisfied conditions of generated equipment, non-transport conditions, support of small-ethic group of residents, a development plan of region and etc. – all these obstacles forces to find a solution in reliable and economic efficient form of electricity supply system. For these isolated areas there are two ways of solution: centralized energy supply system or creation of distributed system based on local resources.

Despite the fact that the construction of power lines would be ensure high reliability, in the majority of these cases it is economically unprofitable. The reason is high construction cost. For some villages with a population of 100–300 inhabitants, a 110-kV transmission line is required [36]. Construction of power lines with voltage up to 35 kV may be expected. For this case must be exist a reasonable distance from them to transmission lines 110–500 kV. From the nearest city Ust'-Ilimsk with centralized energy supply there is 270 kilometers of distance. According to the fact of transmissions losses, this distance does not have any chance to be realize in this case. When transmitting electricity through high-voltage networks, about 9% of the transmitted energy is lost. In the distribution networks of consumers, another 3–4% is lost, that is, the total energy losses amount to 12–13% [39]. In this situation, there is a second option: a creation and development of local modern and highly efficient energy sources in remote areas of the Irkutsk region, using local energy sources.



The Tokma village:

Solar radiation: 3.7 kWh/m^2

Latitude: 58°

Longitude: 105°

Figure 8 – The average for the year the daily amount of solar radiation arriving at the optimally oriented surface [41]

It is necessary to say that in the conditions of the north and remote areas using of micro-hydropower plants is complicated by climatic difficulties. Micro hydro power plant (HPP) do not require significant costs, but seasonal fluctuations of river flow, up to complete freezing in the winter period, when the maximum electric loads, can be considered in exceptional cases for the central and southern areas of the Irkutsk region. The use of geothermal thermal power plants is not feasible in Irkutsk region due to the absence of hot springs. The potential for using wood biomass in the Irkutsk region to replace oil products in the local heat supply system is more than sufficient. However, it is possible in areas with a high level of consumption of oil products in the heat power industry (the city of Irkutsk and Angarsk municipal districts).

Their substitutional requires the use of forest resources from near, transportable areas from the economic point of view [40]. Technical potential of the solar and wind resources of the Far East is quite high [36].

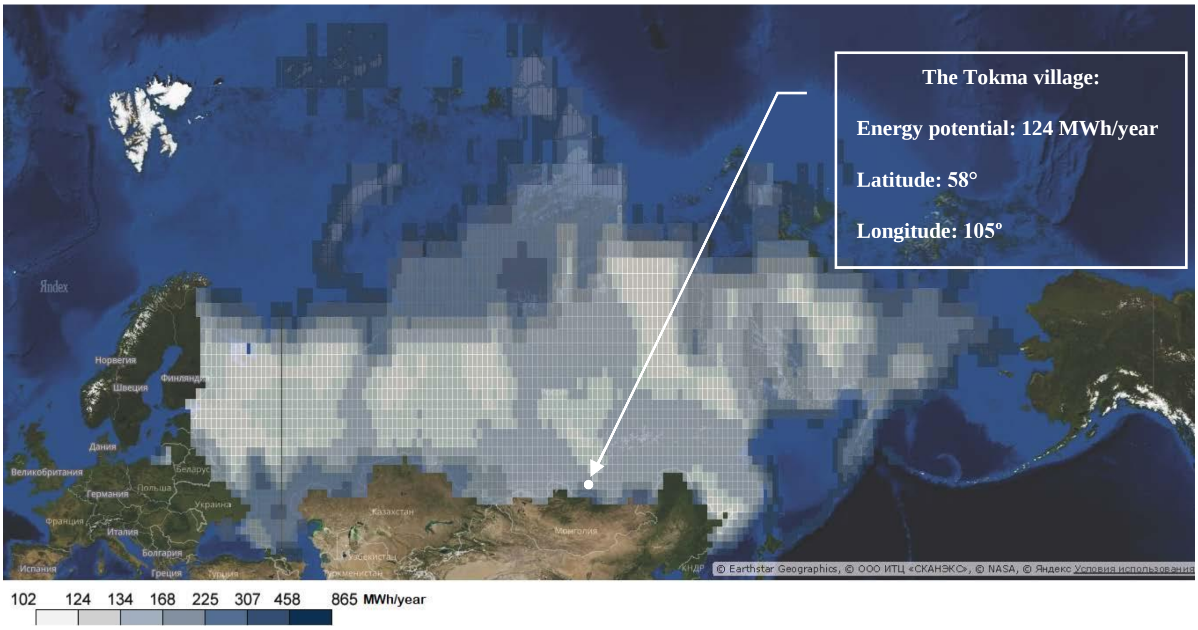


Figure 9 – The annual potential of wind energy at a height of 30 meters [41]

As shown in Figures 8 and 9, the Tokma village is located in the region with the least wind potential compared to the level of insolation. Analysis of long-term meteorological observations showed that the use of wind energy is acceptable for settlements only on the coast of the Baikal Lake. Last but not least, considerable uneven wind speeds and noise from wind generations in this environmental protected area imposes significant problems. From the beneficial and technical points of view, the idea of integration of the distributed PV system to DPP could be better for electricity supply system and consumer.

In addition to information above, in south part of the Irkutsk region there is already operating another hybrid power station (HPS). This power plant is located in the village of Nerha Tofalaria in the Nizhneudinsky district and consists of diesel-solar power station. The main factor in choosing a place for its location was that the Nerha Tofalaria village is the most difficult of approach in the Irkutsk region. Now the electricity supply of the inhabitants is provided for several hours per day – in the morning and in the evening. Electricity is supplied from a DPP [42]. The estimated cost of the project is 77.6 million rubles, of which 70 million rubles are allocated from the regional budget, 7.6 million rubles from the own funds. The expected volume of fuel economy is 51.6 tons per year [43]. According to the calculations of the project organization's employees, such a PV station will compensate 50% of the cost of providing electricity for all settlements in this district. At the same time, electricity supply will be provided all day without interruptions. The constructors convinced that they will be able to provide high-quality electricity supply by increasing the voltage. Also, the new station will have the opportunity to increase capacity. Furthermore, the station already has a five-percent reserve in case of increasing number of consumers.

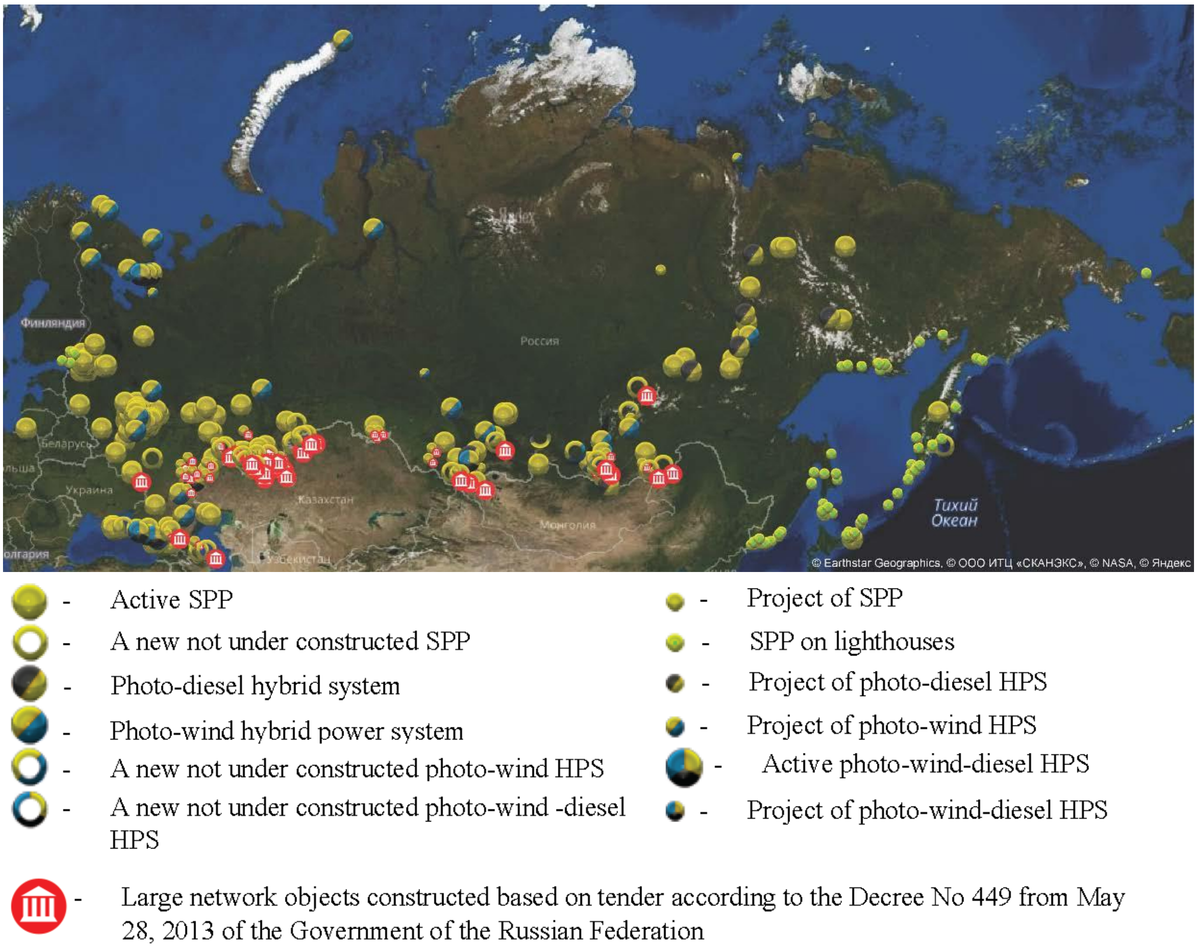


Figure 10 – Map of installed capacity of PV installations in Russia [41]

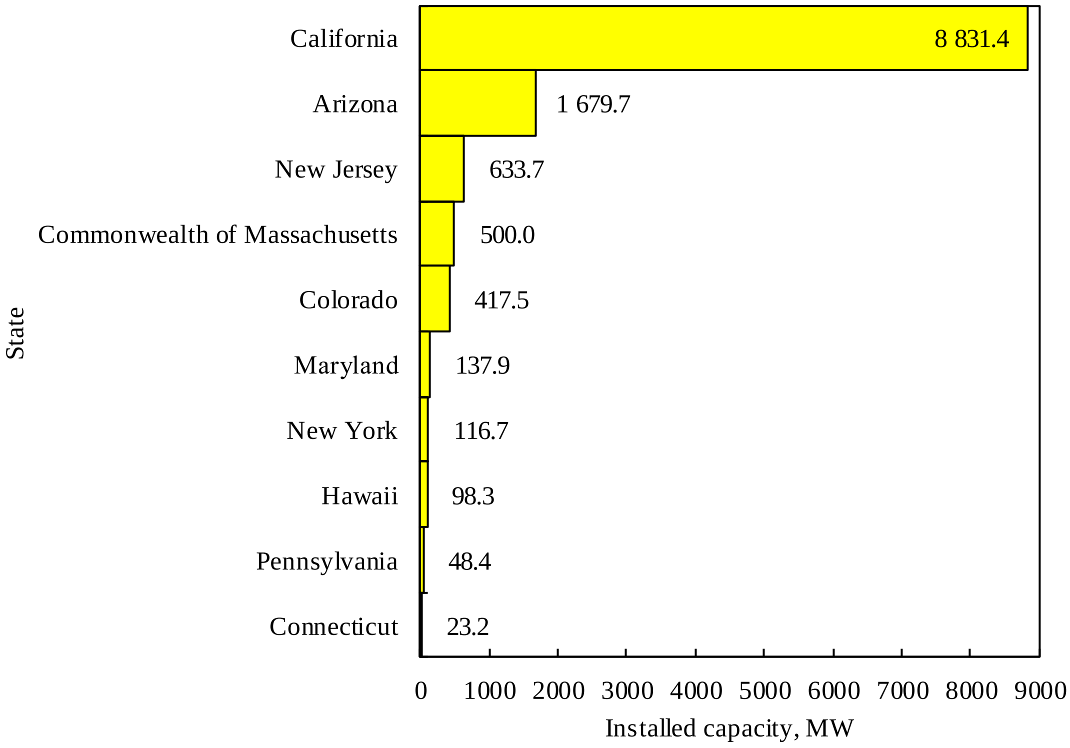
Therefore, one of the possible areas for improving efficient use and reducing energy consumption from a DPP from decentralized settlements is distributed PV system. For the first step of integration distributed PV generation into electricity supply system, this implementation can be carried out by mathematical modeling and subsequent analysis. The developing systems being developed are technically flexible, capable of connecting additional and independent sources of electric power.

United States of America

The programs of reliable incentives, state support combined with relatively high retail trade trends, progressive and adaptable technology to produce renewable energy sources, led the United States to the leading positions in terms of the installed capacity of distributed PV generation. This growth, as well as the development of storage accumulators, the rise of the electric vehicle market and other technologies of distributed energy, led to several successful government’s acts that provoked a numerous of proposals and implementations of RES projects.

In particular, the collaborations of state and municipal incentive programs and the ongoing discussion about the value and future role of distributed energy in the USA are all taking into account in the recent update of the state standard for the development of the State of California, where the main objectives are [45]:

1. Development and use of RES up to 50% by 2030.
2. Reduction of greenhouse gas emissions by 40%, which will be below the 1990 level by 2030.
3. The use of distributed energy should help to reduce the load of infrastructural sector.
4. Solving the problem with the reliability of the electricity network of large state enterprises.
5. Strengthening of market positions that direct the household sector towards receiving additional energy resources from renewable sources. This increases energy efficiency and the demand for distributed energy.

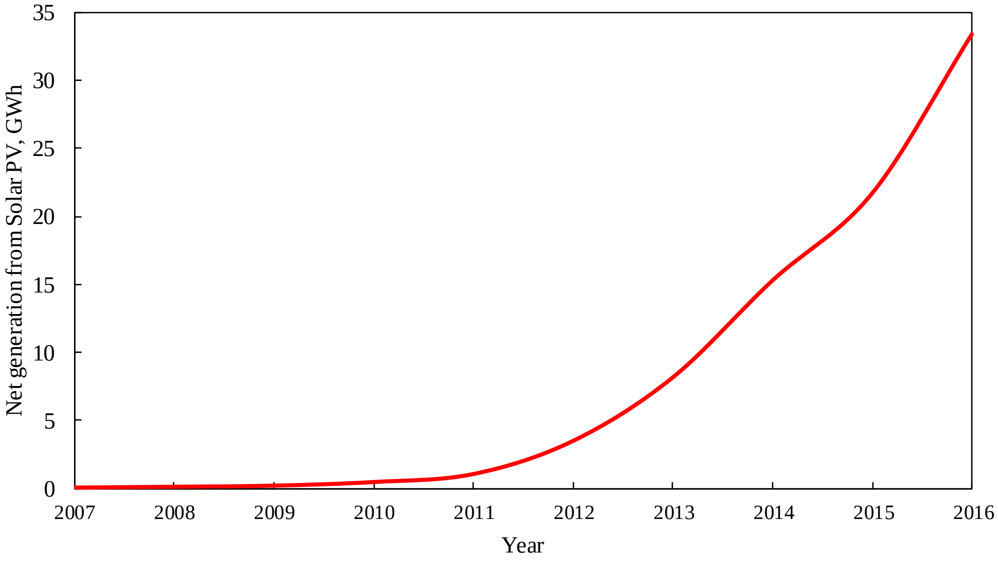


Source: Author’s calculations.

Figure 11 – Generated power from installed capacity of photovoltaic resources for June 2017 [46]

In California solar panels dominate on the roofs of communal sectors, about 40% of the installed capacity of the country, which is largely due to traditional state incentive programs. California Solar Initiative is one of them, as well as retail electricity prices in California, which are among the most high in the country. Arizona, New Jersey, and Massachusetts follow the California, respectively about 10%, 8% and 7% of the total installed capacity of the country.

The growth of distributed PV cells was caused by a sharp drop in the total cost of solar panels. Also further stimulated by a decline in consumer spending due to greater accessibility and adoption of property rights for third parties on the market. Despite the rapid growth of distributed PV and wind generation, these resources contribute very little to the overall electricity supply in the USA [47].



Source: Author's calculations.

Figure 12 – Growth of net generation from Solar PV in the USA [48]

In Figure 12 showed the recent trends in decision-making for distributed PV energy, highlighting the acceleration around the beginning of the century. There are 1721 PV electric plants in the United States. They are generating 1% of the nation's electricity.

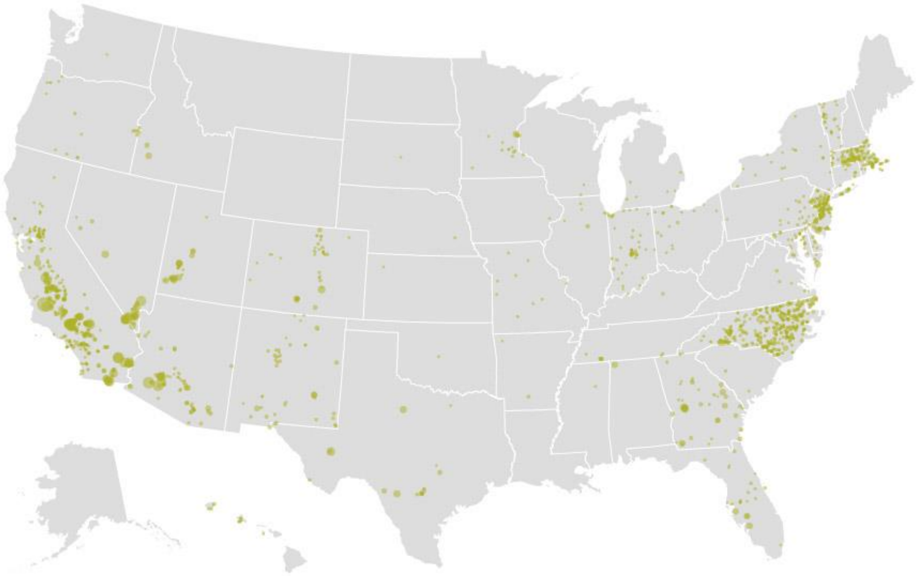


Figure 13 – Map of installed capacity of PV installations in the USA [49]

Figure 13 shows that solar insolation is dominantly used in the Southwest, where the sun shines the most. Only eight states have not PV installations.

Germany

In 2016, Germany had 1.2 GW of new PV capacity installed, which corresponds to approximately 2% of the total capacity of solar power generation around the World. In the German legislation on renewable energy sources EEG (Erneuerbare Energien Gesetz) 2014 and 2017, the federal government set an annual target of 2.5 GW of PV generation.

Nowadays, Germany’s installed PV capacity topped 40 GW, 98% of which could be considered as distributed and 50% of which is under ownership of private sector. PV comprises nearly a quarter of the installed generation capacity in Germany, and, on days of high production, PV can achieve over a third of Germany’s peak demand [45].

To satisfy most of or all of Germany’s energy demand with renewables by 2050, 150-200 GW PV installed capacity is required. This means that an average of 4–5 GW PV must be installed annually up to 2050. The older PV systems must be replaced. As of now, replacing installations have not played a large role yet. Once the targeted capacity of 200 GW PV has been reached and assuming an operating life of 30 years, estimates show that 6–7 GW PV must be replaced each year [50]. The transformation of the entire power sector to renewables is not an aim of the present German federal government. It is assumed a minimum share of 80 % renewables by 2050 is assumed.

Based on the data of the Fraunhofer Institute of Solar Energy Systems (Fraunhofer-Institut für Solare Energiesysteme ISE), trends in the development of energy in Germany are the following:

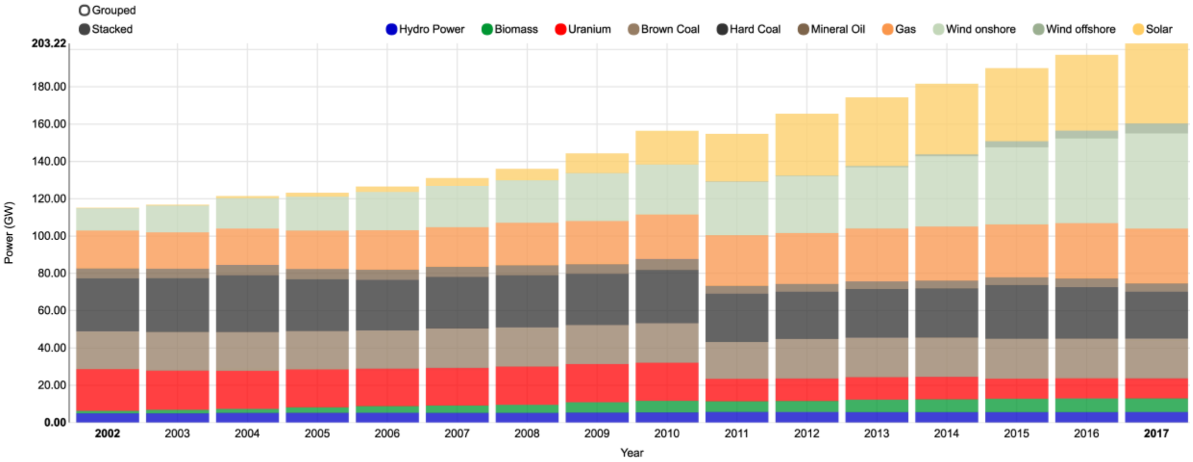


Figure 14 – Net installed electricity generation capacity in Germany [51]

More than 98% (more than one million) PV power plants in Germany are connected to a decentralized low-voltage grid and generate solar electricity near to consumers. Installations PV capacity more than 1 MW is only 15% of the total PV power in Germany. This means that the transmission of solar electricity occurs predominantly in a decentralized manner, thus eliminating any requirement for the expansion of the German national transmission network.

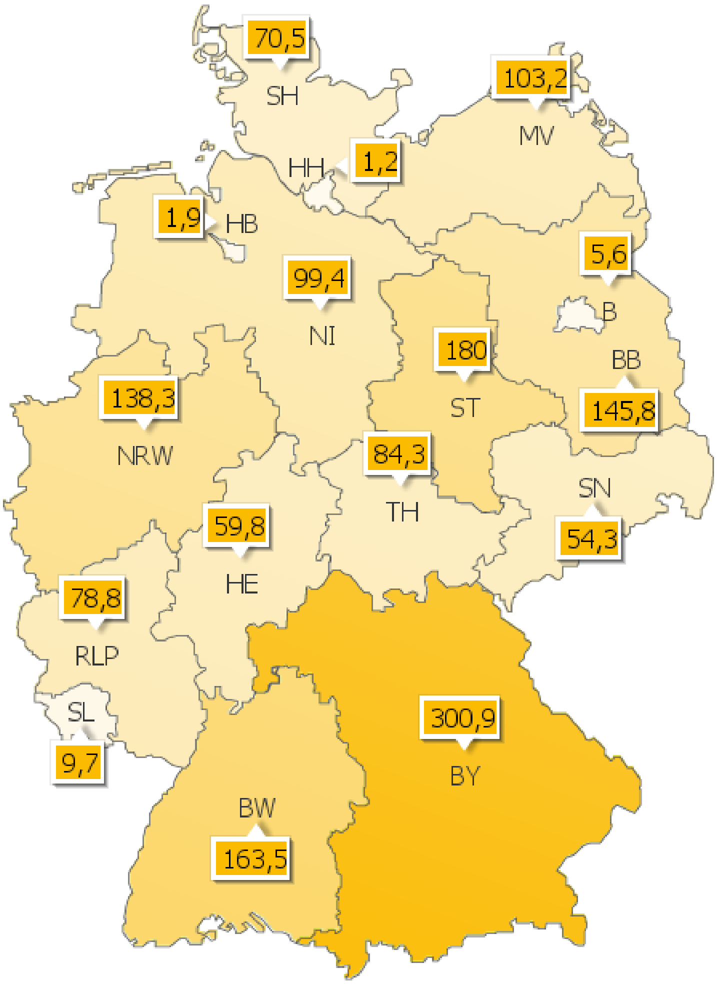


Figure 15 – Installed PV capacity (MWp) in Germany in 2015 [50]

As shown in Figure 15, PV installations are widespread throughout the sixteen states and are not limited to the southern region of the country.

The high density of power plants in the low-voltage section of the power grid can lead to the fact that the generation of electricity will exceed the consumption in this section of the network on days of maximum insolation. In this case, the transformers supply power to the middle-voltage network again. In sections with a high generation density, this can push the transformer stations to their limit values. Equal distribution of PV installations across all sections of the network reduces the need to increase the power supply system [53].

According to Figure 16, decentralized PV power plants in Germany are well localized, thus providing the supply and distribution of the existing electricity to the grid. Large PV installations of small factories in sparsely populated areas require the distribution network and transformer stations be strengthened. Further expansion of the PV systems should be carried out the great attention to the supply of energy efficiency to simplify the distribution of solar electricity. The lands of Bavaria and Brandenburg have three to four times the installed capacity per inhabitant compared to the lands of Saarland, North Rhine-Westphalia, Saxony or Hesse.

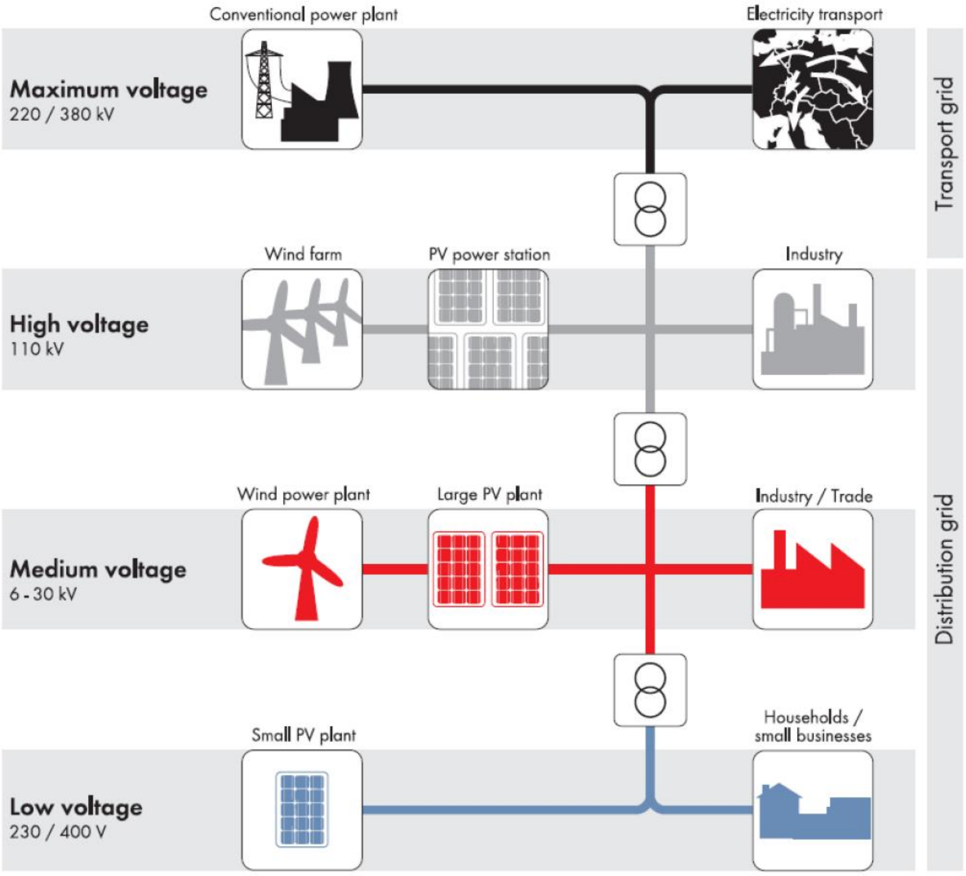


Figure 16 – The structure of the German electric grid system [52]

It is important to notice that during the first three quarters of 2017, 37.5% of Germany's energy was produced based on RES. At the end of 2016, the share of RES was 34%. The amount of renewable energy generation during the period reached 151.6 terawatt-hours.

1. Wind energy produced 16.4% of German electricity (66.6 TWh). Still wind is the largest source of energy in the country after brown coal.

2. Solar energy generated 8.7% – more than gas generation (8.4%). The development of SPP in the first three quarters practically reached the level of the whole of last year.

Coal still dominates in the energy sector of Germany, which negatively affects the ability of the country to fulfill its climate obligations. 25% of electricity was produced based on brown coal, and 15.9% on black coal. In sum, this is slightly less than the share of coal in 2016. In accordance with the German legislation on RES in 2020, RES must produce 40-45% of electricity in the country. According to [54], this goal is likely to be achieved even earlier.

Czech Republic

The power sector of the Czech Republic covers both the production and distribution of all types of energy. These types of energy include the extraction of certain minerals and the use of energy sources such as coal, natural gas, uranium, etc. Discussion among politicians, businessmen and other decision-makers, related to the energy sector, covers topics of sustainability, energy balance, autonomy, regulation, efficiency and the use of RES. The Czech Republic is one of the largest exporters of electricity in the European Union, therefore, the energy sector, especially the electricity market, plays an important role in the Czech economy, as well as in the energy security of Central Europe [55].

In the Czech Republic, generation of electricity is provided by several sources [55]:

1. Thermal power plants (TPP): TPP are the largest energy producers in the Czech Republic. They are situated in regions with large deposits of coal (especially brown coal) and close to rivers. The largest of them are located near the cities of Sokolov, Most, Ostrava, Melnik, and Hvaletice.

2. Nuclear power plants (NPP): NPP are the second largest electricity producer. Two power plants of Dukovany and Temelin are the subject of heated discussions about the completion or extension of their service life. At the moment, the issue of increasing the installed capacity in the Czech Republic is relevant.

3. HPP (including pumping hydro power stations): traditionally, hydro power stations are a stable part of the Czech energy sector, because the Czech countryside is very rich of water sources. The largest hydro power plants are located on a cascade of dams on the Vltava River: Lipno, Kamyk, Slapy, Orlik, and Vranje.

4. Combined and gas power plants (CHP): over the past decade, this source of electricity production has doubled its share in the Czech energy sector. Combined cycle in the production process increases the efficiency of processing energy sources. Therefore, several large-scale projects of such power plants are already actively exploited: Pocherady and Mokhov.

5. PV plants: the growth of photovoltaic power plants is associated with government intervention in energy production (subsidized prices), i.e., in order to diversify energy production towards RES. Among the nearly 30 000 power stations, the largest are located in Northern Bohemia, Central Bohemia, and South Bohemia.

6. Wind power plants: energy produced by wind farms covers an insignificant share of energy consumption in the Czech Republic. Most wind power plants are located in the mountain ranges in the northern part of the state, such as the Jeseníky Mountains, the Orlické Mountains.

Taking into account the share of the energy production, CHP and NPP are significantly dominant. In 2014 the growth of electricity production has reached a total of 87 065 GWh, where 51.4% was covered by TPP and 35.3% by NPP. The remaining sources covered about 13% of the energy production.

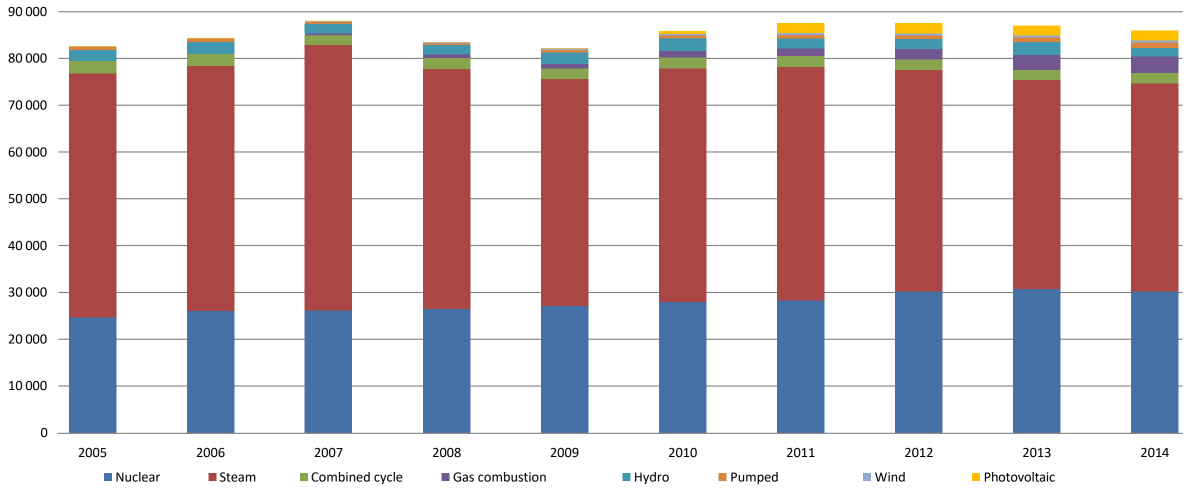


Figure 17 – Electricity production in the Czech Republic (GWh) [57]

The Renewable Energy Support Program was originally based on legislation proposed in 2003. State support for electricity production from RES in the Czech Republic was provided by a special Law No. 180/2005. This law guaranteed financial support for all RES such as: wind energy, solar energy, geothermal energy, water energy, biomass, and biogas. As shown in Figure 17, significant subsidies, based on this law, were provided for all RES constructors. These subsidies have provoked the construction of thousands of power plants, especially in 2009 and 2010. Moreover, this caused a threat to higher prices for electricity consumers in the region by tens of percent.

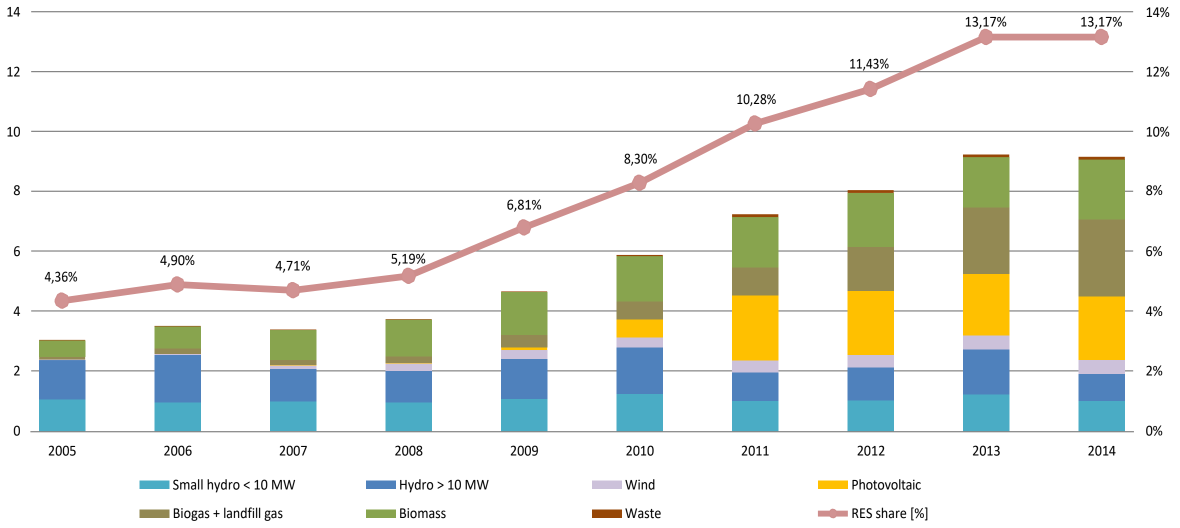


Figure 18 – RES electricity production in the Czech Republic [55]

Between 2008 and 2010, a sharp decline in prices of PV panels (return on investment with subsidies has decreased from the 15 years up to 6–7 years, respectively) caused a sharp increase construction of SPP [57].

Based on the data of the Brno University of Technology Faculty of Mechanical Engineering of Energy Institute (Vysoké učení technické v Brně, Fakulta strojní Energetického ústavu), the share of renewable energy sources in total at the end of 2014 increased to 13.17%. As the main factors were the growth of PV and biogas sources as well.

Production of renewable electricity in 2014 has reached more than 9.24 TWh per year. The most important part of this indicator is covered by hydropower (almost 30% of renewable energy), biogas and landfill gas (more than 24%), PV (more than 22%), and biomass (about 18%) [58].

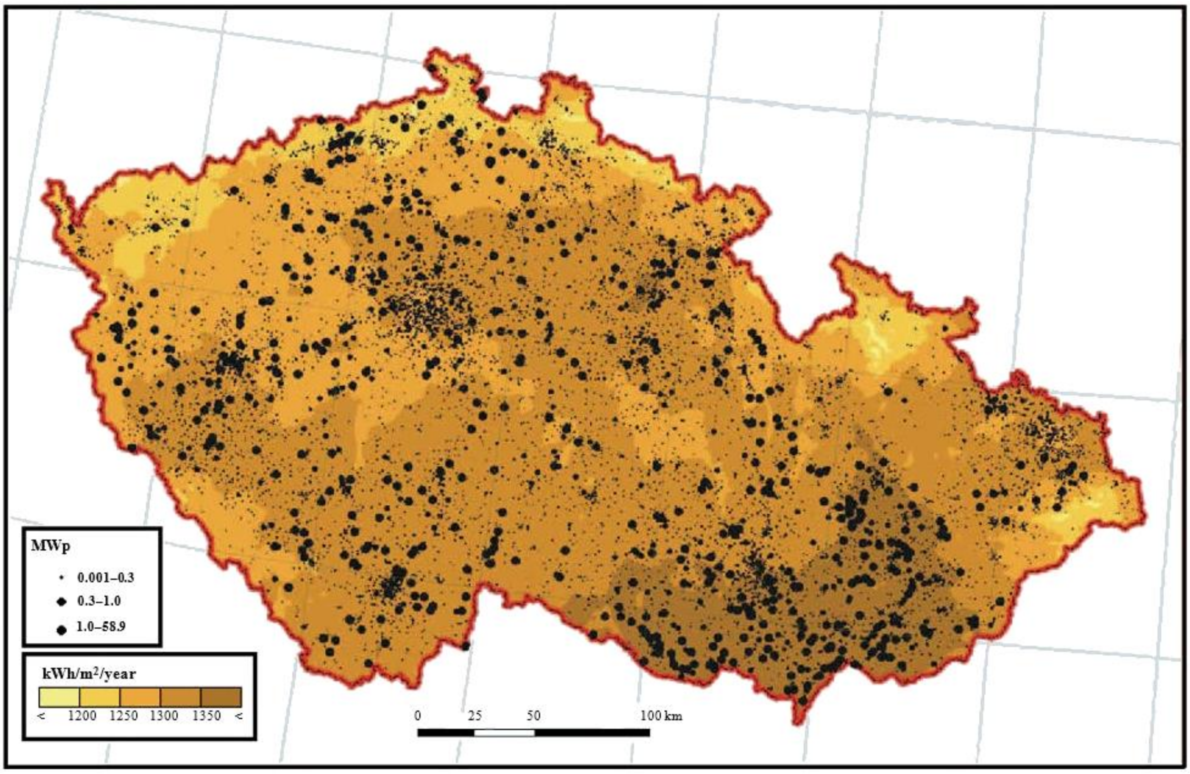


Figure 19 – Spatial distribution of PV power plants in the Czech Republic in 2013 [58]

According to Figure 19, PV installations are widely distributed throughout all territory of the Czech Republic. South Bohemia is the most common area of exploiting PV plants, where we can observe high sensitive of insolation at a level 1300–1350 kWh/m^2 per year.

China

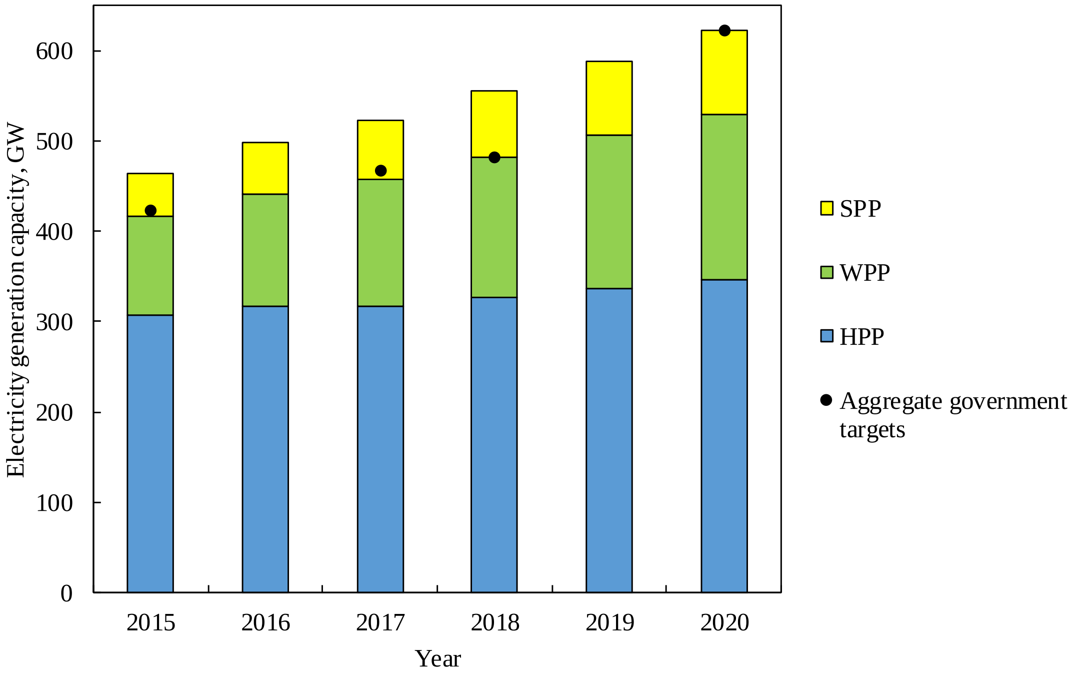
Currently, in China energy policy promotes the use of RES and energy efficiency. It provides a decreasing effect on the environment, increasing the security of energy supply, and ensuring economic competitiveness among other countries. As a result of this development, the levels of integration of DG in electricity networks of China are growing rapidly. The expected growth will play an important role in the China’s energy sector [56].

In spite of the fact that there is some moderation in the predicted economic growth, China remains one of the fastest growing economies in the World. As a result, its total electricity production almost doubles from 4.8 trillion. kWh in 2012 to 9.4 trillion. kWh in 2040 at an average annual growth rate of 2.5%. The impact of China's continued rapid economic development on the environment has become a major problem among environmental policy-makers in China, as well as for the public. In particular, China has introduced a number of proposals aimed at solving the problems related to air quality. In a joint agreement in 2014, both China and the United States committed themselves to take action to ensure long-term emission reductions. China has aimed to reduce CO_2 emissions by 2030. China is targeting to produce more electricity from NPP, RES, and natural gas to solve environmental problems. This diversification policy will change its traditional fuel production to electricity generation towards sources with lower or close to zero greenhouse gas emissions [56].

In 2015, China outlined the important steps required to reduce CO_2 emissions up to 2030. The policy of the INDC (Intended Nationally Determined Contributions) government of China includes the following energy targets:

1. Lower carbon intensity (CO_2 per unit of GDP) by 60–65% compared to 2005 levels.
2. It is necessary to increase the share of non-military fuel in the primary energy mix to about 20%.

To achieve this government targets, it will be necessary to build 800–1000 GW of generating capacity from RES by 2030, which will provide a comparative benchmark for further predictions.



Note: There is no data about the government targets per 2016 and 2019 in [59].
Source: Author's calculations.

Figure 20 – China renewable electricity generation capacity [59]

Nowadays, the cost of renewable technologies continues to decline, with the largest cost reduction observed for solar technology. However, the targets of clean energy policies also play an important role in the adoption of RES in China. The objectives of renewable energy policies include specific national targets formulated in the various five-year plans: the 12th five-year plan (2011-2015) includes the goal of increasing the scarce energy sources (including hydropower, nuclear and renewable energy) to 11.4% of the total energy consumption (compared to 8.3% in 2010). In addition, the plan provides for a 15% overall goal for the share of renewable energy from total electricity production in 2020 [60].

As shown in Figure 20, the gradual growth of both installed wind and solar generating capacity via supporting the forecasted trend by China's government is reflected. The installed solar capacity will increase from 3 GW in 2012 to 184 GW in 2040, and the power of wind energy will increase from 61 GW in 2012 up to 350 GW in 2040.

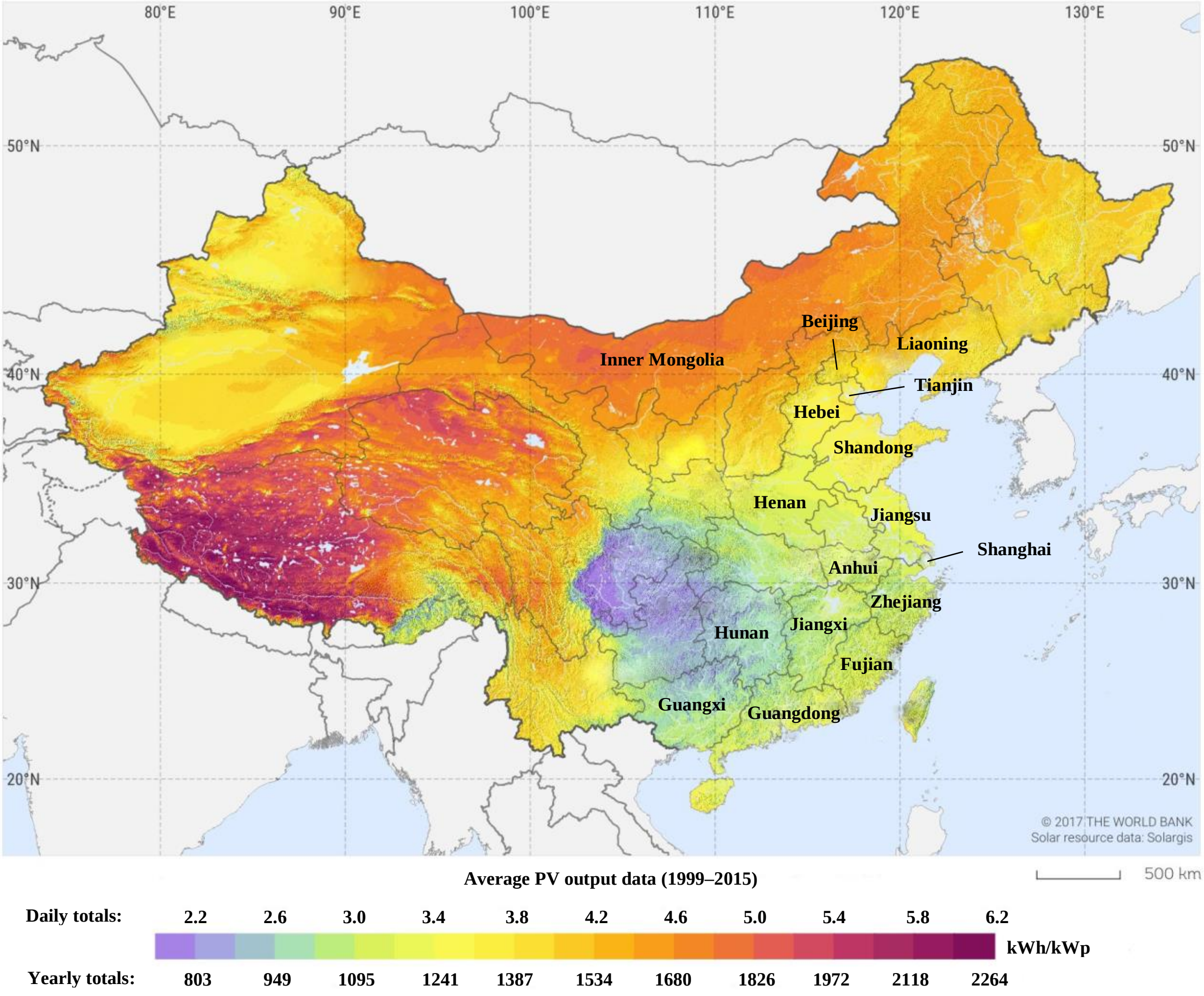


Figure 21 – Photovoltaic power potential in China [61, 62]

Therefore, the development of DG in China can effectively slow down the current problems of energy supply and the impact on the environment. China has a potentially broad market of RES. There are many advantages if China will develop a DG. For instance, that will help to develop appropriate policies to encourage and promote the use of distributed energy technology: distributed wind power, distributed PV, small hydropower, biomass energy generation, small gas stations, etc. [60]. As we can see, based on the experience from the Czech Republic, the United States, and Germany, the positive effect will not be negligible. The electric network of the distributed PV system in China is at the initial stage of development. The standards of distributed energy are not so much, but there are several documents that open access to power from PV, they are the following [64]:

1. GB/T 19939–2005 – System technology requirements of PV on-grid.
2. GB/T 200462006 – PV system grid interface characteristics.
3. SJ/T 11127–1997 – Voltage protection guide for PV power system.
4. National grid technology of PV power station and grid access.

5. Q/GDW 617–2011 – PV power plants connected to the grid. Technology requirements.
6. Technology codes for the remote monitoring of distributed PV.

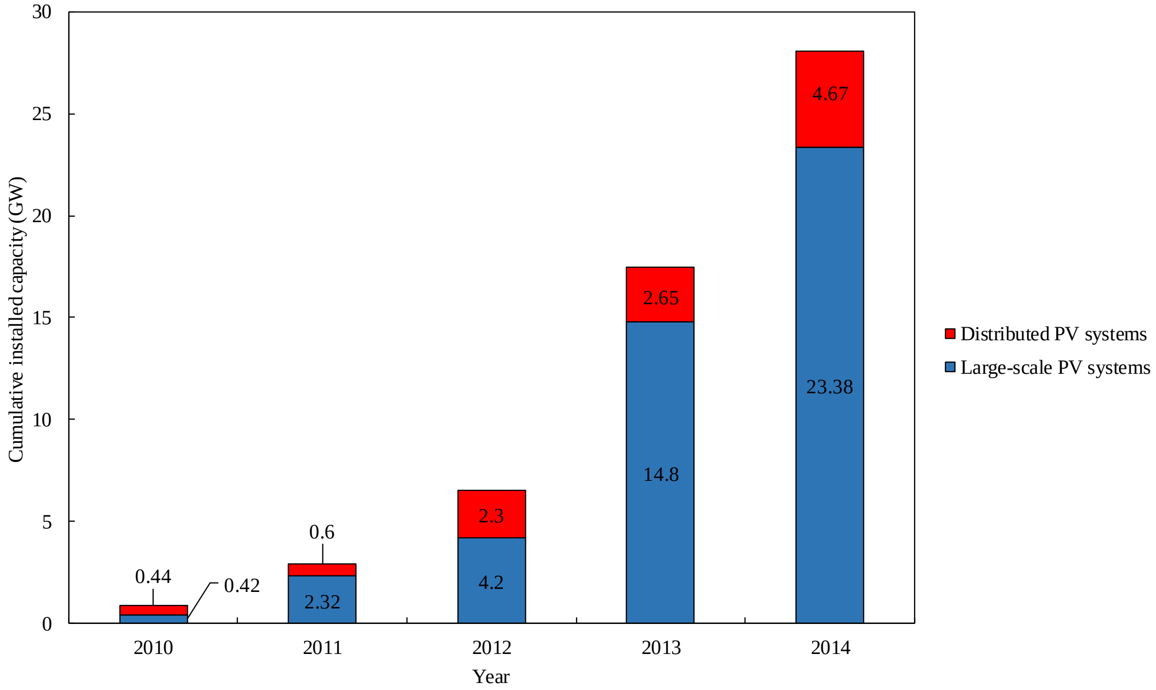


Figure 22 – Installed capacity of PV systems in China [56]

As we can see on Figure 22, the performance of distributed PV systems from the 2010 to 2014 has increased. It is necessary to notice that the share of distributed PV in the total cumulative capacity of PV was 35.4%, 15.2% and 16.7% in 2012, 2013 and 2014 respectively, but below expectations. In 2014 the number of new distributed PV installations was only 2.1 GW, lagging far behind the target of 8 GW set by the government in the beginning of 2014 [56]. The most efficient provinces in terms of cumulative distributed installation are Zhejiang, Jiangsu and Shandong (see Figure 21 and Table 4), which have roughly 73% of the total distributed PV capacity over the all country.

Table 4 – Cumulative and new installed capacity of distributed PV systems in 2014 [56]

Provinces	**Capacity, MW**	
	Cumulative	**New installed**
Jiangsu	850	570
Zhejiang	700	270
Shandong, Anhui	380	180
Guangdong	500	200
Jiangxi	260	150

China's development of distributed PV systems provides useful experience for other countries which are also promoting distributed PV policy. For instance, foreign shareholders and distributed PV project investors should be more involved in policy development. They have relevant data of DG situation than policy makers about the costs and returns of PV projects. The context of each individual country should be given high attention. In China, with government subsidy, the internal rate of return (IRR) of a DG project is theoretically attractive 10.2% with inflation rate 3% [63]. However, given all the barriers such as building ownership problem for the roof's PV installations, the IRR of a distributed PV projects might be less attractive than expected [64].

2 MATHEMATICAL DESCRIPTION OF DISTRIBUTED PV SYSTEM USING SIMULINK IN MATLAB

In this chapter we provide a general description of modeling distributed PV generation using Simulink in MatLab, PV cell behavior under different varying parameters such as levels of solar radiation per season and ambient temperature. Moreover, this chapter focuses on the mathematical description of the solar radiation, uneven changes in rural settlement’s consumption per season day, and diesel generator.

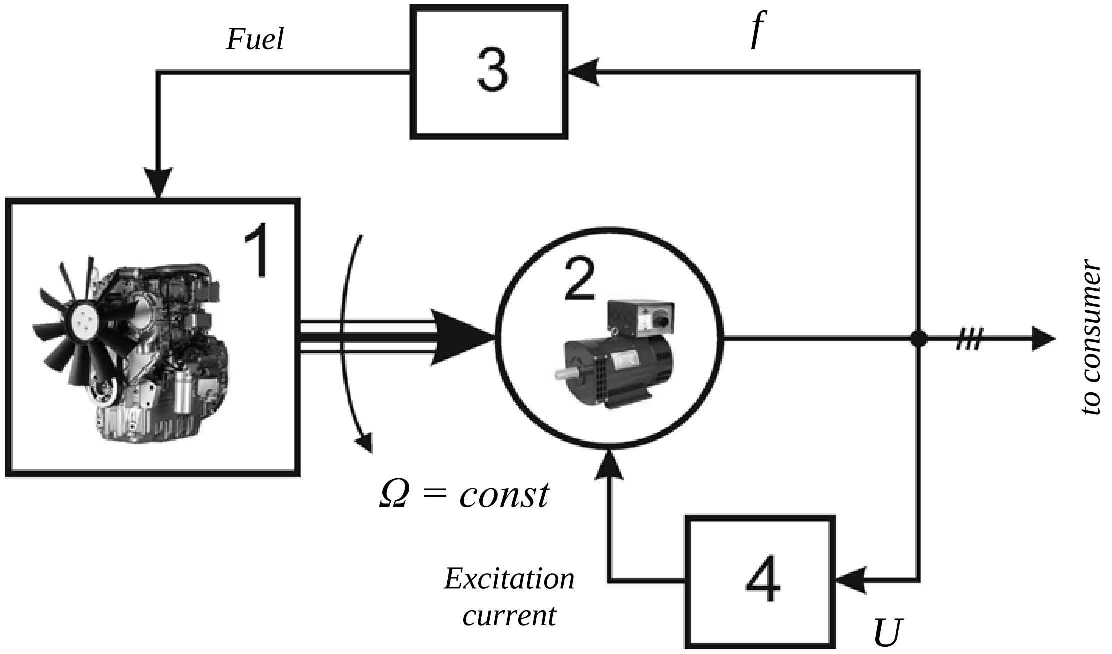
2.1 Diesel power plant block

In Russia the basis of decentralized power system is presented by DPP, most of which meet the requirements for SAPS. A wide nomenclature of DPP is represented on the energy market by domestic and foreign manufacturers. The share of DPP is more than 95% of 49 000 small power plants in Russia [65]. The wide use of DPP is determined by several undeniable advantages compare to other types of energy sources [65]:

1. Relatively high efficiency, up to 0.35–0.4.
2. Fast start (from 1 up to 10 seconds) and high maneuverability.
3. Full automation of all technological processes and the possibility of continuous operation without maintenance.
4. Low specific water or air consumption for engine cooling.
5. Small size, simplicity of auxiliary systems, allowing to get by the minimum quantity of attendants.
6. Small requirements for constructing volumes, up to 1.5–2 m^3/kW, fast construction of plant buildings and equipment installation.
7. Possibility of block-modular execution of power plants, which minimizes construction work at the site of application.

The DPP is based on the diesel engine, which has several advantages in comparison with other types of internal combustion engines: lower cost and fuel consumption, greater lifetime, higher reliability, less stringent requirements for fuel quality, relatively high fire safety requirements [65].

To ensure stable output electrical parameters of the generated electricity, DPP contain an automatic control system. A typical structural scheme of a general industrial DPP is shown in Figure 23.



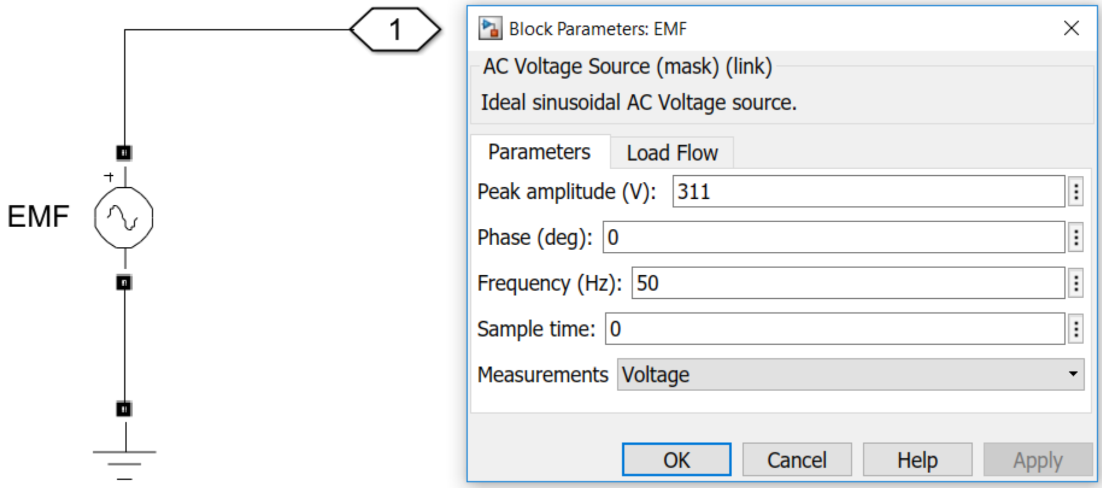
Note: The diesel engine 1 rotates the rotor of the synchronous generator 2. The voltage frequency *f* at the output of the generator is proportional to the rotational speed of the rotor *Ω*, and the value of the voltage *U* is proportional to the *excitation current* of the generator. Speed controller 3 determines the frequency of the output voltage and, acting on the controls of the diesel engine, keeps a constant speed of the engine shaft, thereby ensuring the stabilization of the frequency of the output voltage in all modes. The voltage regulator 4 by influencing the *excitation current* of the generator keeps the value of the output voltage close to the set value for all possible loads.

Figure 23 – Scheme of an automatic control system in DPP [65]

In the classical DPP scheme there are two automatic control systems such as the automatic control system for the diesel engine's frequency (the output voltage frequency) and the automatic control system for the generator output voltage. The purpose of the first automatic system is the stabilization of the diesel engine’s speed, the purpose of the second one is the stabilization of the generator voltage level.

Due to the principle of the DPP operation, for the mathematical description, it was decided to equate the DPP with the regulation of excitation of the synchronous generator by a controlled voltage source of the EMF. This operation was based on papers [20, 18, 66, 67].

In addition to the regulatory functions, the automatic control system of modern DPP must ensure trouble-free, long-term, and efficient operation of the diesel generator. Its main functions such as starting the diesel (manual or automatic) and stopping it (including emergency), monitoring and display of the performance of diesel and generator, issuance of warning signals, when the monitored parameters leave the specified limits, automatic control and monitoring of the operation of the diesel generator with the set parameters and the data obtained as a result of monitoring.



Block Parameters: EMF

AC Voltage Source (mask) (link)

Ideal sinusoidal AC Voltage source.

Peak amplitude (V): 311

Phase (deg): 0

Frequency (Hz): 50

Sample time: 0

Measurements Voltage

Figure 24 – Equivalent source of controlled EMF voltage

Figure 24 shows the parameters of the DPP block through a controlled voltage source. For the set conditions of mathematical modeling was selected a 0.4 kV network of the decentralized region of Russia was selected. The amplitude voltage will have a value of 311 V at an industrial frequency of 50 Hz in a single-phase version.

2.2 Solar power plant block

Currently, SPP can be splitted in two ways as thermodynamic plants and photovoltaic, where the second one will be described more deeply. PV stations use the effect of direct conversion of solar radiation into electricity, discovered in 1839 by the French physicist Becquerel. Devices that convert solar radiation into electric current are called solar cells. This means that they are sources of EMF. Solar cells generate current in direct dependence on daily, seasonal and random changes in insolation. The efficiency of the conversion of solar energy depends not only on the efficiency of the solar cell, but also on the consistency of the dynamic load in the external circuit [3].

Solar cells in most cases are silicon semiconductor photodiodes. When light is absorbed by a semiconductor structure, the photon energy is transferred to the electrons of the material, which causes the appearance of free charge carriers. The charge carriers create a potential gradient in the region of the p-n junction, under the influence of which an electric current arises through the electric receivers. A typical value of the potential difference is 0.5 V, the photocurrent density is 200 A/m^2 at a specific solar radiation power of 1 kW/m^2 [3]. The main field of application of solar panels is associated with lighting systems, water supply systems, remote radio communication stations, beacons, road signs and space vehicles.

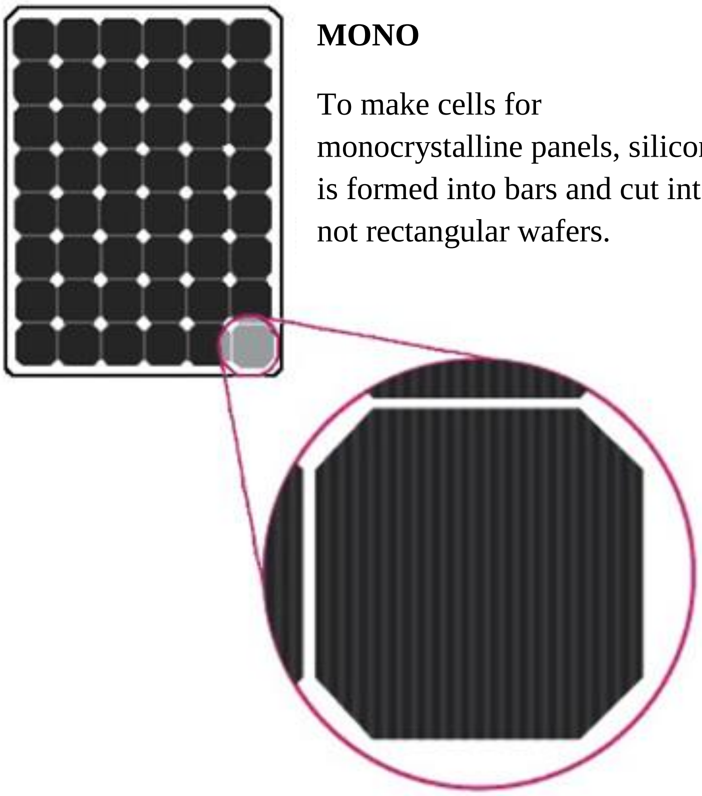
Nowadays, the development of technology and science are moving is very fast. There are three main types of solar panels structure in the market such as monocrystalline, polycrystalline, and thin film. The deep techno-economic analysis of all types is provided in Table B1. For the modeling process we choose the monocrystalline solar panels because these panels are used in the running projects [42, 43]. Moreover, a monocrystalline design has the following advantages [68, 69, 70]:

1. Monocrystalline solar panels have the highest efficiency rates since they are made out. The efficiency rates of monocrystalline solar panels are typically 15–20%. SunPower produces the highest efficiency solar panels on the U.S. market today. Their X-series series provide panel conversion efficiencies of up to 22.2% [69].

2. Monocrystalline silicon solar panels are space-efficient. Since these solar panels yield the highest power outputs, they also require the least amount of space compared to any other types. Monocrystalline solar panels produce up to four times the amount of electricity as thin-film solar panels.

3. Monocrystalline solar panels live the longest. Most solar panel manufacturers put a 25-year warranty on their monocrystalline solar panels.

4. They tend to perform better than similarly rated polycrystalline solar panels at low-light conditions.



MONO

To make cells for monocrystalline panels, silicon is formed into bars and cut into not rectangular wafers.

Figure 25 – Monocrystalline solar panel and solar cell design [71]

A solar cell battery is typically a combination of parallel modules. The solar cell described above is the basic standard unit of the PV system. Typically, the size of such a cell is a few square millimeters, and the removed power is about 1 W. To obtain more power, several such cells are connected in series-parallel circuits and placed on a panel (module) measuring several square decimeters. Solar panels are groups of several modules electrically connected in series-parallel combinations to obtain the required power and voltage [3].

For the analysis of the hybrid system, a mathematical model was created in the Simulink application of the MatLab. The SimPowerSystems library was used to simulate transient processes. The SPP model is based on the approximated characteristics of a PV generator and simplified mathematical functions, which are represented as a subsystem block.

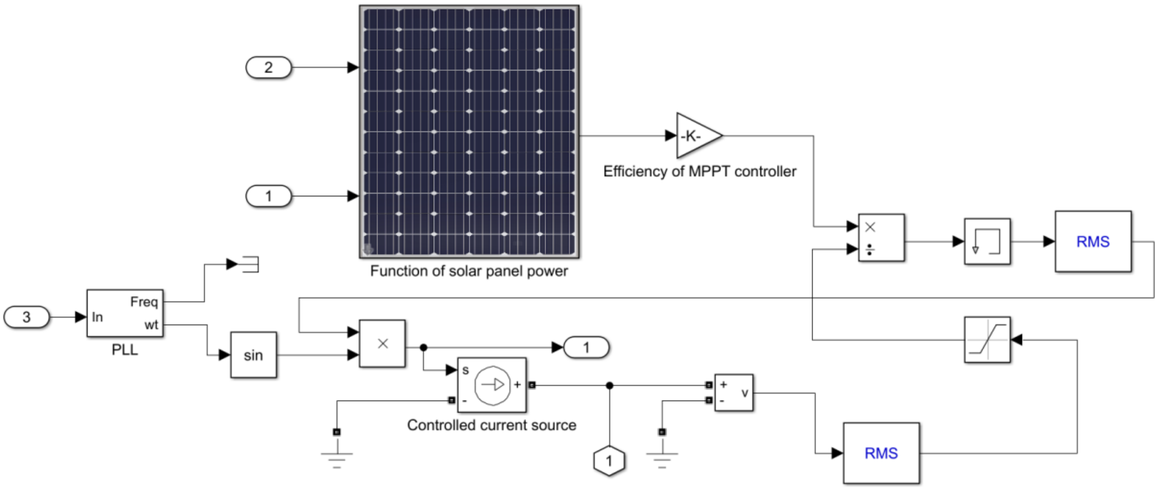


Figure 26 – Mathematical algorithm of working solar power plant in MatLab

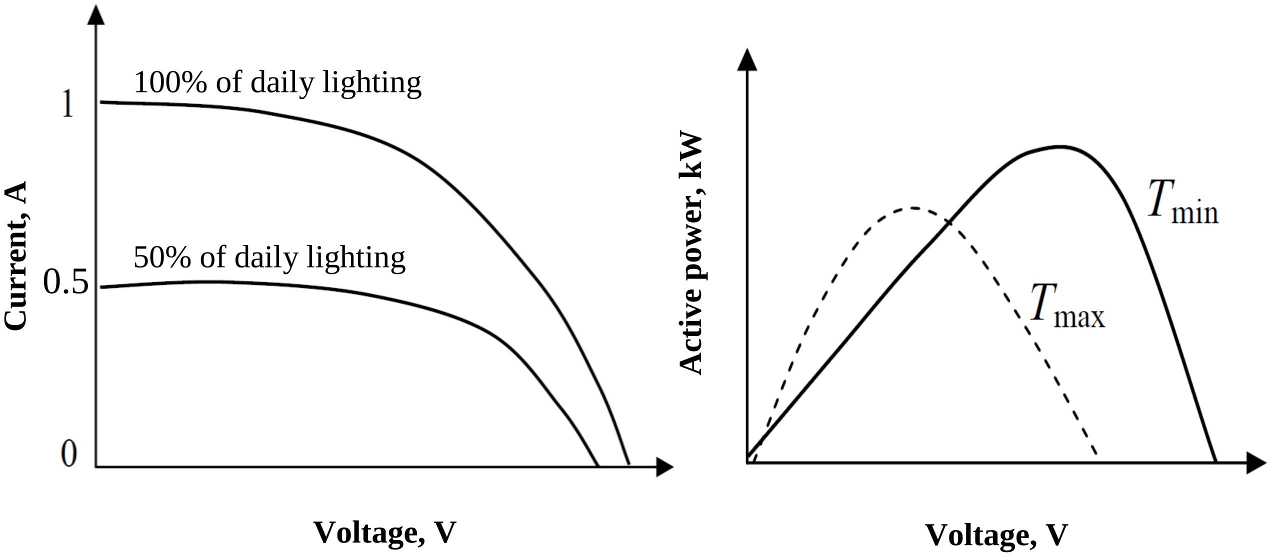
As shown in Figure 26, inside SPP subsystem, solar panel's active power is equivalent to the controlled power function subsystem. This subsystem is connected to a controlled current source. Solar panels are transit the generated photocurrent through a grid-tie or hybrid inverter. Modern inverters with maximum power point tracking (MPPT) functions in their output characteristics can be equivalent to the controlled current source block [20]. The impact of the solar MPPT controller is taken into account in the efficiency of MPPT controller block. The joint parallel operation of two power sources of the DPP and SPP is provided by the phase lock loop (PLL) block. PLL is an automatic control system that adjusts the phase of the controlled current source (SPP) so that it is equal to the phase of the main signal (DPP). The adjustment is due to the presence of negative feedback [20].

The main factors, which are affecting the efficiency of electrical output of solar panels are the following:

1. Intensity of insolation.
2. The angle of sunlight.
3. The value of load.
4. Operating temperature.

For the formulated conditions of this thesis, a decision was made to simplify and approximate the mathematical function of the solar panel. The set of factors, which were described above, will have the following priority:

1. Intensity of solar radiation. The magnitude of the light flux is maximal on a clear, sunny day. In the presence of small clouds, the light flux decreases in direct proportion to the decrease in the intensity of insolation. The volt-ampere characteristic shifts downward with decreasing solar radiation intensity (see Figure 27 on the left side) [3].



Note: Dash line represents low temperature effect and the solid line represents high temperature effect for the right graph.

Figure 27 – Volt-ampere characteristic (left) and the effect of temperature (right) on the output parameters of the solar cell [72]

2. The effect of temperature on the output parameters of the solar panel. As the temperature rises, the short-circuit current increases, and the open-circuit voltage decreases. It is proved that an increase in the operating temperature of the cell by 1 °C leads to a decrease in the output power by 0.45% [3].

Since the current increase is much less than the voltage decreases, at higher temperatures the cell generates less power. The output characteristic of a cell for two different temperatures is shown in Figure 27 on right side. As can be seen, the available output power at a lower temperature is greater. Thus, a lower temperature is better for the operation of the solar cell [72].

Block-subsystem function of solar panel power describes the analytical expression of the influence of temperature and the magnitude of the intensity of insolation. In addition, this function works with the condition that the solar panel is perpendicular to the incident rays [67]:

$$P_{sp} = \frac{C_f \cdot N_{sp} \cdot G \cdot \ln(10^6 \cdot G)}{T_{sp}}, \qquad (2)$$

where N_{sp} is the number of solar panels; C_f – constant factor of parameters in solar panel; G – current level of solar insolation, W/m^2; T_{sp} is the current temperature of the solar panel.

2.3 Solar radiation and ambient temperature blocks

Solar radiation is an inexhaustible, powerful, and environmentally friendly source of energy. In many countries, the use of solar radiation for household needs is gaining popularity. Interest in this problem is constantly growing both from potential consumers of solar energy and from research organizations. Despite all the attractiveness of solar radiation as a source of energy, its use for public needs in most of Russia is limited by climatic features and the lack of reliable methods for its determination. In this case, the main constraining factors are a relatively small number of hot and sunny days per year. Nevertheless, in the decentralized regions of Russia, the energy of solar radiation can find practical application [73].

The magnitude of the primary solar energy, which is available for the conversion of a panel, is determined by the intensity of the total solar radiation at the site of its installation and depends on the geographic coordinates of the SPP. The spatial orientation of the panel and external meteorological factors such as air temperature and cloudiness are also important inputs as well. Most of meteorological factors have a stochastic nature. Based on these papers [16, 17, 18, 75], the probabilistic approaches for calculating radiative characteristics have dominated at the design of the SPP. These approaches are used based on data of special climate directories or electronic databases compiled from the results of long-term meteorological observations [73].

The calculations in this thesis are based on a technique that allows to determine the hourly arrival insolation on the inclined surface proposed by Liu and Jordan [74, 76]. When calculating solar radiation entering an inclined surface, three components of the radiation balance are taken into account [73]:

$$Q_{incline} = S_{incline} + D_{incline} + R_{incline}, \tag{3}$$

where $Q_{incline}$ – total solar radiation incident on an inclined surface, W/m^2; $S_{incline}$ – direct solar radiation incident on an inclined surface, W/m^2; $D_{incline}$ – diffuse solar energy incident on an inclined surface, W/m^2; $R_{incline}$ – solar radiation reflected from the Earth's surface, W/m^2 (this value can be neglected).

The value of $S_{incline}$ can be found from the dependence:

$$S_{incline} = S_{orth} \cdot \cos\theta, \tag{4}$$

where S_{orth} is the direct solar radiation on the surface orthogonal to the solar rays, W/m^2.

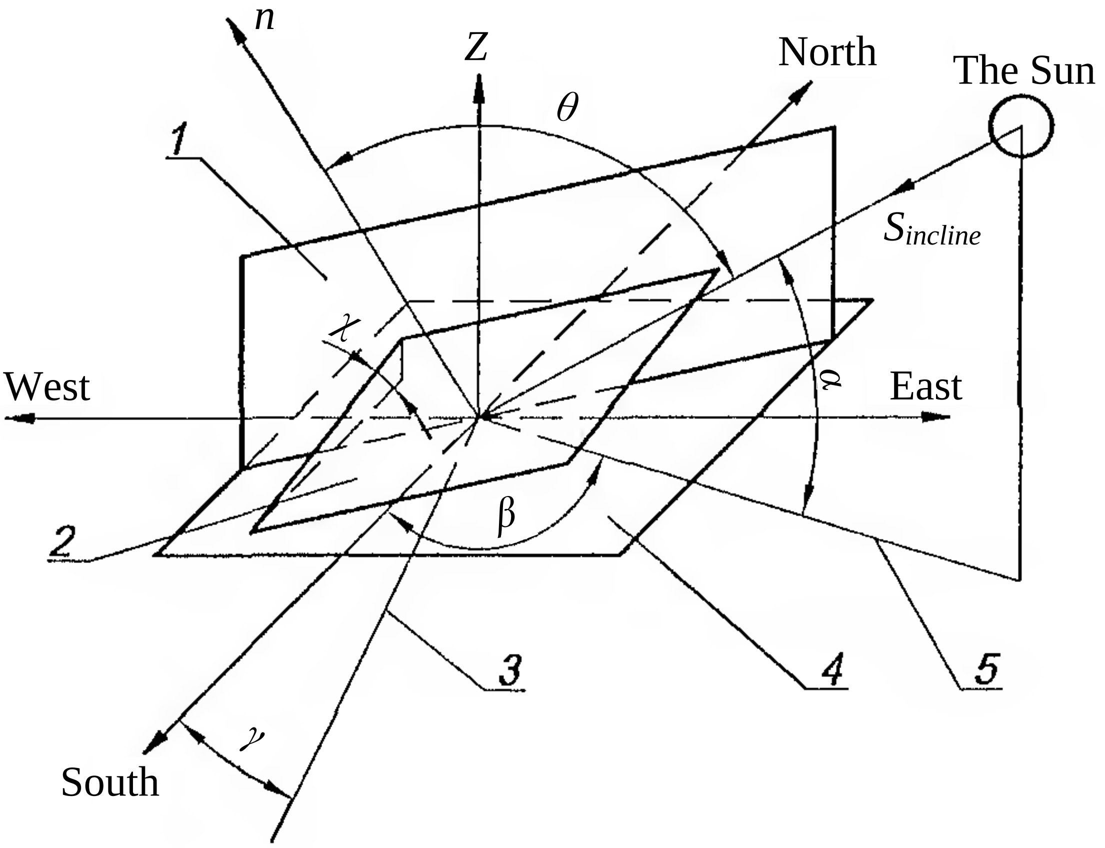
$$S_{orth} = \frac{S_0 \cdot \sin\alpha}{\sin\alpha \cdot c}, \tag{5}$$

where S_0 is the solar constant, 1395 W/m^2; c is an index of the atmosphere clearness.

The cosine of the angle of incidence of direct solar radiation on any surface in the dependence (4) is determined as follows:

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

where φ is the latitude of the area, radians; δ – declination of the Sun, radians; χ is the angle of inclination of the surface to the horizon, radians; γ is the azimuth angle of the surface, radians; ω is the hour angle, radians.



Note: *1* – vertical surface; *2* – inclined surface; *3* – horizontal projection of the normal *n* to the inclined surface; *4* – horizontal surface; *5* – horizontal projection of the Sun's rays; *Z* is the normal to the horizontal surface; *n* is the normal to the inclined surface; β – azimuth of the Sun.

Figure 28 – Scheme for calculating the arrival of solar radiation on the Earth's surface [73]

Declination (δ) is the angular position of the Sun in the solar noon relative to the equator. The azimuth angle of the surface (γ) is the deviation from the normal to the surface from the local meridian. The height of the Sun (α) is the angle between the direction of direct solar radiation ($S_{incline}$) and the horizontal projection of the solar ray. The hour angle (ω) is the angle that determines the angular displacement of the Sun during the day. One hour corresponds to π/12 radians. At noon the hour angle is zero [73].

The declination δ can be estimated from the approximate Cooper equation:

$$\delta = 0.41 \cdot \sin(360 \cdot \frac{284 + N}{365}), \tag{7}$$

where N is the ordinal number of the day in the year, counted from January 1.

The sine of angle α is found by the equation:

$$\sin\alpha = \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos\omega . \tag{8}$$

The diffuse solar radiation entering the inclined surface is determined by the equation:

$$D_{incline} = D_{horiz} \cdot [0.55 + 0.434 \cdot \cos\theta + 0.313 \cdot (\cos\theta)^2], \tag{9}$$

where D_{horiz} – the flux of diffuse solar energy (W/m^2) to the horizontal surface, is determined from the dependence:

$$D_{horiz} = \frac{1}{3} \cdot (S_0 - S_{orth}) \cdot \sin\alpha . \tag{10}$$

Diffuse solar radiation reflected from the ground:

$$D_{ground} = 0.47 \cdot A_{ground} (S_{incline} - D_{horiz}), \tag{11}$$

where A_{ground} is the albedo of the Earth. The Earth's albedo is the integral ratio in fractions to the unit of the solar energy flux reflected from the Earth in all directions to the stream that fell on the reflecting surface of the Earth [73].

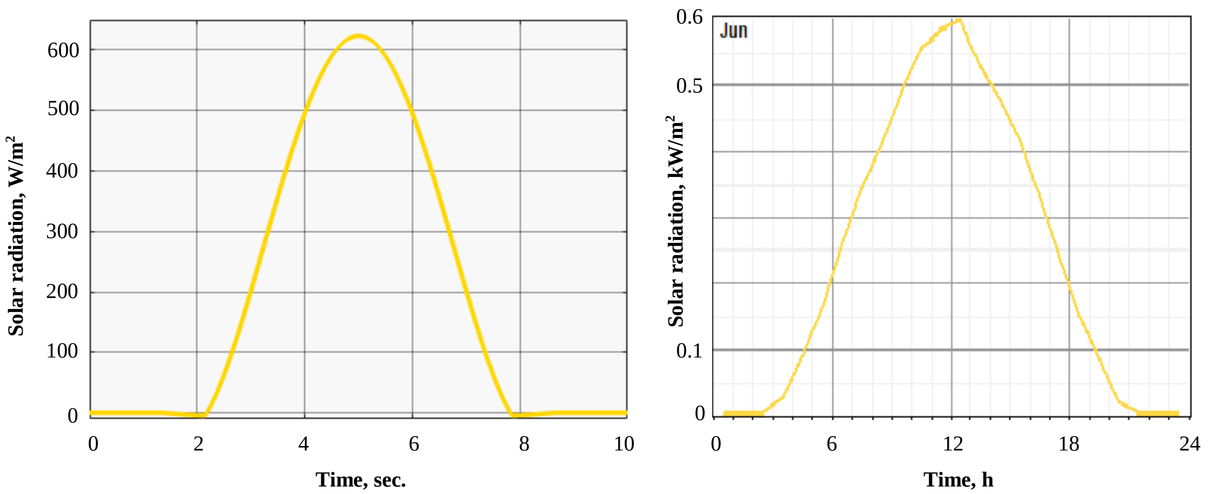
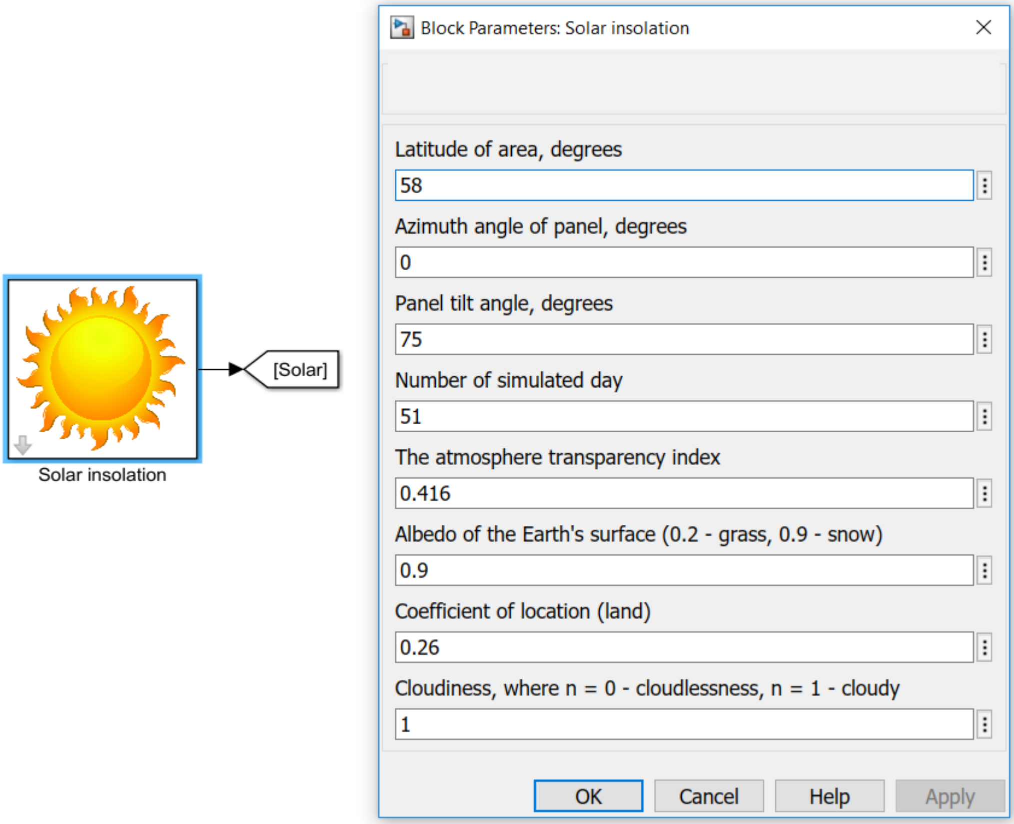


Figure 30 – Comparison of simulated results between Homer Energy (right) and the constructed block (left)

The created block of insolation makes it possible to determine the current values of the magnitude of incoming solar radiation for any day of the year in a random geographic location of the panel on arbitrarily oriented surface. For acceptability appraisal of the created block on validity, simulation results must be compared with a valid software. In this case it will be Homer Energy. It is necessary to notice that Homer Energy uses National Aeronautics and Space Administration (NASA) data observations, its observations period was started in 1983 and has finished in 2004. As we can observe, for the chosen daily solar radiation value in June the created block has approximately the same results as in Homer Energy.

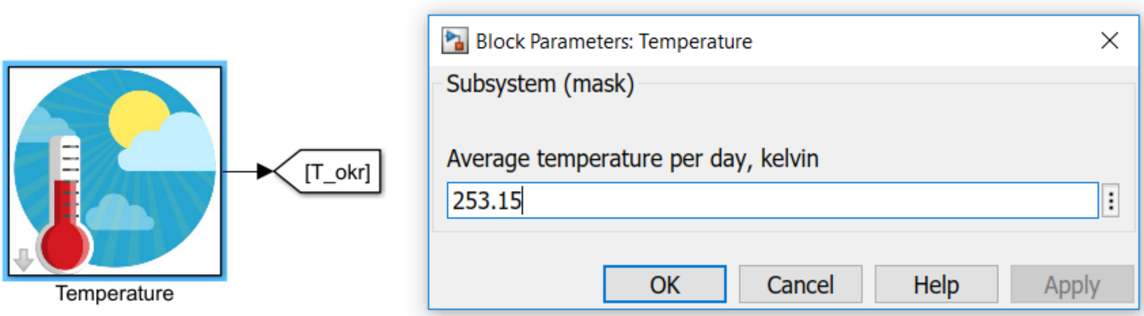
As shown in Figure 31, the block of insolation is made as a subsystem consisting of eight basic functional blocks providing the solution of equations (3) – (11):



Latitude of area, degrees: 58
Azimuth angle of panel, degrees: 0
Panel tilt angle, degrees: 75
Number of simulated day: 51
The atmosphere transparency index: 0.416
Albedo of the Earth's surface (0.2 - grass, 0.9 - snow): 0.9
Coefficient of location (land): 0.26
Cloudiness, where n = 0 - cloudlessness, n = 1 - cloudy: 1

Figure 31 – The subsystem of the insolation block in MatLab

The magnitude of the ambient temperature has the dominant influence on the output characteristics of PV panels as well. For SPP located in high northern latitudes, which include most of Russia's territories (the Tokma village has 58° of north latitude), external meteorological factors can have a significant impact on panel output. The average monthly and average daily temperature values of the ambient air are determined most simply. They are independent quantities from the parameters of the designed electrical installation. The initial data for their determination is the statistical data of meteorological observations, which can be obtained from archives of meteorological sites and climate directories [77].



Average temperature per day, kelvin

253.15

Figure 32 – The subsystem of the ambient temperature in MatLab

The modulation results have shown that the developed blocks are simulated with satisfactory accuracy.

2.4 Consumers and a transmission line block

Numerous of various consumers of electrical energy are usually fed from the electric networks in rural areas. These consumers are thought of as a receiver or group of electrical energy receivers that are united by a technological process and located in a certain area. The receiver of electrical energy (electric receiver) refers to an apparatus designed to convert electrical energy into the energy of another kind, for instance, thermal, chemical etc.

In the decentralized or remote rural areas, the following consumers of electrical energy are the following:

1. Residential houses of workers and employees in populated areas, farms.
2. Objects of social importance: hospitals, schools, social clubs, shops, kindergartens, etc.
3. Small-scale enterprises for processing natural resources and agricultural products.

Electric load in decentralized objects is a continuously changing quantity: some consumers are switched on, others are turned off. The power consumed by the switched-on electric receivers also decreases or increases with the change in the load of the operating machines. In addition, over time, the total electrical load is continuously increasing, as the degree of electrification of agricultural production and everyday life of the rural population is increasing [66].

For simulation the different types of electrical loads of decentralized objects in rural areas, the indicators of values are determined according to normative typical schedules of real electrical loads. The data of this schedules was obtained during statistical observations of the period from 5 up to 10 years [66].

For the purposes of this thesis, daily load schedules are appropriate. The basic model of electric load was a typical graph of the active and reactive load of rural houses, etc., typical for stand-alone consumers.

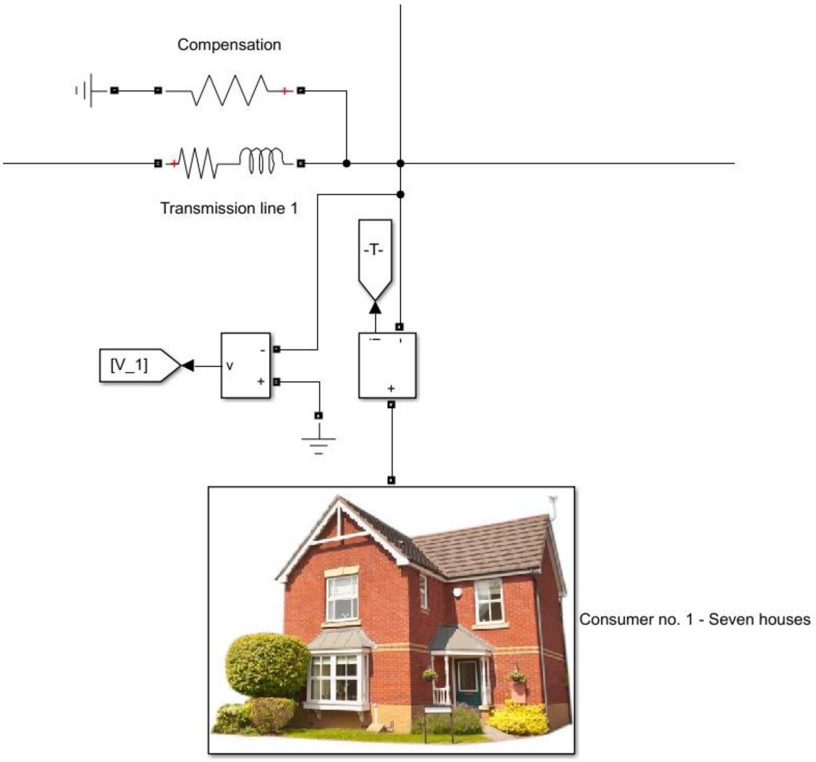


Figure 33 – The subsystem of the first group of consumers (seven houses) in MatLab

The simulated load model is built based on controlled switchers in accordance with the division of time intervals during of the day: morning, afternoon, evening, night. These switchers are commutating value of actively-inductive resistances of the circuit (see Figure 34).

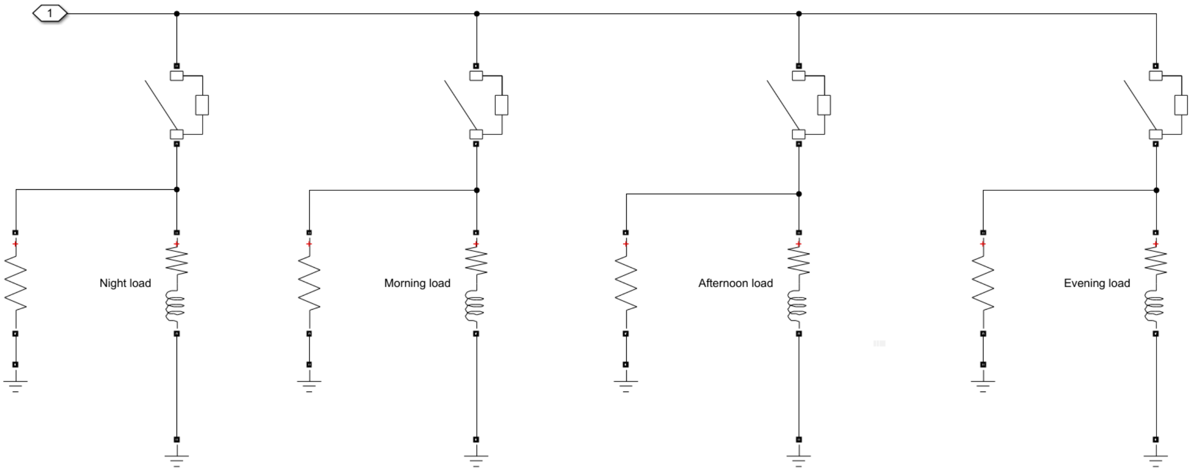
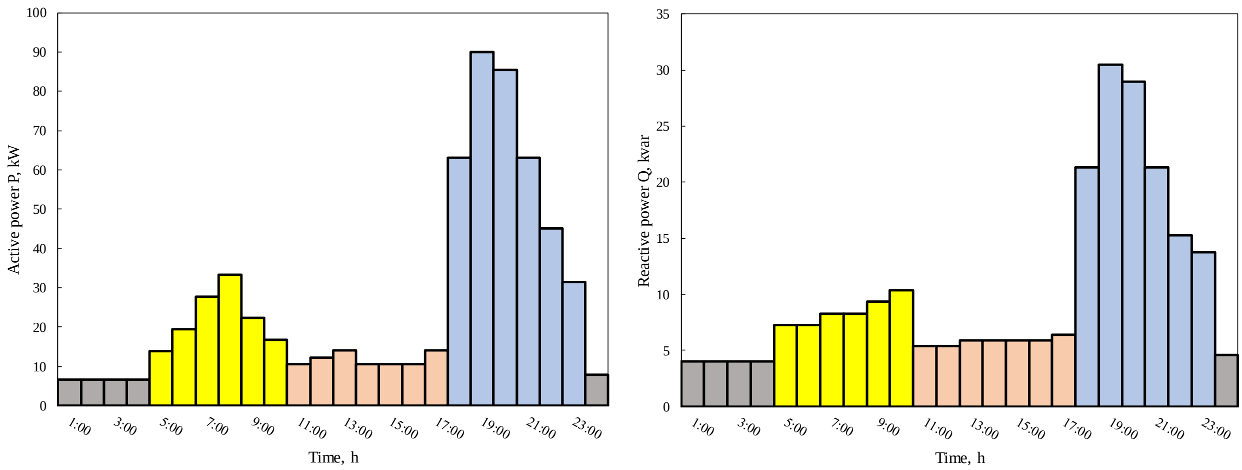


Figure 34 – The inner part of the consumer’s subsystem (seven houses) in MatLab

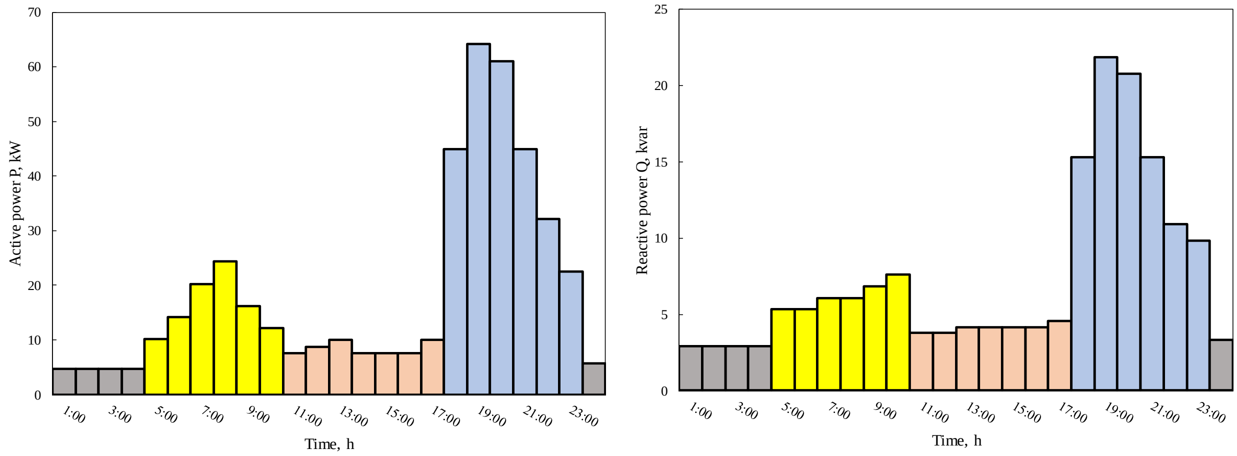
Below we can see the calculations, aggregated in a table form, the graphs of electrical loads of the Tokma village. This rural settlement consists of two groups of residential houses with different amounts of electricity consumption (the first one seven houses, the second one eight houses), a school building, a shop building, and an administration building. Color gradation of the load diagrams divides the hours of diurnal phases during the simulated day.



Note: A gray color it is a night, a yellow color represents morning consumption, a peach color it is an afternoon, and blue one it is an evening.
Source: Author's illustration.

Figure 35 – Dependencies of active and reactive power consumptions of the Tokma village per winter season

As shown in Figure 35, at 19:00 we can observe a maximum of active and reactive power consumptions per winter time. According to DPP nomenclature in the Tokma village, which was described in Chapter 1, there are two DPP with a nominal power 30 and 60 kW respectively. For the power and electrical needs of the system, usually, compare two classical seasons of power consumptions – winter and summer time.



Source: Author's illustration.

Figure 36 – Dependencies of active and reactive power consumptions of the Tokma village per summer season

This thesis investigates the power supply system for summer season conditions which is expedient as winter insolation in central Russia (55–58˚ north latitude) is 15 times less than for summer [20]. It defines the creation of SPP that will only be effective for the summer season. In winter, with an increase in power consumption and a decrease in insolation, the role of SPP is significantly reduced and it has virtually no effect on the electrical mode of the power supply system. This determines the creation of a mathematical model of a SPP with distributed PV generation.

Consumers are connected through sections of supply lines with active-inductive parameters. The length of the transmission lines is limited by the maximum allowable voltage deviation at the load at the end of the line relative to the nominal value. The State Standard specifies a limit value to any deviation of not more than 10% [20]. Thus, the line length will depend upon known factors such as the specific linear resistance wires and power loads. The calculation of the resistances of five sections of the main transmission line with a voltage of 0.4 kV is presented in the following table:

Table 5 – Conversion of resistances of transmission lines

No. of line	Parameters		
	Length, m	R, Ohm	L, H
1	200	0.17	$2.7\cdot10^{-4}$
2	10	0.0085	$1.3\cdot10^{-5}$
3	10	0.0085	$1.3\cdot10^{-5}$
4	25	0.0213	$3.3\cdot10^{-5}$
5	50	0.0425	$6.6\cdot10^{-5}$

3 TECHNO-ECONOMIC ANALYSIS OF SAPS USING DISTRIBUTED PV GENERATION

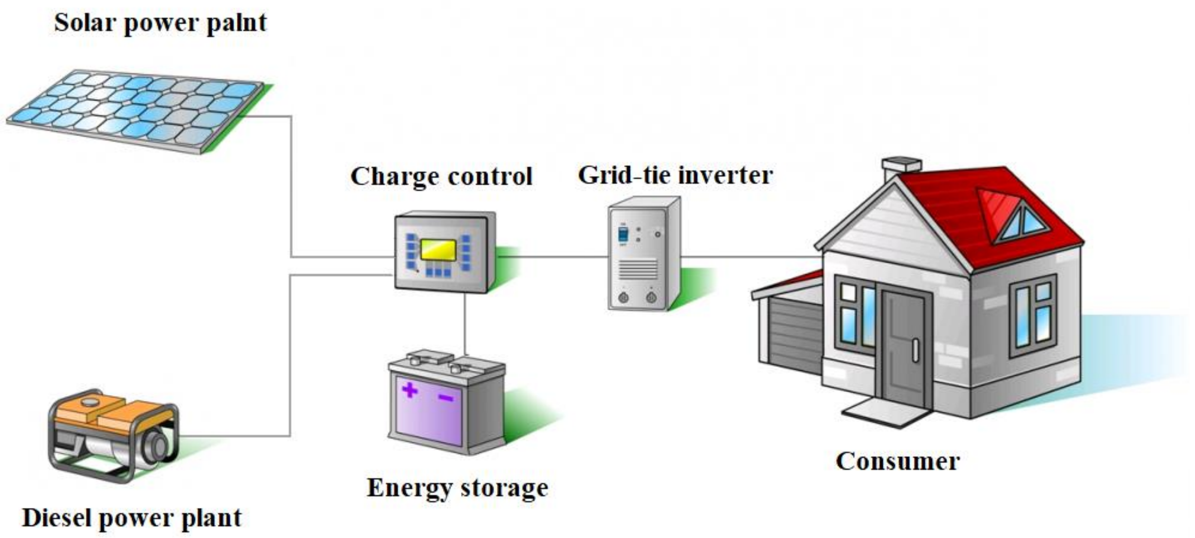
This chapter focuses on a structure of a hybrid stand-alone power system (SAPS). We provided a general description of equipment, which was used for modeling transitional processes. The simulation results include the cases of a single solar power plant (SPP) and distributed installation designs. Recommendations for the quality issues such as increasing the voltage level at the end of the transmission line, reduction of power losses are provided as well. These results will be compared with the case of SAPS without RES. Cost and benefit analysis will describe the influence of this RES integration into SAPS from the economic and environmental points of view.

1.1 Quality improvement issues

Block-scheme of SAPS with a distributed PV system

A complete electricity supplying scheme of the SAPS with a distributed PV system is presented in Figure 37. The DPP and SPP are connected in parallel to supply the load. It is necessary to carry out a number of mathematical calculations to adjust the model and obtain the most accurate results from the point of view of electric power indicators. A modeling process will be divided into two groups of calculations:

1. Single SPP without distribution over the network.
2. Distributed SPP over the network.



Note: Charge controller – limits the rate at which electric current is added to or drawn from electric batteries, Grid-tie inverter – inverters are installed between local power sources: solar panels, batteries, a hydroelectric power plant, and the main source of electricity.

Figure 37 – Block-scheme of stand-alone PV power supply system [78]

A share of green electricity in the total energy balance of the hybrid electricity supply system is usually at least 50%. The load on DPP increases with a smaller installed capacity of renewable energy installations. An increase in the duration of the regimes of generation of RES not enough for the current load coverage determines the appropriateness of the parallel operation modes of the hybrid power plant [1].

It is important to notice that the grid-tie inverter can operate in parallel only with a sufficiently powerful electrical supply network. In the stand-alone systems, such a power system is created by a DPP. Leading manufacturers of solar invertors do not recommend reducing the current capacity of DPP in PV-diesel engines to less than 40–50% relative to the power of total generation. This constraint is based on the conditions of stability of the power supply system [1].

This system has the following advantages: both grid and stand-alone inverters can be applied even with a minimum set of options and are presented on RES market in various variants from numerous producers; batteries are always fully charged and are used in a buffer mode only when grid outages occur. Such a system is advisable to use in power supply systems where electricity is consumed mostly during the daylight and grid outages are rare and short. This system has only one disadvantage: solar power production stops when grid outages occur [1].

In the daytime, a network inverter provides power to all consumers. Excess energy is sent to the common network only in those cases when the consumption is less than the generation of SPP, while the energy of the sun is also used for the batteries charge. The efficiency of network inverters is more than 90%, which ensures good energy performance of the entire power supply system.

Solar power plant adjustment and number of solar panels

The annual electricity consumption by a decentralized village is 195.1 MWh/year, where it was assumed that the number of family members, living in residential buildings, is from two up to five people. Therefore, the proposed power supply model should provide this load with the selected power ratio between the sources.

For that case of simulation, it is necessary to know a number of solar panels, which will be used for the quality improvements, reduction of fuel consumption, and reduction of power losses in the transmission lines as well. According to the described principle of operating mode of the grid-tie inverter in the chapter above, the limited installed power of SPP must be at least 50% of the main source of electricity in SAPS. That constraint in installed power should be taken from the main power source in the Tokma village. Thus, installed power of SPP is 40% from 76 kW of DPP, where the final value is 30.4 kW.

Based on the installed power of SPP, we can calculate a number of necessary solar panels. For the modeling was chosen a monocrystalline solar panels TSM–200 [79], which have the following parameters:

Table 6 – Parameters of the solar panel TSM–200

Parameter	**Value**
Rated power (P_{nom})	200 W
Rated voltage (U_{nom})	24 V
Open circuit voltage (U_{oc})	43.2 V
Short circuit current (I_{sc})	6.22 A
Current at maximum power (I_{mp})	5.56 A
Rated operating cell temperature	-40…+85 ˚C
Size	1580 x 808 x 40 mm^2
Weight	17.3 kg
Structure	Monocrystalline

For the first proposes the number of solar panels will be described by the equation:

$$N = \frac{P_{spp}}{P_{nom}^{pan}} = \frac{30.4}{0.2} = 152 \,. \tag{12}$$

It is also necessary to determine an optimal value of the angle of the receiving area (solar panel). For carrying out calculations, it is better to use known mathematical software packages, for instance, Simulink in MatLab.

There are a few possible cases of the orientation of solar panels during their operation [1]:

1. An orientation via the sensors and tracking systems. These systems are perpendicular to the incident radiation flux. In this case, tracking options are possible for both the two axes (azimuth and inclination) and one axis (inclination).
2. Software rotations of solar panels, depending on the location of the sun by means of special drives. In this case, the variants of rotations are possible both along two axes (azimuth and inclination) and one axis (inclination).
3. Discrete seasonal change in the angle of inclination of the panel. At the same time in the azimuth of the panel is oriented to the south.
4. A fixed position of the panel, both in the angle of inclination and in azimuth, for the whole period of operation.

For the modeling proposes it is better to use the third option. The third option has a lower energy efficiency than the first or second one, but it is easy to implement. It is usually used in small-capacity power plants (for example, in villages) or when solar panels are integrated directly into the structure of a building. It should be noted that the orientation by the azimuth to the south cannot be performed very accurately (with an accuracy of several degrees). As researchers have shown in [1], a change in the azimuth of 15° reduces the arrival of solar radiation on the surface by 5%.

Usually, solar panels are placed at an angle of inclination equal to the latitude of the area with the south orientation. If the number of solar panels allows making seasonal changes in inclination with acceptable labor, this feature should be taken into account. The energy potential of solar radiation is distributed more uniformly throughout of Russia. The possibility of PV usage not only of direct solar radiation but also diffuse makes it possible to use SPP between 55–58° north latitude [20].

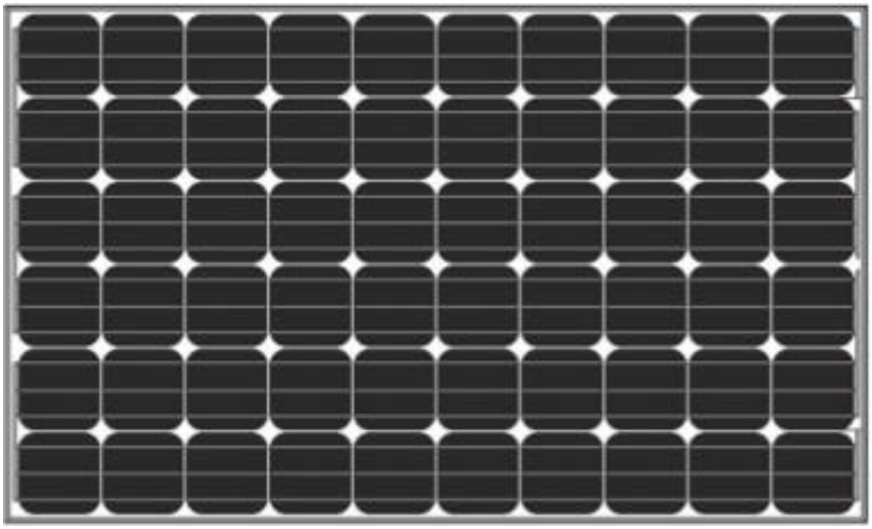


Figure 38 – Solar panel TSM–200 [79]

Thus, using the described option, it is possible to set up the angle of inclination of the receiving surface of a solar panel for a typical day of the year under average cloud conditions for the analyzed season.

The results of calculations of optimal inclination angle of the solar panel and azimuth orientation are provided in the following table:

Table 7 – Results of modeling solar panel orientation

Season	Inclination	Azimuth orientation
Winter	75°	south, 0°
Spring	30°	south, 0°
Summer	30°	south, 0°
Autumn	75°	south, 0°

Inverter

Inverter – is a device that converts direct current into alternating current with specified parameters (voltage, frequency). In addition, as an intellectual system, it controls the operation of the entire energy system. SMA Solar Technology AG [80] is one of the world's leading companies in the development, production and sale of power equipment and devices for building various power supply systems.

SMA technologies, developed using the latest advances in electronics, allow to maximize efficiency from stand-alone, network and standby power systems based on both traditional and renewable energy sources. As a technology leader, SMA Solar Technology develops and manufactures high-performance inverters from 2 to 1000 kW for installations of any size, all power classes, and specifications. The main activity of SMA is the development and manufacture of inverters. The inverter is technically the most important component of any power system that uses DC generating plants, such as a solar panel, a wind generator, DPP, and others.

SMA offers a variety of inverter models that can be divided into three important characteristics: power, DC-on-side mode, and circuit topology. The usable power of the inverter lies in the range from 1600 W to several megawatts. The rated power can be from 3 to 6 kW for private sector power systems, 10 to 20 kW for commercial PV installations on roofs of enterprises or household buildings, and 500 to 800 kW for SPP [1].

An important technical characteristic of inverters is a method of switching on the side of the direct current, which determines the possible options for connecting PV installations with the inverter. This problem is caused by the fact that in many SPP, a solar module can contain several arrays of PV panels, which have different illumination, a different type, and correspondingly, different output characteristics. To maximize the use of solar energy, SMA has developed special multi-link inverters.

Depending on the temperature and intensity of the incident radiation, there is always an exact correlation between the strength of the electric current and the voltage, allowing the PV module to produce the maximum power. This is also called the maximum power point. Since the temperature and intensity of the incident radiation are constantly changing (especially thanks to clouds), the inverter control system must continuously monitor the maximum power point so that the PV modules produce the largest possible amount of electrical energy. For this purpose, a program the maximum power point tracker (MPPT) is used. Multiple inverters have several trackers of maximum power in their composition so that the different links work independently.

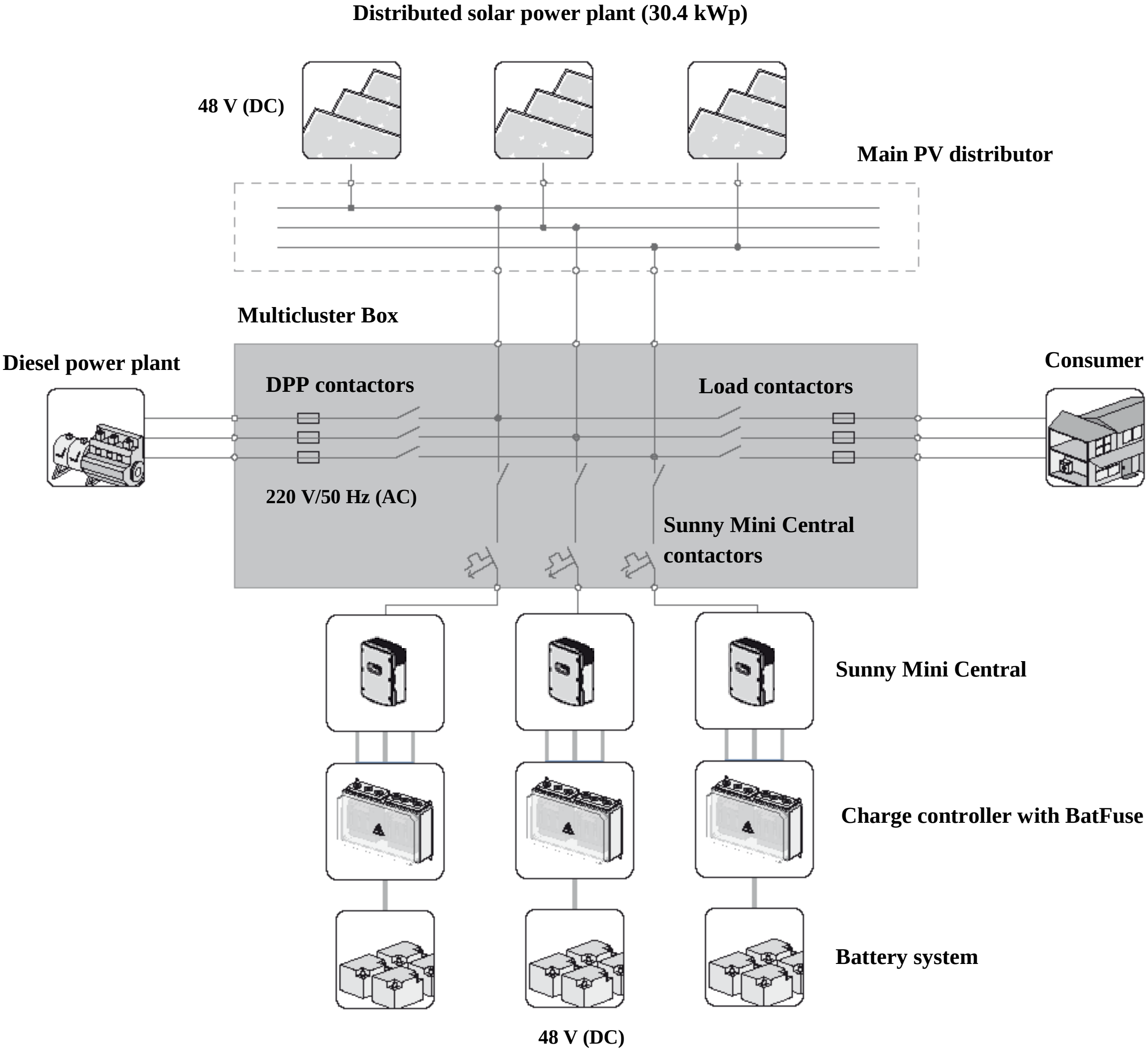
Multi-link inverters have two or more links of inputs, each of them has its own tracker for searching for an MPPT. A special interest is an array of solar panels with many partial surfaces that are directed in different ways or partially shaded. Despite the higher output power, the main inverters have only one tracker for a maximum power search. They are particularly suitable for a large-scale SPP with a homogeneous array of solar panels.

According to the specific algorithm of operation, in that case, was decided to use grid-tie inverter Sunny Mini Central. SMA Sunny Mini Central – it is a solar inverter with highly efficient solar energy converters with having an efficiency of up to 98%. This inverter is ideally suited for building solar energy systems of medium power (from 15 kW and more). Advanced technical solutions, as well as the best price/performance ratio, allow Sunny Mini Central inverters to be ideal converters for medium and large solar installations, and a small power gradation provides design flexibility and allowance for accurate configuration system. SMA Sunny Mini Central inverters are also great for building stand-alone power systems [80].

Figure 39 – Inverter SMA Sunny Mini Central 10000TL-10 [80]

Inverter Sunny Mini Central is equipped with a variety of functions that increase the capabilities and performance of the system, as well as simplifying their installation. The tracking function OptiTrac MPP allows Sunny Mini Central inverters to always operate constantly in the selected mode, even with sudden changes in weather conditions, reliably converting solar energy with the maximum efficiency. The integrated ESS DC load shedding system simplifies installation and at the same time reduces the total cost of the photovoltaic system. A cast aluminum housing and the OptiCool active temperature control system allow the installation of inverters directly near the solar panels, thereby reducing the cost of cable lines, as well as operating solar inverters in any climatic conditions.

Inverters of Sunny Mini Central, in combination with charge controller, allow forming a stand-alone AC network with batteries, which meets the highest quality standards. In systems based on Sunny Mini Central inverters, generators and electricity consumers are integrated into the network in equal measure. PV and wind systems, DPP and micro HPP or CHP can be connected on the AC side of 220 V in the same way as ordinary consumers [1].



Note: Multicluster Box - is a component of the multicluster technology of SMA company for systems with stand-alone electric networks. The Multicluster Box is the main AC distributor, to which up to twelve three-phase clusters can be connected. Each cluster consists of two devices of the same type of Sunny Mini Central, connected in parallel to the DC side. BatFuse secures the Sunny Mini Central’s battery connection cables [80].
Source: Author’s illustration.

Figure 40 – Electrical scheme of stand-alone power supply system

Sunny Mini Central supports parallel operation of up to four devices on one phase or three devices on three phases without additional coupling devices.

The inverter allows creating self-contained power supply systems power from 15 kW. The presented inverter has a set of important parameters, which will be taken for the future calculations. Provided information is formalized into the following table:

Table 8 – Parameters of Sunny Mini Central 10000TL-10

Parameter	Value
Rated frequency	50 Hz
Rated voltage of network (U_{nom})	220 (180–260) V
Rated power (P_{nom})	10 kW
Maximum input voltage	333–500 V (DC)
Efficiency	98%
Rated operating temperature	-25…+60 ˚C
Size	468 x 613 x 242 mm
Weight	35 kg
3-phase system / parallel connection in single-phase system	yes/yes

The choice of inverters is based on the power of SPP. SPP has 30.4 kW installed power with a number of solar panels 152. It means that taking into account installed power of Sunny Mini Central 10000TL-10 10 kW, a number of inverters will be described by this equation:

$$N = \frac{P_{spp}}{P_{nom}^{inv}} = \frac{30.4}{10} \approx 3. \tag{13}$$

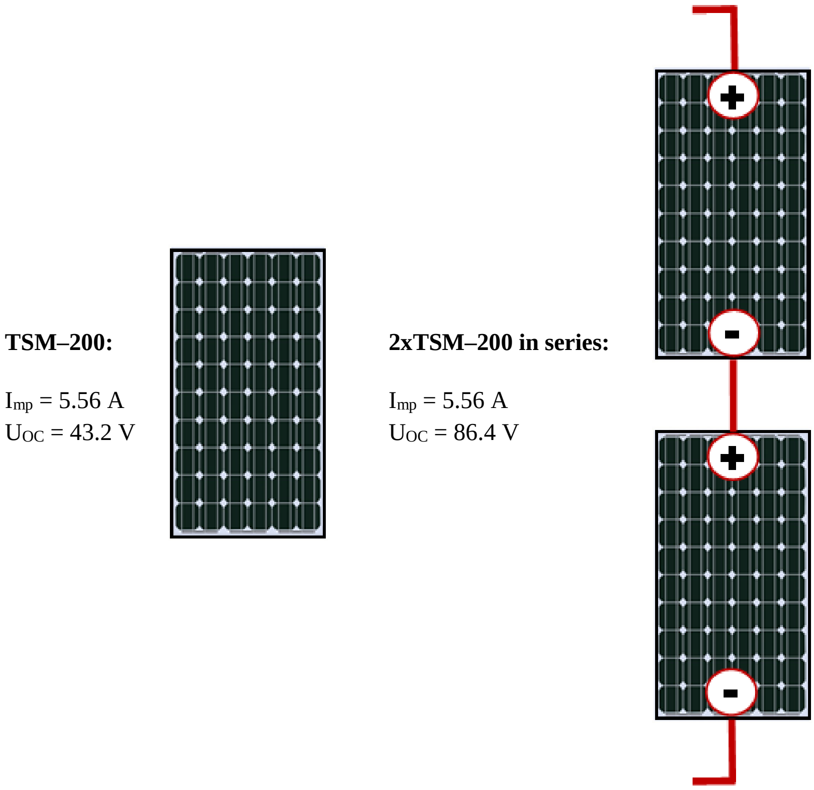
Manufacturers regulate the voltage of the connected solar panels. Therefore, the maximum permissible input voltage specified in the inverter's technical data must correspond to the open circuit voltage of the solar panel or to the sum of the open circuit voltage of a group of solar panels connected in series, plus a reserve of at least 20%. The reserve is due to several reasons [1]:

1. The input voltage specified by the manufacturer can be overestimated.
2. When the solar activity is high, the open circuit voltage of the solar panel may be higher than that indicated by the manufacturer.

$$U_{\max}^{pan} = 1.2 \cdot U_{OC} \cdot N_{series} \le U_{\max}^{inv}, \tag{14}$$

where U_{OC} – open circuit voltage of the solar panel, N_{series} – the number of solar panels, which are connected in series, $U_{\max}^{inv}$ – input voltage for the solar panels.

According to the rule of parallel and series connection of electrical circuit elements, a number of solar panels must satisfy the equation (14). As was described above, the number of inverters is six; it means that for each phase of three-phase stand-alone power supply system will be two inverters. Each inverter will include the requirement of (14) equation. Thus, solar panels will be linked to the following approach:



Source: Author’s illustration.

Figure 41 – Electrical scheme of solar panel connection in SPP

Based on Figure 41, the order of solar panel connection will be in case of modeling: two panels in series are connected into twenty-six set of parallel arrays. This array will consist of fifty-two solar panels with one inverter. The same principle will be for the remaining part of inverters. It is necessary to notice that number of solar panels must be raised up to 156 for the symmetric structure of the array.

$$U_{\max}^{pan} = 1.2 \cdot 43.2 \cdot 2 = 103.2\ V \le 230\ V\,. \tag{15}$$

As we can see in equation (15) the requirement is satisfied. Thus, we use 156 solar panels with tree inverters by SMA Sunny Mini Central.

Batteries

Stand-alone power supply systems with PV generation are used where there is no centralized power supply network. To provide power energy in the dark or during periods without bright sunlight, you need a rechargeable battery.

The main conditions for choosing batteries are the following [1]:

1. Resistance to cyclic operation.
2. Ability to withstand deep discharge.
3. Low self-discharge.
4. Stability to the violation of charging and discharging conditions.
5. Durability.
6. Easy maintenance.

An important parameter of small solar systems is the compactness and tightness. These requirements are fully met by batteries made using the technologies dryfit or recombination technology with absorbent glass mat (AGM). They are characterized by a lack of operating costs and overlap the range of capacities of 1–12 000 Ah. Gases produced during charging, do not leave the battery, so the electrolyte is not consumed, and maintenance is not needed.

Operation of batteries with deep discharge leads to the need for their frequent replacement. The price and maintenance of such systems are rising significantly. The depth of discharge of batteries in solar systems tend to be limited at the level of 30–40%, which is achieved by switching off the load (reducing power) or using larger capacity. Therefore, to control the charging process, the solar power plant must include the battery discharge charging controllers.

Figure 42 – Delta DTM 12250 L battery based on AGM technology [81]

In the batteries with AGM, a fiberglass mat saturated with sulfuric acid is used. AGM batteries are sometimes also called dry batteries, because the fiberglass mat is saturated with sulfuric acid only by 95%, and there is no excess liquid in it. The AGM battery is cleaner, for instance, when transporting it, you do not need to meet the requirements for dangerous materials. They are great for most cases, they are able to operate under rather difficult conditions and do not leak even in case of damage. Their main disadvantage compared to the liquid batteries is the high cost (they cost 2–3 times more) [1].

To determine the number of batteries, it is necessary to calculate the excess energy during the generation of electricity via SPP. Exceeding the generation of electricity by SPP in relation to consumption occurs during all seasons, but only spring and summer have a maximum. Based on the calculation technique [3], we should consider the most sunshine season per one modulated year. MatLab modulations are showed that spring has the maximum of insolation, because of lack of cloudiness during the season. Exceeding the generation energy per spring season has 141.1 kWh/day.

Calculation of the capacity of the battery, taking into account the permissible depth of discharge, for batteries (the block consists of four series-connected batteries):

$$W_{batt} = U_{nom}^{batt} \cdot C_{nom}^{batt} \cdot k_{disch}, \tag{16}$$

where U_{nom} – rated voltage of the battery in series, V, C_{nom} – rated capacity of the battery, A·h, k_{disch} – a limitation of the depth of discharge of batteries at the level of 40%.

Based on the excess of energy during the generation of electricity via SPP, we can calculate a number of batteries. For the modeling was chosen the Delta DTM 12250 L battery [81], which has the following parameters:

Table 9 – Parameters of the Delta DTM 12250 L battery

Parameter	**Value**
Rated capacity (C_{nom})	250 A·h
Rated voltage (U_{nom})	12 V
Lifetime	10 years
Self-discharge	3% per month
Maximum charge current (I_{mchar})	75 A
Maximum discharge current (I_{mdisch})	1250 A
Rated operating cell temperature	-20…+60 ˚C
Size	520 x 269 x 227 mm
Weight	74 kg
Type	AGM

According to the equation (16), maximum accumulated energy with 40% restriction will be 4.8 kWh for one Delta DTM 12250 L battery. After this calculation, we are able to determine the number of blocks with the following equation:

$$N_{blocks} = \frac{W_{batt}^{ex}}{W_{batt}} = \frac{141.1}{4.8} = 29.39 \approx 30. \tag{17}$$

Based on Figure 41, the order of batteries connection will be the same as for the solar panels. In that case of modeling: four batteries in series are connected into thirty sets of parallel arrays. This array will consist of forty batteries with one inverter. The same principle will be for the remaining part of inverters. Finally, the number of batteries will be 30 blocks, which is consists of four batteries – 120 batteries in total.

Diesel power plant

As it is already mentioned, diesel generators are a very popular 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. In this part, we have chosen to supply the settlement with three units of diesel generators. They are able to cover the load, where two of them are 16 kW (one reserved) and the already installed 60 kW respectively. According to the information from Chapter 1, the Tokma village has a 30 kW diesel generator with unsatisfied state of work. Two 16 kW diesel generators will be installed instead of 30 kW. This replacement, based on the integration of new sources (SPP and batteries), leads to increasing the load of a diesel generator. It means that optimal ratio of the diesel generator load will be between 40%–80% in contrast to the old 30 kW diesel generator, which loads with RES was less than 30%.

A presented diesel generator has a set of important parameters, which will be taken for the future calculations of the economic benefits. Provided information is formalized into the following table:

Table 10 – Parameters of DPP AD-16-T400-P1 [82]

Parameter	**Value**
Rated power (P_{nom})	16 kW
Reserve power (P_{max})	18 kW
Generated current	3-phase/ 400 V/ 50 Hz
Fuel consumption (75% of the load)	5.2 l/h
The volume of the fuel tank	200 l
Stand-alone mode of work	38.6 h
Size	1810 x 1020 x 1550 mm
Weight	950 kg
Specific fuel consumption (100% of the load)	220 g/kWh

As shown in Table 10, for the hybrid system, this diesel generator meets all the requirements. The load ratio lies in the range of 40–80%, and we can use this generator for the modeling. It will work for the whole range efficiently. The diesel generator is an easily adjustable source of energy for the settlement. However, in the case, if the load will increase, new equipment will be needed, because the existing generator will work on the conditions close to the nominal power most of the time.

Figure 43 – Diesel power plant AD-16-T400-P1 [82]

The total reference price for diesel generators will be around USD 14 610 [82] (for the reserve and main DPP). This price will be used further for the calculation of investment costs.

Results

Voltage deviations should not exceed 10% from the voltage level established by The State Standard [83]. The result of the voltage deviations in the system with and without SPP is summarized in the table below:

Table 11 – Results of voltage deviations reduction

Phase of day	**Single SPP**			
	Winter deviation, %		**Summer deviation, %**	
	With SPP	**Without SPP**	**With SPP**	**Without SPP**
Night	1.82	1.82	1.36	1.36
Morning	0.45	5.91	0.45	4.55
Afternoon	0.45	2.73	0.45	2.27
Evening	1.36	14.09	0.91	11.82

When the DPP is used without an SPP, then we find that the voltage level at the end of transmission line reduces by 6% and 5% in winter and summer time respectively. An auxiliary power source via SPP helps to reallocate electricity power between DPP and SPP. According to this impact of SPP, the result is a changing in the current value of the voltage at various parts of the transmission line. This integration reduces power losses in the conductors and provides greater voltage stability at the connection points of consumers of electric power.

It is necessary to add another result from the split SPP integration throughout all length of transmission line of the Tokma village. This integration consists of several small SPP with a particular number of solar panels. The number of solar panels was taken based on proportion value of each consumer's intake. When the voltage is applied, a non-zero current flows in the power line, which is directly proportional to the consumed power of the village at a certain hour. Inside the transmission line, there is a constant electric field, which drives the charges along the conductor. The electrical field of the conductor (transmission line) is always directed towards a decreasing potential, or we can say that an electric field – it is a minus of the potential gradient. The simulation results showed that the closer to the voltage source, the greater is the potential of the conductor surface. The corresponding variant with the splitting of a single SPP along the transmission line at small stations showed practically the same results as with a single SPP. This option requires more equipment and can be justified only with a positive economic analysis.

The results showed that using power from the single SPP with the battery at the rate of one half of the nominal load of the system will reduce voltage drops at the end of the line by up to 4–10%. This is achieved by connecting the SPP at a distance from DPP that is not less than half of the total length of the electrical transmission line [20]. The magnitude of the losses is significantly reduced as well. This reduction per each season is provided in the following table:

Table 12 – Results of reduction of losses in the transmission line

Season	**Reduction, %**
Winter	-7.8
Spring	-4.1
Summer	-2.8
Autumn	-5.4

The effectiveness of using the SPP in stand-alone power systems without energy storage systems is significantly limited by the operating conditions of the network inverters. To stabilize the voltage in the power system and reduce electricity losses it is advisable to use SPP with energy storage systems and connect them closer to the end of the distribution line or to the connection point of the most powerful consumer. The generation power of the SPP is limited to a half of the maximum capacity of electricity consumption [20].

According to the obtained data of reduction of losses in the transmission lines and increasing of voltage, it is necessary to provide a relevant economic model. The economic model must reflect all sides of this renewable source integration. The model should include the calculation of saved costs of fuel consumption and cost of distribution losses. The next step for extension of the model will be a calculation of project's investments, production costs, net present value (NPV). The model will include the environmental part with the dependence of CO_2 and other components emission on capacity load during the power system operation.

1.2 Cost and benefit analysis

Reduction of fuel consumption from diesel power plant

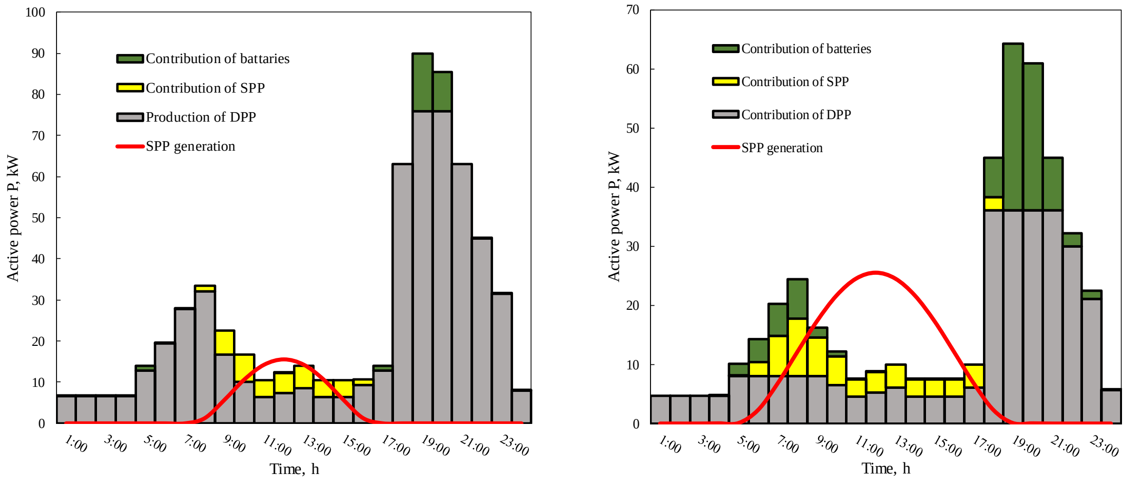
The integration of SPP into the DPP will be economically viable only if the estimated costs of RES are comparable with the cost of the saved fuel and the cost of losses. The efficiency of renewable energy installations is largely determined by the potential of the primary energy resource: the more hours the installation works in a year, the greater the savings in fuel from the DPP and the less the cost of repairs. The cost of diesel fuel, including the cost of its delivery, and the cost of maintenance and preventive maintenance of DPP, also largely determine the effectiveness of the joint work of power sources.

The absolute fuel consumption by the diesel generator for electricity supply at each i-th stage of the daily schedule is determined by the formula [1]:

$$G_1 = K_{os} \cdot G_{nom} + (1 - K_{os}) \cdot G_{nom} \cdot \frac{P_1}{P_{nom}}, \qquad (18)$$

where G_1, G_{nom} – current and nominal fuel consumption; P_1, P_{nom} – the actual and nominal power of DPP; K_{os} is a coefficient characterizing the diesel fuel consumption at open circuit mode ($K_{os} \sim 0.3$).

Based on equation (18), it is possible to determine the amount of fuel consumed during the period under consideration. It is provided via specific consumption of the diesel for the appropriate load conditions and the amount of electricity produced. This obtained information must be transformed into the energy balance graph per each season.



Source: Author’s illustration.

Figure 44 – Contribution to the energy balance by DPP, SPP, and batteries in summer time (right) and in winter time (left)

The calculations results based on simulation of diesel fuel consumption has shown that the expected volume of fuel economy is 27% and losses reduction is approximately 25% per year. Taking into account the cost of one kWh of diesel fuel as 0.26 USD (16.21 rubles), and the tariff on electricity production from DPP in the Tokma village as 0.73 USD/kWh (44.87 rubles/kWh) [84], the total cost of the saved fuel and the cost of saved energy from losses per each year will be 325 USD (19 485.93 rubles).

Mitigation of environmental pollutions

Production of energy by burning fossil fuels leads many pollutants to the environment. Indeed, all means of generating energy, including PV, create pollutants when their entire life cycle is taken into account. Life-cycle emissions result from using fossil-fuel-based energy to produce the materials for solar cells, modules, and systems, as well as directly from smelting production, and manufacturing facilities.

For that case, the emissions related to the Tokma village can be derived from a standard specific consumption of diesel needed for individual activities. Russian standard values of diesel consumption were used [85]. This standard indicates the specific emissions per one ton of consumed diesel fuel from the DPP.

The gross emission of i-component for a year by a stationary diesel unit is determined by the formula:

$$W_{emis} = \frac{1}{1000} \cdot q_{emis} \cdot G_{tot}, \tag{19}$$

where q_{emis} – ejection of i-component per one kg of diesel fuel, when a stationary diesel unit is operated, taking into account the set of regimes, G_{tot} – fuel consumption per one year by DPP. The reduction by each component of emissions is provided in the following table:

Table 13 – Results of mitigation of pollutions

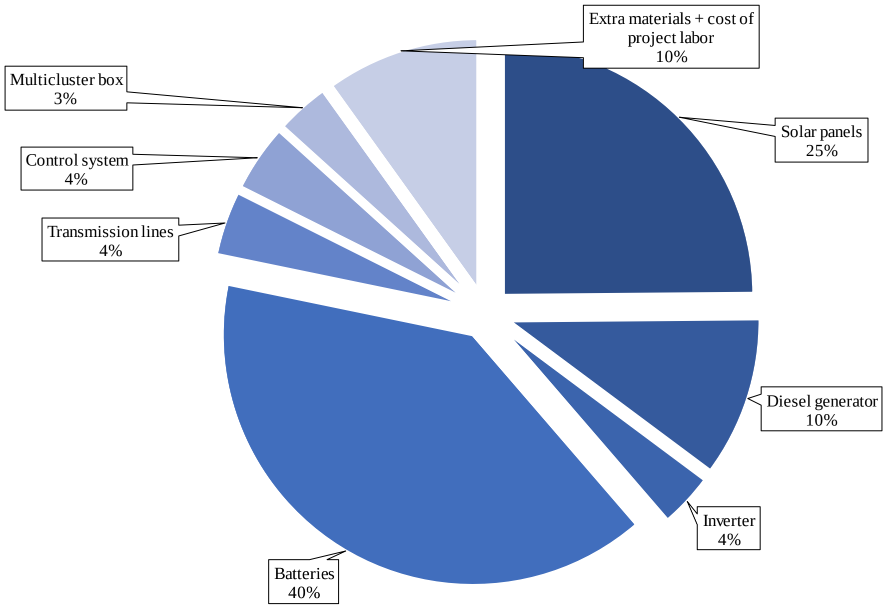
Component	**Mitigation, kg**
Carbon dioxide (CO_2)	363.9
Nitric oxide (NO_x)	414.5
Hydrocarbons (C_xH_y)	190.1
Sulfur dioxide (SO_2)	46.5
Carbon black (soot) (C)	37.9

According to Table 13, it is necessary to notice that mitigation of pollution in the environmentally protected region is pretty much enough. The integration of SPP into the SAPS causes a reduction of emissions into the atmosphere each year approx. by 3.8% respectively. In addition to the information above, we must know about direct and indirect emissions. The integration of RES into the SAPS causes not only direct effect on emission reduction according to Table 13. There is no doubt that indirect effect has not less influence, such as reduction of mining manufacturing, liquid fuels costs, transportation costs, and railway or other approaches of delivery and transfer of fuels [86]. The environmental taxes were calculated based on Russian legislation for the diesel power plants, where the price of a particular component of emission was taken per one ton of fuel consumption.

The integration of SPP into the SAPS does not have an influence of reduction of environmental tax in the economic model. This case has only one positive effect – the reduction of emissions weight from the DPP system. This result has a clear meaning, because of tax should be charged for one ton of emission and decreasing of emissions with SPP is not enough for the free-charge of tax in that case. All these mentions were used in economic model in the next subchapter.

Capital investments

The total investments, including the transportation, initial commissioning, design and survey work, operational costs, and equipment are shown in Figure 45. As for depreciation costs, the capital assets in Russia are divided into two forms: taxable and non-taxable assets [87]. The taxable assets are divided into groups, depending on the lifetime of equipment, which is defined by the specifications of the equipment [87]. The defined lifetime of the equipment is set to the time horizon of the project, which is twenty years (solar panels, diesel generators, transmission lines, and multicluster box as well). The lifetime of the batteries is set to ten years, control system and inverter is five years respectively. All these items will follow by the reinvestment according to the time horizon.



Source: Author’s illustration.

Figure 45 – Capital investments for the SPP integration

As shown in Figure 45, the main part of investment goes to installation of solar panels and batteries. However, we should take into account that diesel generators have high operational costs, due to the fuel component. The operation and maintenance costs are estimated in the next subchapter.

Depreciation

Russian legislation allows two kinds of depreciation – straight-line and accelerated [88]. Moreover, it is not appropriate to change the type of depreciation and to apply different techniques of depreciation to various units in one group of assets. Most of the capital assets are referred to the eighth depreciation group (solar panels, diesel generators, transmission lines, and multicluster box) with lifetime of around twenty years. The battery system refers to the sixth group with lifetime of around ten years, inverter and control system refer to the third group. This means that we will use the straight-line method of depreciation, as for the assets of the eighth group by the following equation:

$$\begin{cases} Depreciation_{year}^{1'st} = \dfrac{Investment}{2 \cdot T - 1} \\ Depreciation_{year}^{n'th} = \dfrac{2 \cdot Investment}{2 \cdot T - 1} \end{cases}, \tag{20}$$

where *Investment* – the total amount of money, which is required for the SPP integration into the SAPS (USD 140 285), *T* – useful life for each item of investment depending on a group of depreciation.

Operational, maintenance, and other fixed costs

According to the producer of solar panel TSM–200, each year of operation period the solar panel will lose by 0.5%–1% from electricity production [69]. This guarantees the buyer that in 20–25 years his solar installation will produce 80–85% of the installed capacity for the year of production. And even after this 20-year service life, the solar panel will not fail immediately. It will continue to work for decades, but with slightly worse performance characteristics. For the estimated lifetime of solar cells, you are likely to change two, and even three inverters.

This degradation factor fact is already included in the economic model. A yearly maintenance of solar panels includes: checking the state of solar panels, contacts and insulation of the solar cable connection, testing and cleaning the inverter from dust, inspection of fastening systems for corrosion or loose bolted connections, checking the efficiency of grounding, and cleaning the surface of solar panel from dirt and snow. The maintenance cost for solar panels was taken as 2% from solar panels investment per each year.

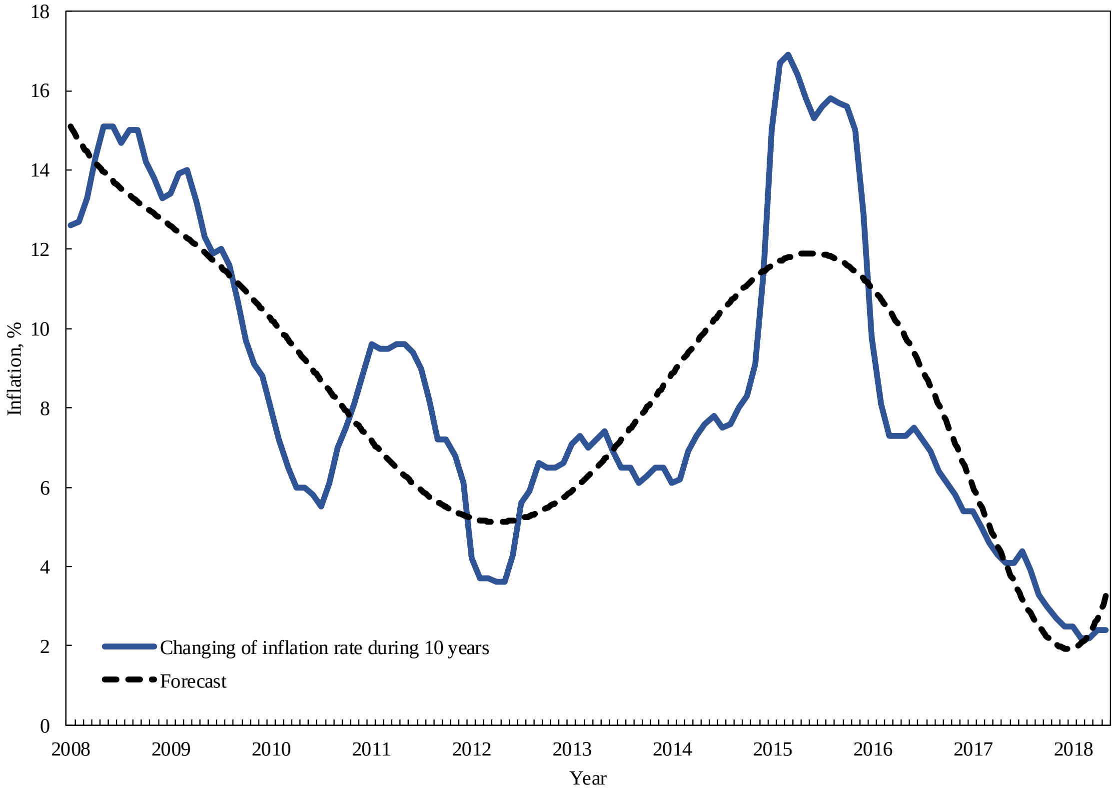
The maintenance of batteries is used as 1.5% from an investment of them biennially. For the diesel generator, the yearly maintenance is estimated to the 5% of its cost [89]. We should also consider the main operational cost – the yearly price of fuel for the diesel generator.

To find the amount of fuel, we modeled the system for all seasons and got the amount of fuel consumed. For winter season the consumed fuel is 15.6 tons by diesel generators without SPP (with SPP is 12.95 tons). For summer season the consumed fuel is 5.42 tons without SPP (with SPP is 2.8 tons). The price for the fuel is estimated to USD 0.26. The total expenses for the fuel are therefore USD 55 602 annually with an escalation growth.

The wages are set to the typical value for the branch of industry [90] for the personnel of 2 people – USD 15 382 annually. Rent and taxes include the payment for the land, paid to the administration of the region and taxes, excluding profit tax. These payments are set to USD 2 030.

Inflation and (de-) escalation rates

To provide validity result in the economic model, we need to define the rates. These rates are used to increase the cash flows over the project horizon period. Rent and taxes are expected to grow approximately with the rate of inflation, which is shown in Figure 46 – the current rate of which is 2.4% (is the rate for electricity) [91].



Source: Author’s illustration.

Figure 46 – Yearly inflation rate in Russia

The analysis of statistical sources and the reports of Trading Economics global macro models and analysts expectations [91] are expecting to have the inflation at this rate 4.1% due to the difficult economic situation in the world, which restricts the price for main export of Russia in the long-term operating projects. The rate for the growth of wages is usually said to be slightly faster than the rate of inflation. In the long-term, the Russia Real Wage Growth is projected to trend around 5% in 2020, according to our econometric.

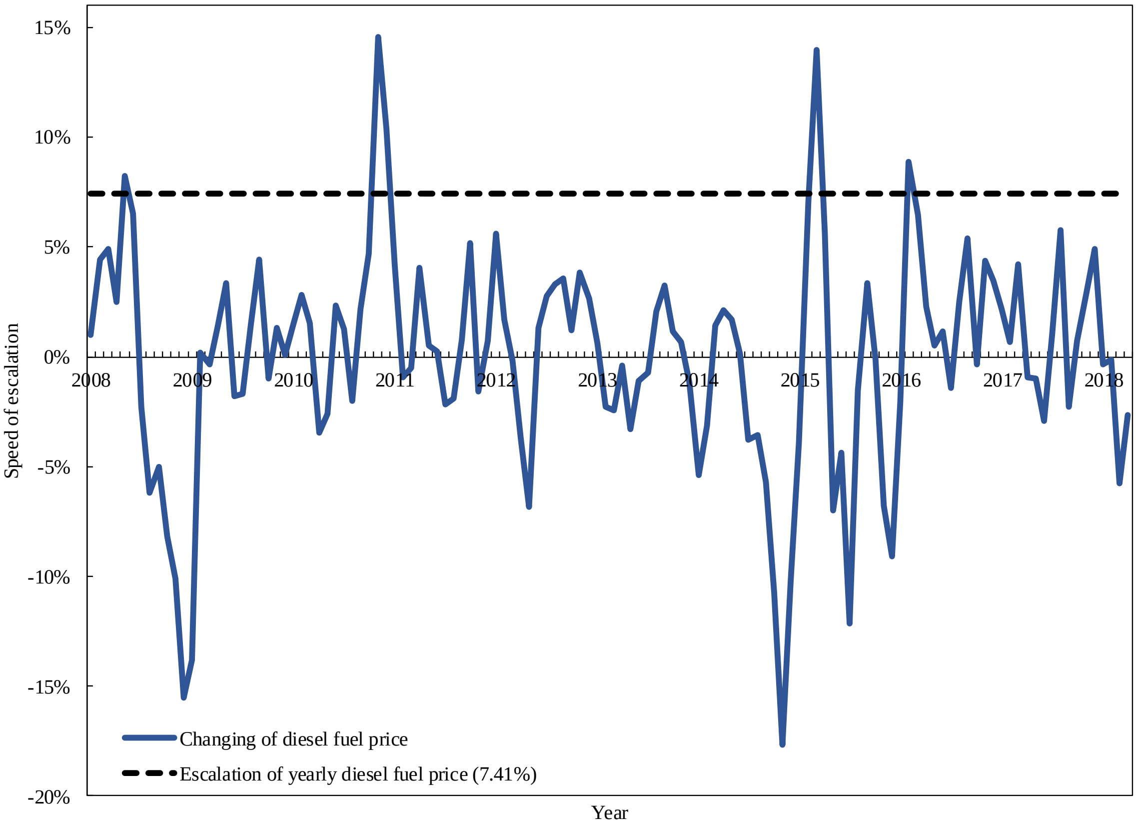
The changing of the diesel fuel price is a hardly predictable parameter (see Figure 47). The important fact that the biggest part of its price depends on the transportation to the region (Irkutsk region in our case). Analyzing the data provided by Russian Economic School (Rossiyskaya Ekonomicheskaya Shkola), we set the escalation rate for the fuel to 7.41%. This value was obtained based on ten-years observation per each month and formalized into the following equation:

$$g_{feuel} = \left(\frac{P_1}{P_2}\right)^{\left(\frac{1}{T-1}\right)} - 1, \tag{21}$$

where g_{fuel} – monthly rate of increase in the price of diesel fuel, P_1, P_2 – an indicator of the current period and base period indicator, T – number of periods.

According to the equation (21), we can estimate a yearly escalation of diesel fuel price:

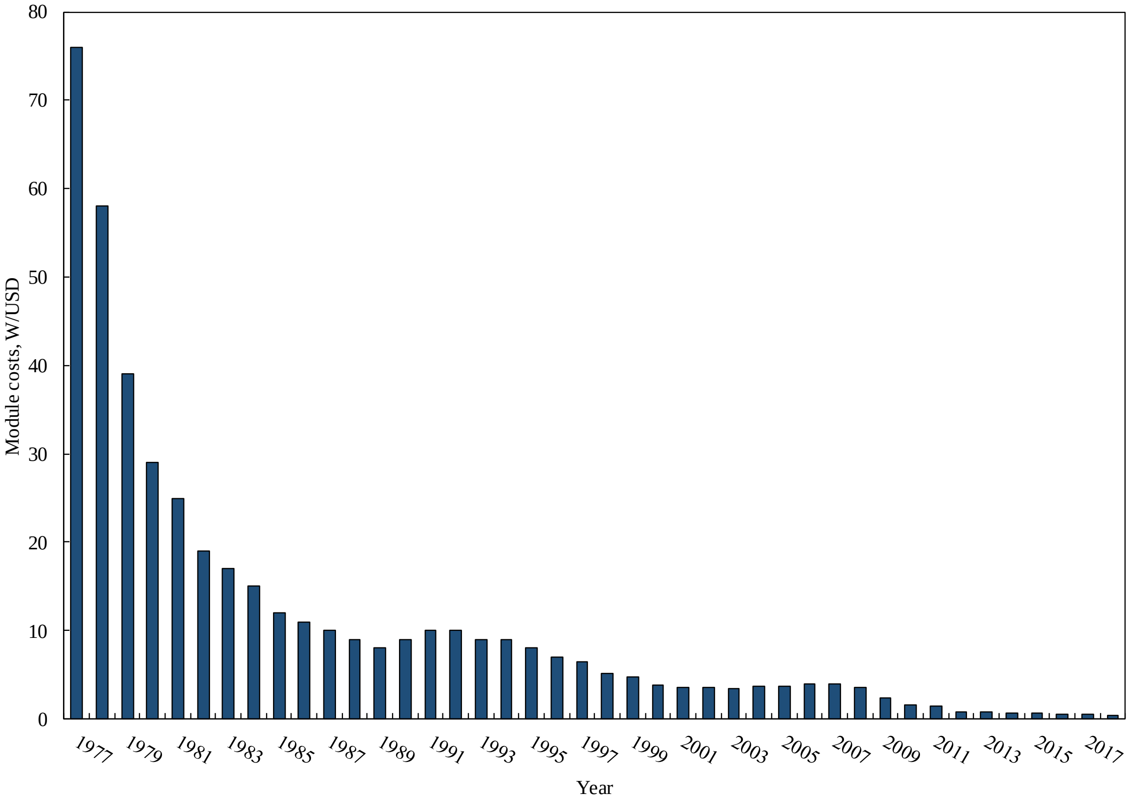
$$(1 + g_{fuel})^{12} - 1. \tag{22}$$



Source: Author’s illustration.

Figure 47 – Changing of diesel fuel price in Russia from 2008 to 2018 per each month

The progress in PV systems has also been noteworthy. Recent technical developments and reductions in the costs of all major categories of solar energy technologies have been significant. First, historical costs are shown in Figure 48. In the early 1970s, the costs of PV modules were several hundred thousand USD per peak kilowatt, and applications were largely confined to aerospace and other specialized uses. By the early 1980s costs had fallen tenfold to around USD 25 000 to USD 50 000/kWp, and by 1990 to USD 6 000/kWp, and PVs had become commercially viable for a full range of small-scale users (especially for the decentralized supply systems) [92].

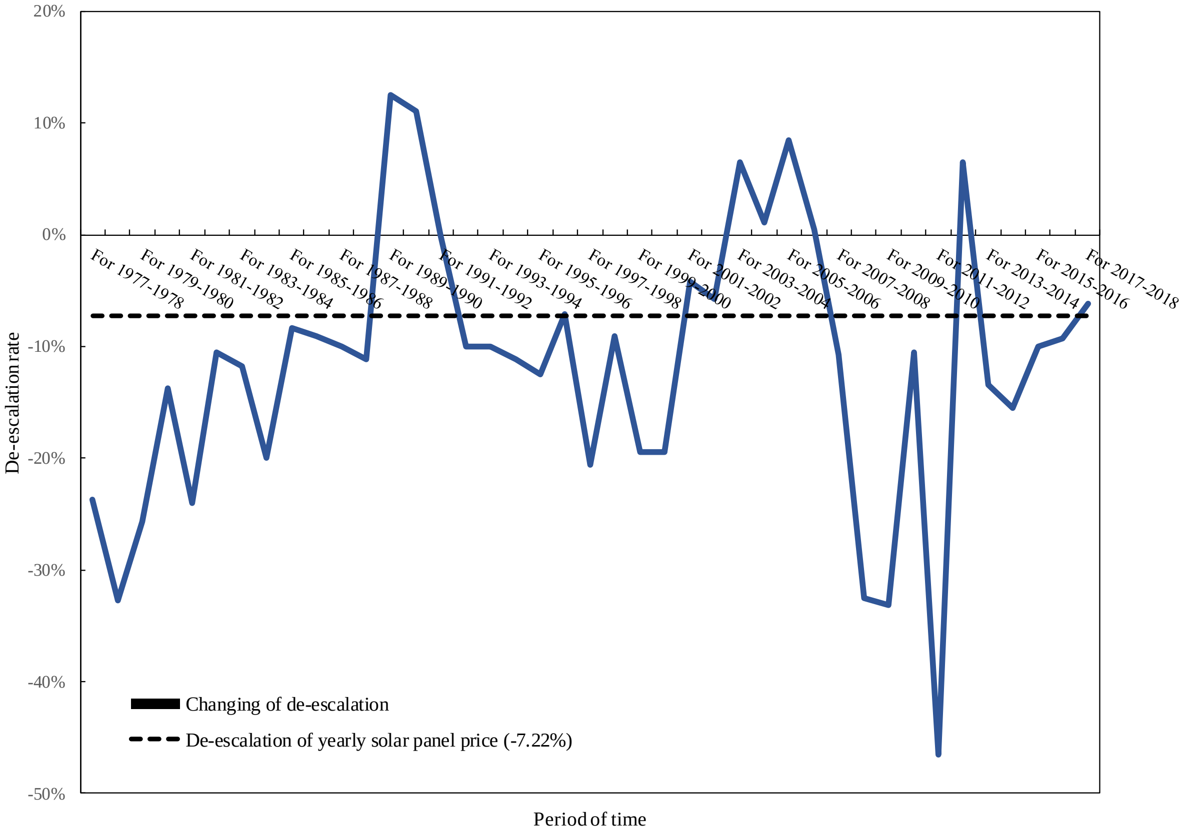


Source: Author’s illustration.

Figure 48 – Photovoltaic module costs from 1976 to 2017 [92]

Based on that aggregate data, we can define the de-escalation growth. The critical remark must be informed in our case. It is about the decades of observing periods. There is no doubt that solar energy systems are pretty new technologies, which progress is moving very fast. We need to consider a fact of PV modules prices for a relevant period of our economic model. Only last seven years can be chosen for the observation. This observation period has a shape of the curve, which is close to flat form, it will defend our model from the previous prices drops. According to that assumption, we will get a valid de-escalation growth during the last decade with a temporary dependent level of solar panel prices.

The same principle of solar panels price de-escalation is used. For our case, we took a period between 2018 and 2017. Calculation of de-escalation solar panel price by equations (21) and (22) have got value -7.22% annually. All changes are presented in Figure 49 with the estimated de-escalation rate for solar panel price.



Source: Author’s illustration.

Figure 49 – Changing of solar panel price from 1977 to 2018

The developments during the past century in solar technologies were much stimulated by high oil prices in the period of 1973–1985 and attracted the interest of several major companies. The collapse of oil prices in the mid-1980s led some companies to scale back their investments plans, and in some cases even to shelve them, but those that continued their programs reduced costs by amounts comparable with the fall in oil prices. Thus, as real oil prices fell by 75% between 1980 and 1992 (from USD 60 to under USD 20 per barrel), those of PV modules fell by roughly 80% respectively [92, 100].

The consumption in the village will be constant. This assumption was taken from the population growth data [38]. During the five years, the population has not been changing. It is necessary to say that no additional industry is planned in the region. The profit of the company is calculated at corporate tax level of 20%. From 2017 to 2020, 3% is credited to the federal budget, 17% – to the budget of the constituent entity of Russia.

Capital assets pricing model

To estimate the discount rate for the SPP integration project, we use capital assets pricing model (CAPM). It needs three main inputs: risk-free rate, market risk premium, and beta coefficient as well. It is expected to be a municipal activity, where a primary aim is the implementation of hybrid power supply system but not the profit generation. That is why we assume a significantly lower discount rate than a discount rate of 11% from market-based decision making [92].

1. For the risk-free rate we use the national bonds of Russia [93], which are currently yielding to 5.5% for Russia-2043 bonds.
2. For the market risk premium, we use the research, made by STATISTA [94] – average market risk premium in Russia from 2011 to 2016. It is estimated that the market risk premium for Russia is around 7.9%.
3. For the beta for Power industry we use the data of Moscow Exchange (MOEX) [95]. We choose unlevered beta in Russia for the power industry and get beta of 0.89.

The rate of return is described by the following equation:

$$r_{CAPM} = r_f + \beta \cdot (r_m - r_f) = 5.5 + 0.89 \cdot (7.9 - 5.5) = 7.6\% . \qquad (23)$$

Accumulating all of the given data, we create an Excel economic model of the project, which we will use to calculate the efficiency of the investment and mainly, the investment in distributed PV system.

1.3 Financial model

Investment criteria

Economic models for the estimation of the possible future influence on the price are based on cash flow (CF) analysis of the projects focused on the production from SAPS with distributed PV system. Such economic models must reflect all necessary process and whole project cycle, the market prices of individual inputs, expected SPP yields and the opportunity cost including proper time value of money [86]. The investment criteria show the effectiveness of the investment. We will use standard investment criteria such as net present value (NPV), discounted payback period, and internal rate of return (IRR).

The economic model in our case applies the rate of return approach based on CAPM model. It means that we need to use an NPV analysis. An investor will accept an entrepreneurial project only if the project NPV if greater or, at least, equal to zero. NPV equal to zero means that an investor gets the same rate of return as in case of other possible alternative investments – and thus the NPV equal to zero represents the boundary for the project acceptance.

A standard financial model of the projects is based on an NPV evaluation of the project inputs. But an NPV formula can be applied in reverse order, for instance, to set NPV of the project to zero (it is an IRR definition) and then to find the reduction of electricity price for the Tokma village. This price represents a benefit from distributed PV integration (decrease in fuel costs, reduction of transmission losses, etc.).

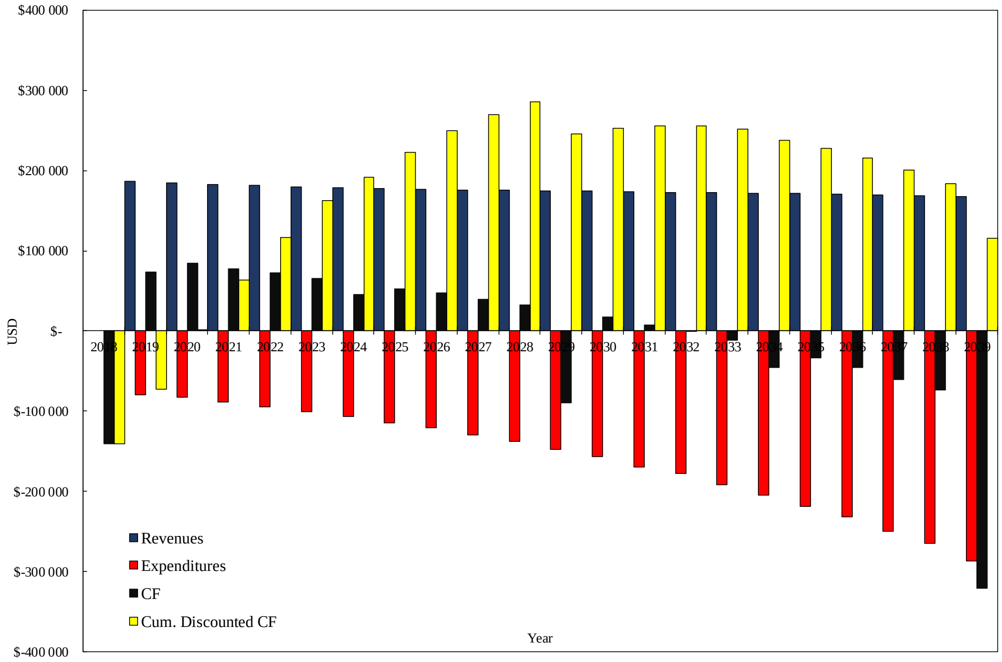
The equation for the price of electricity in Tokma village calculation is presented from the NPV equation:

$$NPV = \sum_{t=1}^{T} CF_t \cdot (1 + r_{CAPM})^{-t} = \sum_{t=1}^{T} \left(p_{new,t} \cdot Q_t + S_t - E_t \right) \cdot (1 + IRR)^{-t} = 0, \qquad (24)$$

where t – year of project realization, r_{CAPM} – discount rate, which is calculated from CAPM model, $p_{new,\,t}$ – a new price of electricity for the Tokma village in year t [USD/kWh], CF_t – cash flow of the project in year t [USD], Q_t – amount of energy is consumed by the Tokma village [kWh/year], S_t – benefits from the SPP integration (subsidy, reduction of fuel costs, reduction of transmission losses) [USD], E_t – project expenditures in year t [USD], T – project lifetime [years].

The estimated NPV for the project is around USD 115 494. This estimation is somewhat vague, because of the stochastic behavior of many input parameters, but gives us essential investment information that investment in this project is profitable as NPV is greater than zero. However, the price used to sell electricity is exceptionally high, because we use the amount taken from the case without SPP integration.

To find a new price for electricity, we use Excel Solver analysis. We set a cell with the value of NPV to zero and change the amount of cost for electricity. This way we show, what is the price, which we can offer to the customers, satisfying the rate of return asked by investors. The results of analysis give us a new amount for the Tokma village inhabitance of USD 0.66 per kWh. This price is still higher than the price for the customers, connected to the grid. Nevertheless, integration of distributed PV system into SAPS is gave decreasing of the price around 8.4%, especially for the transportation fuel costs. It means that the total economy for the customers for the year 2019 will be over USD 13 692, which is a very impressive result.



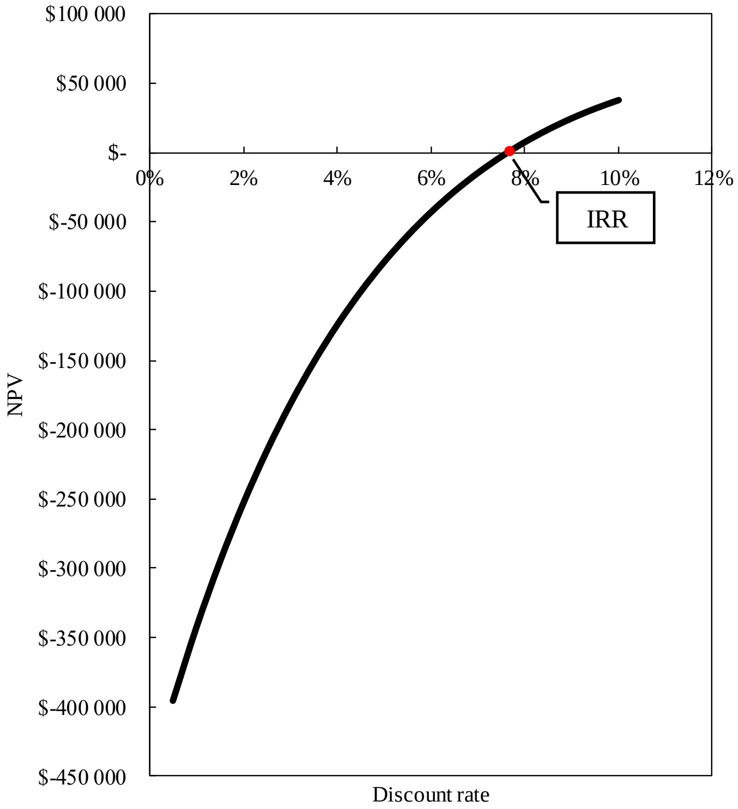
Source: Author's illustration.

Figure 50 – Expenditures, revenues, cash flow and cumulated cash flow distribution during the lifetime

Discounted payback period is a capital budgeting procedure used to determine the profitability of a project [96]. In contrast to an NPV analysis, which provides the overall monetary value of the project, a discounted payback period gives the number of years, which takes to break even from undertaking the initial expenditure. This procedure is similar to a payback period, but the payback period only measures how long it takes for the initial cash outflow to be paid back, ignoring the time value of money. For the base price of electricity, the discounted payback period is only around three and half years, which proofs the profitableness of the project.

Sensitivity analysis of the investment

The sensitivity analysis of the project allows us to estimate how the resulting indicators of the project implementation, for instance, NPV, IRR, are changing for different values of the specified variables required for the calculation. This type of analysis allows us to identify the most critical variables that can have the most significant impact on the feasibility and effectiveness of the project. This is especially important in planning for such a long lifetime project. Some of the parameters may change considerably during the lifetime of the project, and we should be aware of evaluating these changes.



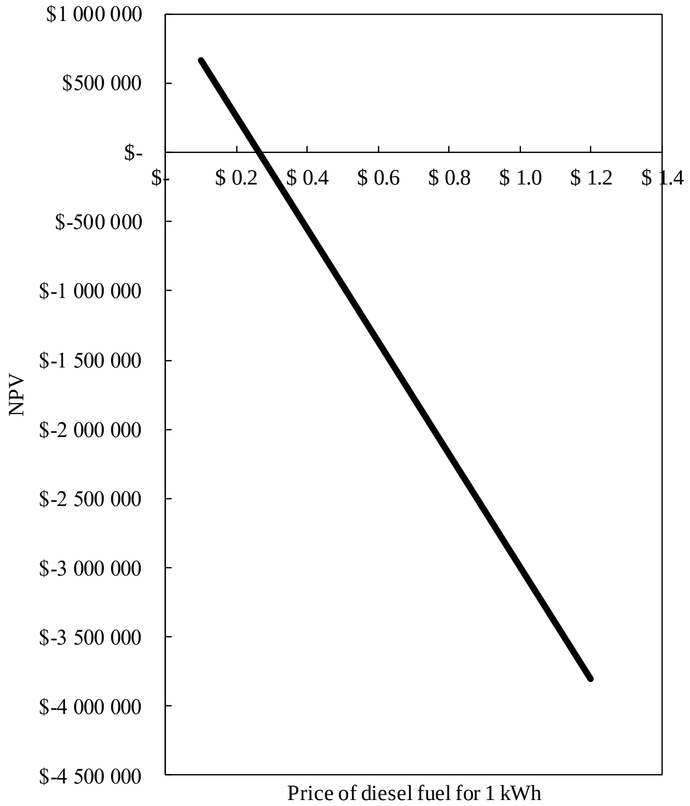
Source: Author’s illustration.

Figure 51 – The dependency of NPV and discount rate

The discount rate is one of the most critical factors. If this project will be treated as to provide the minimum possible price of electricity, the discount rate is the only way of satisfying the needs of investors. Therefore, we should carefully define the discount rate and the internal rate of return. As we are now calculating the price of electricity equal USD 0.66, the internal rate of return will be very close to the used discount rate, which is defined by CAPM model. To increase it, we need to raise the price of electricity, as it is the only one positive cash flow in the operation of the project. The dependence of NPV on the discount rate is presented in Figure 51, where we can see the value of IRR – an intersection of a curve with the horizontal ax.

Figure 51 showed that each raising of a discount rate, NPV is gaining monetary value. Discounting is the process of determining the present value of a payment or a stream of payments that is to be received in the future. As Ivo Welch mentioned about the time value of money, a dollar is worth more today than it would be worth tomorrow [97]. NPV and project's profit increase significantly with the increase of discount rate. This dependency is correlating with an escalation rate of fuel price. The point is that the bigger the price of fuel will raise the greater benefits a project will get from that. This sentence could be interpreted in another meaning. Already obtained escalation growth rate of diesel price fuel 7.41% gives us the flexibility of changing in price value. The shape of a curve in Figure 51 has an investor behavior.

Figure 52 shows how the price of diesel fuel from DPP influence on project performance:



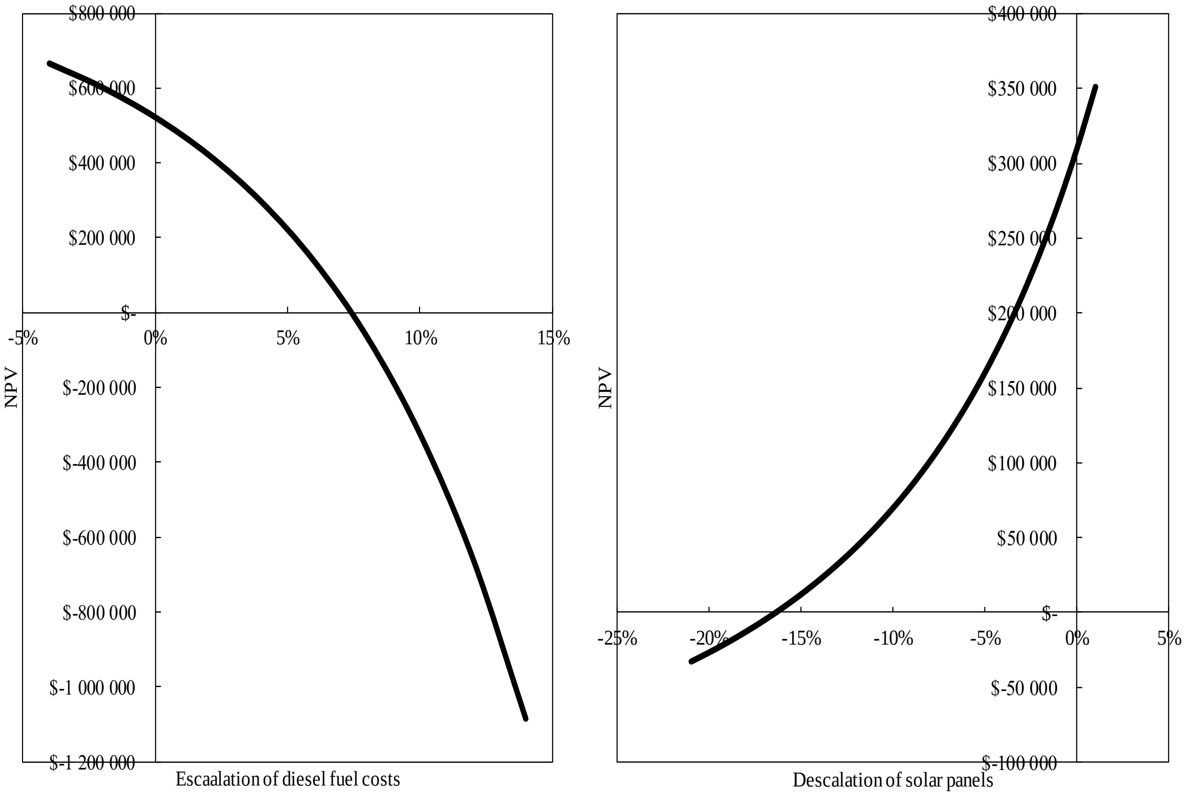
Source: Author's illustration.

Figure 52 – The dependency of NPV and price of diesel fuel

Currently, the electricity supply in the region is provided by the diesel generator. One of the reasons, why it is so expensive is a high cost of fuel and especially the transportation costs.

We can see how it is expensive and how it is significantly affecting NPV result in the Tokma village.

According to Figure 52, there is a specific influence of fuel price on the NPV of the project. However, the distributed PV hybrid system is designed to minimize the dependency on the fuel. The SPP generates the high share of the energy, and in the case of much higher demand, we can increase the area of SPP. That will be our benefit of flexibilities from SPP integration.



Source: Author’s illustration.

Figure 53 – The dependency of NPV and escalation of diesel fuel costs (left), de-escalation of solar panels (right)

Figure 53 shows the interesting correlation. Cost escalation is defined as changes in the cost or price of specific goods or services in a given economy over a period. This is similar to the concepts of inflation and deflation except that escalation is particular to an item or class of objects, it is often not primarily driven by changes in the money supply, and it tends to be less sustained. While escalation includes general inflation related to the money supply, it is also driven by changes in technology, practices, and particularly supply-demand imbalances that are specific to a good or service in a given economy. The more escalation then less will be an NPV in our case because this escalation has a positive sign and has expenditure meaning for the CF.

The yearly energy consumption for the Tokma village is 195.1 MWh. With old equipment, the cost for 1 kWh produced was USD 0.73. Based on SPP integration, taking into account the investment costs and a life expectancy of a project equal to twenty years, the cost of fuel, transportation, and transmission losses are decreased by approximately 8%. This result also helps to evaluate of yearly subsidies needed to provide electricity for the customers for the price of a tariff. The government will pay this amount, but this amount will be decreasing by a yearly drop of solar panels price. Based on that benefit, this project will get a high possibility to attract administration of the region as an investor.

CONCLUSION

The problem of energy supply for the decentralized consumers is a nonlinear and multi-criteria function, especially for SAPS. There are not only technical, but also economic, social, and environmental constraints as well. This work combines those features and comprises an in-depth technical analysis with extensive and relevant economic evaluation. According to Energy Strategy of Russia for the period until 2035 [8], we compare all possible options of supplying electricity in the rural settlement – the Tokma village.

In the first chapter we provide a general description of the meaning of DG, literature review related on DG, as well as an international experience on the examples of Germany, the USA, China, and the Czech Republic. Also, we explain the state of DG in Russia. Aggregate results of this part have an interesting description. Based on legislation level in countries, which were presented above, all of them have a link between government and RES owners. The programs of reliable incentives, state support combined with relatively high retail trade trends, progressive and adaptable technology to produce renewable energy sources, brought the United States and Germany to the leading positions with respect to the installed capacity of distributed PV generation. This growth, as well as the development of storage accumulators, the rise of the electric vehicle market and other technologies of distributed energy, also led to several successful government's acts that provoked a number of proposals and implementations of RES projects.

In Russia, despite growing rates of construction of DG facilities, the process of focusing government's forces does not find a clear place in the long-term planning of the power supply system. There is still no understanding of the contribution that DG could make to improve development of the system and its modernization, and there is no developed state policy on this case. Therefore, one of the possible areas for improving efficient use and reducing energy consumption from a DPP as well as transmission losses from decentralized settlements is distributed PV system.

In the second chapter we present a structure of a hybrid stand-alone power system in MatLab. There we provide a general description of equipment, which was used for modeling transitional processes. The simulation results include the cases of a single SPP and distributed installation designs. The issues of electricity quality and power transmission losses of rural networks in Russia were discussed there as well. These results are compared with the case of SAPS without RES.

When the DPP is used without an SPP, then we find that the voltage level at the end of transmission line reduces by 6% and 5% in winter and summer time respectively. An auxiliary power source via SPP helps to reallocate electricity power between DPP and SPP. Based on the impact of SPP, we suggest changing the current value of the voltage at various parts of the transmission line. This integration reduces power losses in the conductors and provides greater voltage stability at the connection points of consumers of electric power. The results show that using power from the single SPP with the battery at the rate of one half of the nominal load of the system will reduce voltage drops at the end of the line by up to 4–10%. This is achieved by connecting the SPP at a distance from DPP that is not less than half of the total length of the electrical transmission line. The effectiveness of using the

SPP in stand-alone power systems without energy storage systems is significantly limited by the operating conditions of the network inverters. In order to stabilize the voltage in the power system and reduce electricity losses it is advisable to use SPP with energy storage systems and connect them closer to the end of the distribution line or to the connection point of the largest consumer. It is necessary to say that it would be interesting to conduct a more in-depth study and, therefore, to attract funding and sources for this purpose. Nevertheless, we discuss possible causes of long-term changes in the state of the Tokma village.

In the third chapter we present an economic model, which reflects all aspects of integrating renewable sources. The model includes the calculation of saved costs of fuel consumption and cost of distribution losses. The estimates of project's investments, production costs, NPV approach are considered as well. The model includes the environmental part with the dependence on CO_2 and other emission components on capacity load during the power system operation.

The annual energy consumption in the Tokma village is 195.1 MWh. The calculation results based on simulation of diesel fuel consumption show that the expected volume of fuel economy is about 27% and loss reduction is approximately 25% per year. Taking into account the cost of one kWh of diesel fuel as 0.26 USD (16.21 rubles), and the tariff on electricity production from DPP in the Tokma village as 0.73 USD/kWh (44.87 rubles/kWh) [84], the total amount of saved fuel and decreased transmission losses per year will be 325 USD (19 485.93 rubles). Based on SPP integration, taking into account the investment costs and a life expectancy of a project equal to twenty years, the cost of fuel, transportation, and transmission losses are decreased by approximately 8% for the final tariff (41.11 rubles/kWh or 0.66 USD/kWh). The integration of SPP into the SAPS causes a reduction of emissions into the atmosphere each year approx. by 3.8%. The integration of SPP into the SAPS does not have an influence on reduction of environmental tax in the economic model. This case has only one positive effect – the reduction of emissions weight from the DPP system. All these data were obtained with well-known financial tools such as escalation and de-escalation growth rates, inflation rate, as well as usage of discounted payback period.

Our methodology could be applied to other projects in the Irkutsk region. Even though the research in the area is extensive, this work is one of the several examples of full evaluation for Siberian electricity supply issues. The proposed hybrid for energy supply in the Tokma village shows good technical (consumption of fuel, hybrid start-ups, use of storage device) and economical (NPV, IRR) results. Potential benefits of using a hybrid power supply system could be the efficient use of energy storage device, SPP integration and its configuration in SAPS, which are useful for the decentralized areas.

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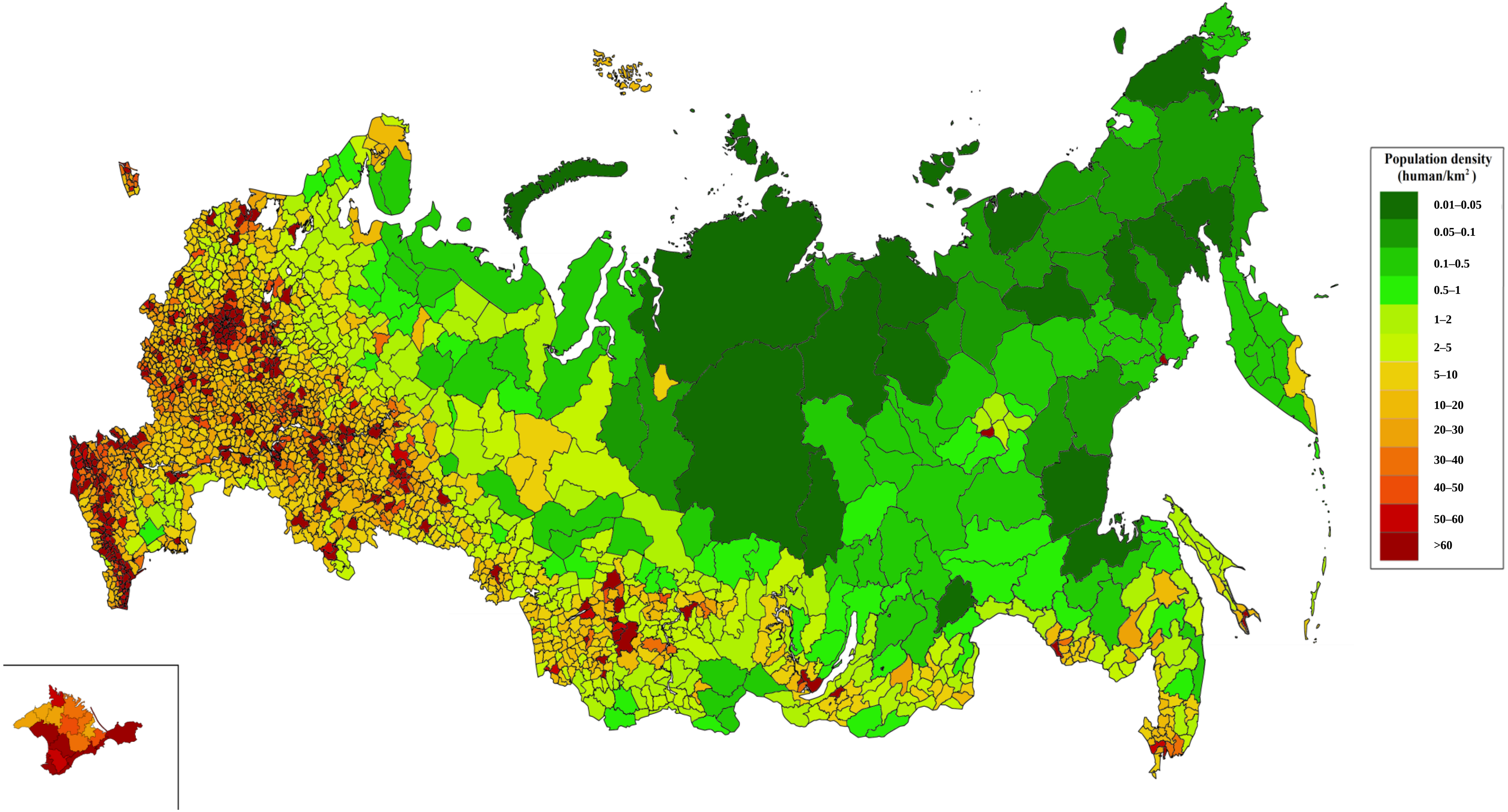
APPENDICES

A Figures

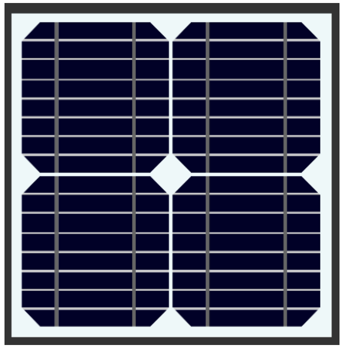
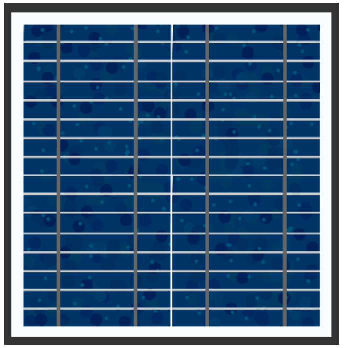
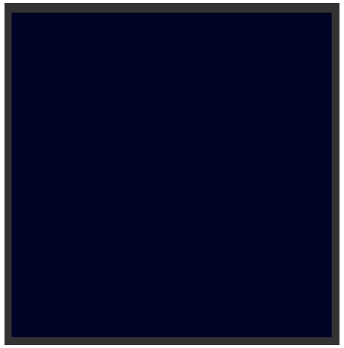
A.1 – Map of density population in Russia in 2017 [98]



A.2 – Map of centralized electricity supply system in Russia [99]

B Tables

B.1 – Techno-economic analysis of solar panel types [68–71]

Design	 Monocrystalline solar panel	 Polycrystalline solar panel	 Thin film solar panel
Efficiency	15%–22%	13%–18%	9%–11%
Temperature resistance	Performance drops 10–15% at high temperatures	Less temperature resistant than monocrystalline	Tolerates extreme heat
Life time	25–30 years	20–25 years	15–20 years
Length of warranty	25 years	25 years	10–25 years
Lowest price	0.75 USD/W	0.62 USD/W	0.69 USD/W
Area required for 1 kWp	6–9 m^2	8–9 m^2	13–20 m^2
Additional details	Oldest cell technology and most widely used	Less silicon waste in the production process	Tend to degrade faster than crystalline-based solar panels. Low availability on the market

Note: *Monocrystalline* solar cells are made from crystalline silicon wafers, which are cut from a single crystal. This single crystal has been specially grown via the Czochralski method. It has the highest purity, is presented in the market by dark and uniform design. This panels usually has a distinct feature of rounded edges as four sides are cut off from a crystal ingot to form it up like a uniform wafer. *Polycrystalline* silicon, which is easier to manufacture and therefore lower in cost, is also used, although the energy conversion efficiency of the resulting solar cells is less than that of monocrystalline panels. Instead of the circular silicon wafers, polycrystalline panels are generally square or rectangular, but the substrate is made of small pieces of silicon. The Czochralski method is not used for polycrystalline panels. Also, of growing interest is *thin-film technology*. The process uses an automated production line to apply a thin solar coating to rolls of flexible foil, using amorphous silicon – far cheaper than the crystalline silicon now used – as the substrate. Unlike the rigid panels, thin-film PV can be used to coat curved or irregular surfaces. Both polycrystalline and thin-film PV are less efficient at converting light into electricity than monocrystalline panels, but their lower cost and greater flexibility make them suitable for many different types of installation. Obvious areas for their use are in atriums, on louvres and in cladding. There is an obvious trade-off between cost of production and efficiency of conversion of solar radiation into electricity, and this is an area which is under very active development.