Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Economics, Management and Humanities

Residential building power supply with renewable energy sources

MASTER THESIS

Study program: Electrical Engineering, Power Engineering and Management
Branch of study/Specialization: Management of Power Engineering and Electrotechnics
Scientific supervisor: Ing. Bc. Blanka Kučerková

Anton Makarov

Prague 2020

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Makarov Anton** Personal ID number: **492119**

Faculty / Institute: **Faculty of Electrical Engineering**

Department / Institute: **Department of Economics, Management and Humanities**

Study program: **Electrical Engineering, Power Engineering and Management**

Specialisation: **Management of Power Engineering and Electrotechnics**

II. Master's thesis details

Master's thesis title in English:

Residential Building Power Supply with Renewable Energy Sources

Master's thesis title in Czech:

Residential Building Power Supply with Renewable Energy Sources

Guidelines:

- Describe environmental background of the chosen region
- Describe and compare proposed power supply systems
- Prepare mathematical simulation and financial model for project evaluation
- Provide technical and economic evaluation and sensitivity analysis
- Find optimal solution of the issue and make conclusion

Bibliography / sources:

1. Brealey, Myers, Allen – Principles of Corporate Finance, McGraw-Hill, 2016, 12th edition, ISBN:9781259253331
2. Sistemy elektrosnabzheniya s vetrovymi i solnechnymi elektrostanciyami: uchebnoe posobie/ B.V. Lukutin, I.O. Muravlev, I.A. Plotnikov – Tomsk: Izd-vo Tomskogo politekhnicheskogo universiteta, 2015.

Name and workplace of master's thesis supervisor:

Ing. Bc. Blanka Kučerková, Department of Economics, Management and Humanities, FEE

Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **13.01.2020** Deadline for master's thesis submission: **22.05.2020**

Assignment valid until: **30.09.2021**

Ing. Bc. Blanka Kučerková Supervisor's signature	Head of department's signature	prof. Mgr. Petr Páta, Ph.D. Dean's signature

III. Assignment receipt

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

.

Date of assignment receipt Student's signature

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".

May 2020 *Anton Makarov*

Abstract

Current research is focused on economic estimation of renewable energy efficiency in regions with low wind potential. The problem is that in some regions, such as Russian Federation, using of renewable energy sources are less than 1% and all produced electricity are generating by fossil fuels, because of specific environment. Because of this reason, there are few additional problems, such as exhaustibility of the resources, electricity price strongly dependent on resources price and environmental pollution.

The main purpose is to find an economically effective way to use renewable energy sources in specific regions. My thesis is based on example of residential building in Tomsk region, supplied with electricity using renewable energy.

In my diploma thesis I considered 5 different combination of electric supply and their estimated balance of energy consumption and generation by different power sources. In order to obtain the most relevant results, I these scenarios with different type of financing and evaluated them from technical, economical and customer point of view.

Keywords

Renewable energy sources, alternative energy, wind generator, PV cells, gasoline generator, cottage power supply, wind potential, solar potential, energy balance, economic evaluation, sensitivity analysis, managerial decision making.

Contents

List of abbreviations

AC	Alternating Current
ATS	Automatic Transfer Switch
AU	Astronomical Unit
CSP	Concentrated Solar Power
DC	Direct Current
DCF	Discounted Cash Flow
HPP	Hydraulic Power Plant
IEA	International Energy Agency
IEPP	Industrial Enterprises Power Plant
IES	Integrated Energy System
IRENA	International Renewable Energy Agency
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
NPP	Nuclear Power Plant
NPV	Net Present Value
PV	Photovoltaic
RES	Renewable Energy Sources
RPM	Rotations Per Minute
SPP	Solar Power Plant
TPP	Thermal Power Plant
UES	Unified Energy System
WPP	Wind Power Plant

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Introduction

Nowadays one of the most urgent issues is electric power supply. In our modern world dominates the use of exhaustible energy sources. They possess higher efficiency than renewable sources, however electric power consumption increases on daily basis. Problem of energy exhaustion is unavoidable and should be solved sooner or later, because humanity cannot abandon use electrical power. Therefore, exhaustion problem becomes more valuable. Especially this issue is relevant in the regions that unavailable to supply with power network. Because only option to supply with electrical power there is to use independent generators, however prices for the fuel are growing on daily basis, but renewable energy become more and more accessible.

The main purpose is to find an economically effective way to use renewable energy sources in specific regions. Experience of other countries shows that every year the use of renewable energy sources become more efficient, and the energy they generate become more accessible. In my research I will design and analyze wind and solar power supply systems in the low wind regions on the Tomsk sample. Tomsk is a significant pattern with low wind potential and average number of sunny days no more than 150 per year. Additionally, renewable energy sources allow us decrease level of environmental pollution and improve ecological situation due to the fact that replacement of thermal power plants with renewable will reduce amount of carbon dioxide that humanity produce.

My work consists of four main parts. The first one is analytic part, including review of current condition in the field of renewables, environmental analysis for creation of power supply systems, and analysis of current condition of the electric power industry in Russia. It includes estimation of solar and wind potential in Tomsk region, review of the electricity prices on the market, estimate and analyze all possible options house electrical supply. The second part is descriptive, which is about description of the consumer and equipment. There I have included typical equipment that customer will use in his house and equipment that will supply these house and detailed description of the equipment. The third part is a mathematical simulation and economic estimation. The last part of my work is about final decision making and a conclusion. These parts, that I provided here, are not the exact chapters, but it is the way, that I tried to follow.

1. Review of the current condition in the field of renewables

Renewable energy is at the center of the transition to a less carbon-intensive and more sustainable energy system. Renewables have grown rapidly in recent years, accompanied by sharp cost reductions for solar photovoltaics and wind power in particular. The electricity sector remains the brightest spot for renewables with the exponential growth of solar photovoltaics and wind in recent years, and building on the significant contribution of hydropower generation. But, electricity accounts for only a fifth of global energy consumption, and the role of renewables in the transportation and heating sectors remains critical to the energy transition. [1]

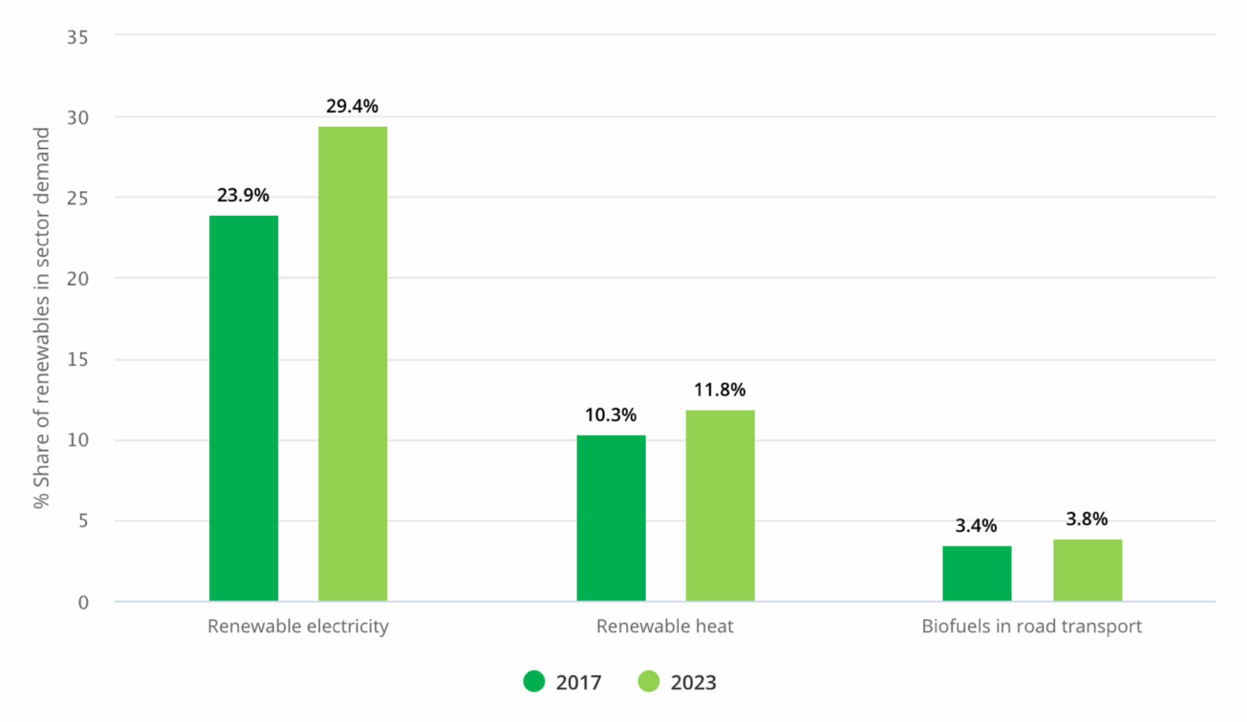

Figure 1. Shares of renewables in electricity heat and transport 2017 and 2023. [1]

In the Renewables 2018 forecasts, the share of renewables in meeting global energy demand is expected to grow by one-fifth in the next five years to reach 12.4% in 2023.

Renewables will have the fastest growth in the electricity sector, providing almost 30% of power demand in 2023, up from 24% in 2017. During this period, renewables are forecast to meet more than 70% of global electricity generation growth, led by solar PV and followed by wind, hydropower, and bioenergy. A modest increase in the share of renewable heat is foreseen, as robust growth in total heat demand is expected to result from continuous economic and population growth. Renewables in transport have the lowest contribution of all three sectors, with their share growing only minimally from 3.4% in 2017 to 3.8% in 2023. Although they expand by almost one-fifth over the forecast period, renewables cover only a small portion of all energy demand in transport because of ongoing petroleum product consumption. [1]

Wind energy

Wind power is one of the fastest-growing renewable energy technologies. Usage is on the rise worldwide, in part because costs are falling. Global installed wind-generation capacity onshore and offshore has increased by a factor of almost 75 in the past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 564 GW by 2018, according to IRENA's latest data. Production of wind electricity doubled between 2009 and 2013, and in 2016 wind energy accounted for 16% of the electricity generated by renewables. Many parts of the world have strong wind speeds, but the best locations for generating wind power are sometimes remote ones. Offshore wind power offers tremendous potential. [2]

Wind is used to produce electricity using the kinetic energy created by air in motion. This is transformed into electrical energy using wind turbines or wind energy conversion systems. Wind first hits a turbine’s blades, causing them to rotate and turn the turbine connected to them. That changes the kinetic energy to rotational energy, by moving a shaft which is connected to a generator, and thereby producing electrical energy through electromagnetism.

The amount of power that can be harvested from wind depends on the size of the turbine and the length of its blades. The output is proportional to the dimensions of the rotor and to the cube of the wind speed. Theoretically, when wind speed doubles, wind power potential increases by a factor of eight. [2]

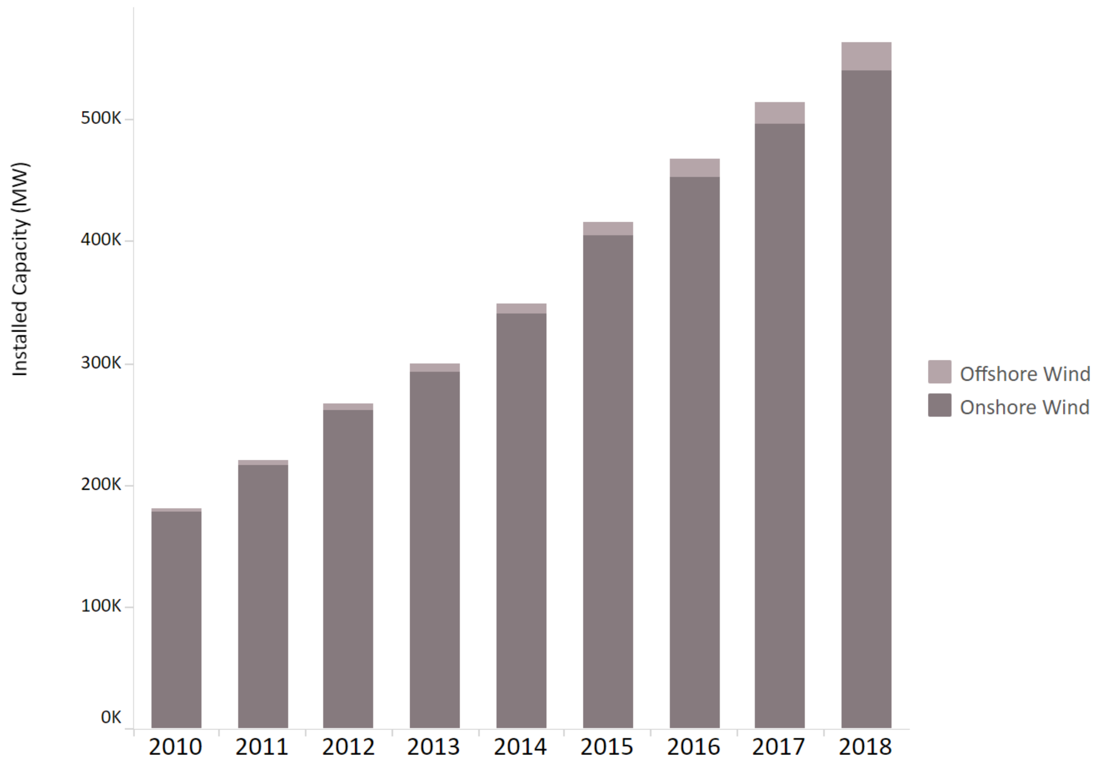

Figure 2. Worldwide installed wind capacity trends from 2010 to 2018 years. [2]

Solar energy

Energy can be harnessed directly from the sun, even in cloudy weather. Solar energy is used worldwide and is increasingly popular for generating electricity or heating and desalinating water. Solar power is generated in two main ways:

Photovoltaics (PV), also called solar cells, are electronic devices that convert sunlight directly into electricity. The modern solar cell is likely an image most people would recognize – they are in the panels installed on houses and in calculators. [1]

Solar PV installations can be combined to provide electricity on a commercial scale, or arranged in smaller configurations for mini-grids or personal use. Using solar PV to power mini-grids is an excellent way to bring electricity access to people who do not live near power transmission lines, particularly in developing countries with excellent solar energy resources. [1]

The cost of manufacturing solar panels has plummeted dramatically in the last decade, making them not only affordable but often the cheapest form of electricity. Solar panels have a lifespan of roughly 30 years, and come in variety of shades depending on the type of material used in manufacturing. [1]

Concentrated solar power (CSP), uses mirrors to concentrate solar rays. These rays heat fluid, which creates steam to drive a turbine and generate electricity. CSP is used to generate electricity in large-scale power plants. [1]

A CSP power plant usually features a field of mirrors that redirect rays to a tall thin tower. One of the main advantages of a CSP power plant over a solar PV power plant is that it can be equipped with molten salts in which heat can be stored, allowing electricity to be generated after the sun has set. [1]

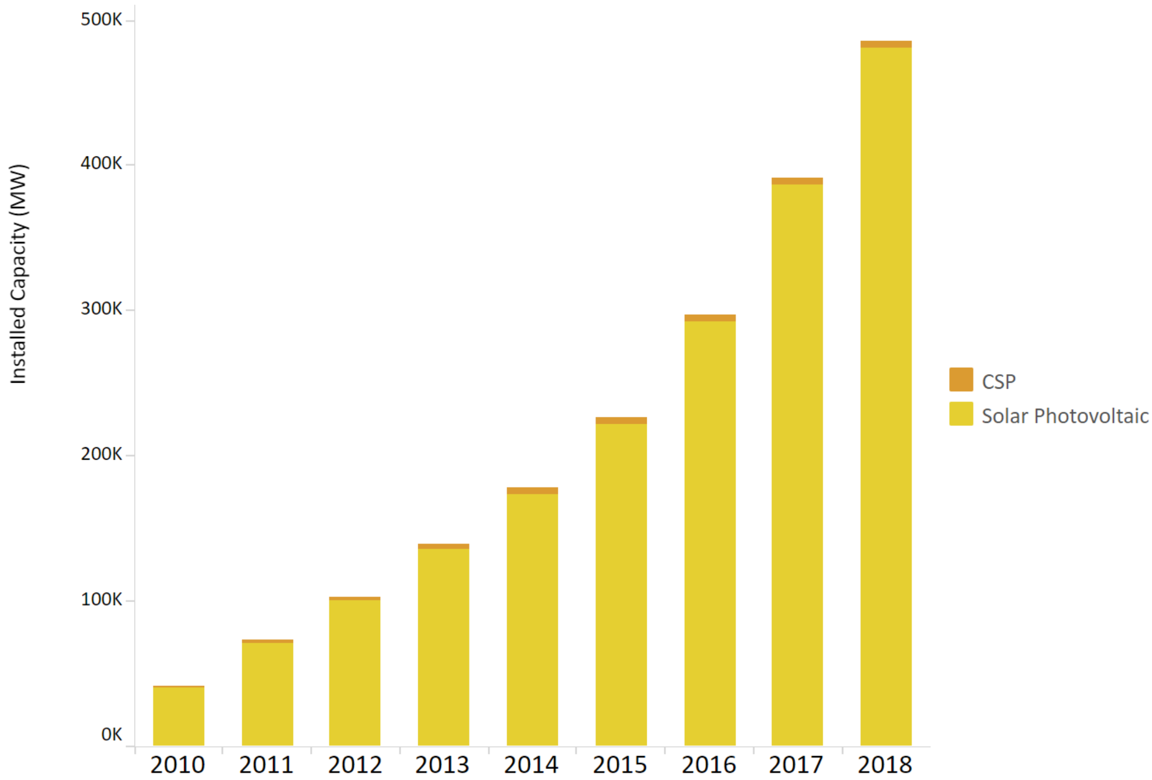

Figure 3. Worldwide installed solar capacity trends from 2010 to 2018 years. [1]

2. Environmental analysis for the creation of power supply systems

Tomsk Oblast is located in the southeast of the West Siberian Plain; it occupies an area of 316.9 thousand km^2. The territory under the jurisdiction of the municipality of Verticos rural settlement is 15.392 thousand ha. [3]

The climate in Tomsk region is sharply continental. Winter is harsh and long (average January temperature from -19 ° C to -21 ° C); summers are warm and short (average July temperature is + 17 ° C ... + 18 ° C). The growing season is 135-140 days. in the north, 150 days. on South.

Annual precipitation is 400-570 mm, of which 78-66% falls in liquid form, and the rest in solid form. The average height of the snow cover is 60-80 cm, snow is held in the north of 190-197, in the south - 176-182 days.

Seasonal permafrost spreads wide. The depth of soil freezing varies from 0.5-0.6 m in peat bogs to 3.5 m in sand, an average of 1.0-2.0 m. [4]

On average, in more than half of all days of the year, conditions are created in the city that facilitate the accumulation in the surface layer of exhaust gases from cars and harmful emissions from factory pipes.

The duration of stable snow cover is an average of 170 days. The average snow depth for winter is 60 cm. The severity of the climate in this period of the year is determined not only by low air temperature, but also by the combination of low temperature and significant wind speed, which leads to heat loss of people and rooms, creates a strong climate discomfort, which must be taken into account when heat engineering calculations. [5]

Gusty winds well ventilate the territory, but create additional dynamic loads on buildings and structures. The repeatability of significant wind speeds with negative temperatures reaches 28-35%, therefore, measures for wind protection of built-up areas are necessary. [6]

The discomfort of the environment is aggravated by snow tolerance - snow deposition can reach $350m^3$ per 1 m running. lengths. The average number of days with snowstorms is 51, with snowdrifts - 26 days. Snow carried during snowstorms and snowdrifts endangers access roads, city streets, industrial sites and other facilities. Special snow protection measures are required, carried out in conjunction with wind protection, including a combination of appropriate building techniques and green spaces.

For most of the year, air in terms of humidity is characterized as moderately dry and moderately humid, which is favorable from the point of view of the human heat perception. The average annual rainfall is 535 mm. In some years, precipitation may be below normal, but the lack of precipitation is insignificant, not more than 10%. About a quarter of the days in a year is kept uncomfortable relative humidity - 80% or more. [6]

The number of days with a thunderstorm (average 27, maximum 42) is significant, which determines the need for lightning protection. [6]

The number of days with fogs, as well as hail, is on average small. [6]

2.1. Wind potential analysis

When solving the problems of evaluating the wind energy potential, its contribution to the energy supply system of a particular or other object and the ecology of the region, there is a need for a large amount of information over the long-term conditions. Wind is the most volatile and unstable meteorological element.

The presence of various obstacles on the surface (topography, vegetation, water spaces, man-made structures) has a very strong effect on the speed and direction of the wind. The influence of these obstacles is characterized by the roughness parameter of the underlying surface. The roughness of the underlying surface exerts influence not only on the surface of the earth, but also on sufficiently high altitudes. This feature makes it necessary to use information about the wind recorded in various points only taking into account the uniformity of the territory. If the location of the points and the weather stations under consideration is not different, then these weather stations can be considered as suitable. Data from meteorological stations can be applied to points located at a distance of up to 50 kilometers. [5] Under conditions of open terrain, the indications of two stations close to each other may differ depending on the location of the weather vane at the station, its degree of protection by trees and buildings located in the station area.

Over time, the conditions around the stations are also subject to changes and they must be taken into account when analyzing the wind regime and the degree of protection of the weather vane [7].

In order to obtain reliable data on the average wind speeds of the territory, it is necessary to use significant volumes of measurements for a fairly long time.

The average annual wind speed is defined as the arithmetic mean value obtained as a result of speed measurements at regular intervals over a given period. [7]

Average monthly and annual wind speeds over long periods of time are the main and initial data for compiling characteristics of the general level of wind intensity. According to the characteristics, it is possible to preliminarily judge about the prospects of placing wind energy equipment in the required area. When compiling the characteristics, it is necessary to remember that the wind speeds strongly depend on the surface roughness and that the data of weather stations may change over time with the change in the surrounding territory. This should be taken into account when comparing the average wind speeds and bring them to equal conditions [7].

In order to obtain reliable data on the average wind speeds of the territory, it is necessary to use significant measurement volumes for a sufficiently long time.

In our case, we can use the data from the meteorological database [8]. Due to the functionality of this service, we can use a pre-calculated average value for the period from 1.01.2015 to 23.11.2019. Take the data on the wind speed at the Tomsk airport, located in the village of Bogashovo.

To calculate wind speeds, observations from weather stations provided by site rp5.ru will be used.

The average wind speed is determined as the mean value obtained as a result of multiple measurements of wind speeds over equal time intervals for a given time interval (day, month, year), is calculated by the formula [7]:

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

where V_{av} – average wind speed, [m/s];

n is the number of time periods;

V_i - wind speed in a certain period of time, [m/s];

The calculated data is summarized in table 1.

Table 1 – Average monthly and annual wind speed, based on data from [8]

Year	2015	2016	2017	2018	2019	Average
	Wind speed, m/s					
January	0,67	2,21	4,60	4,27	4,47	3,25
February	4,42	3,33	4,83	2,94	4,35	3,97
March	4,18	3,75	4,03	4,55	4,40	4,18
April	3,90	3,09	4,95	4,94	4,38	4,25
May	3,54	3,52	4,82	4,13	4,38	4,08
June	2,99	2,90	3,05	3,63	3,20	3,15
July	3,05	2,98	2,34	3,03	2,90	2,86
August	3,66	2,74	2,54	2,71	2,69	2,87
September	3,04	2,56	3,25	3,45	3,82	3,22
October	4,65	2,64	3,58	5,00	4,57	4,09
November	3,73	3,76	4,12	5,25	4,80	4,33
December	5,16	4,71	3,97	3,28	-	4,28

For clarity, I present the data obtained on the figure 4.

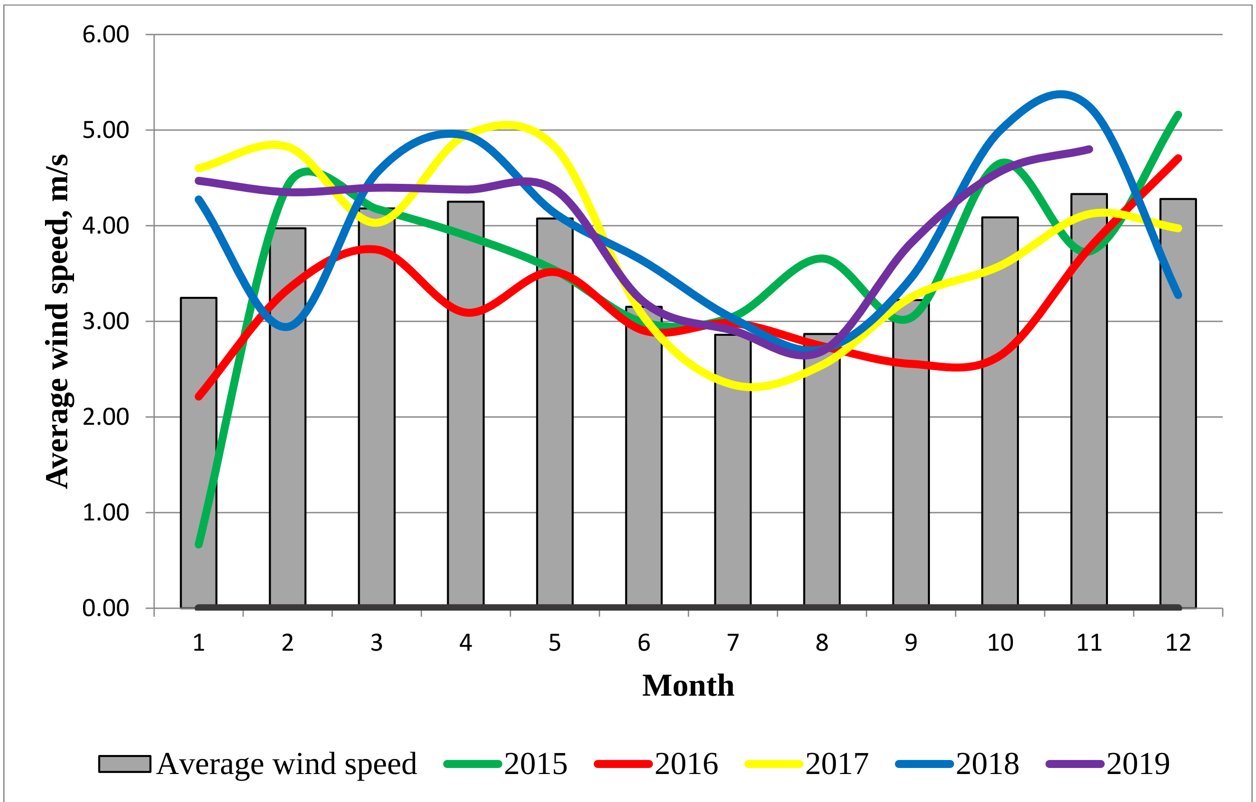

Figure 4. Average monthly and annual wind speed from 2015 to 2019 years

According to the calculations, the average wind speed at an altitude of 10-12 meters above the earth's surface, averaged over a 10-minute period, is V_{av} = 3,71 m / s.

For a numerical estimation of the dispersion of wind speeds from the average value, the coefficient of variation of average speeds is used, which is determined by the following expression [7]:

$$C_v = \frac{S_v}{V_{av}} \qquad (2)$$

where S_v is the standard deviation of the current wind speed from the average value.

Thus, from [8] S_v for the selected period, according to calculations, is 2,33 m/s. Following the formula (2), the coefficient of variation of average speeds will be

$$C_v = \frac{S_v}{V_{av}} = \frac{2{,}33}{3{,}71} = 0{,}63$$

It is known that the wind speed increases with distance from the underlying surface and the air flow becomes more stable. The degree of increase in wind speed with height is highly dependent on the roughness of the underlying surface. Approximately the wind speed at a height h can be estimated by the formula [15]:

$$V_H = V_M \cdot \left(\frac{h}{h_M}\right)^{\alpha}, \qquad (3)$$

Where V_H – wind speed on the height H, [m/s]
V_M – wind speed on the height of the mast, [m/s]
h_M – height of the mast, [m]
α - coefficient related to the average wind speed at the height of the mast

Table 2 – Dependence of α on wind speed V_M [15]

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

I take a height equal to H = 20m. Then, according to formula (3), the average wind speed at a height of H will be

Table 3 – Recalculated wind speed at the height of 20m

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average wind speed, [m/s]	3,25	3,97	4,18	4,25	4,08	3,15	2,86	2,87	3,22	4,09	4,33	4,28
Wind speed at a height of 20m, [m/s]	3,83	4,68	4,93	5,01	4,81	3,71	3,37	3,38	3,80	4,82	5,11	5,05

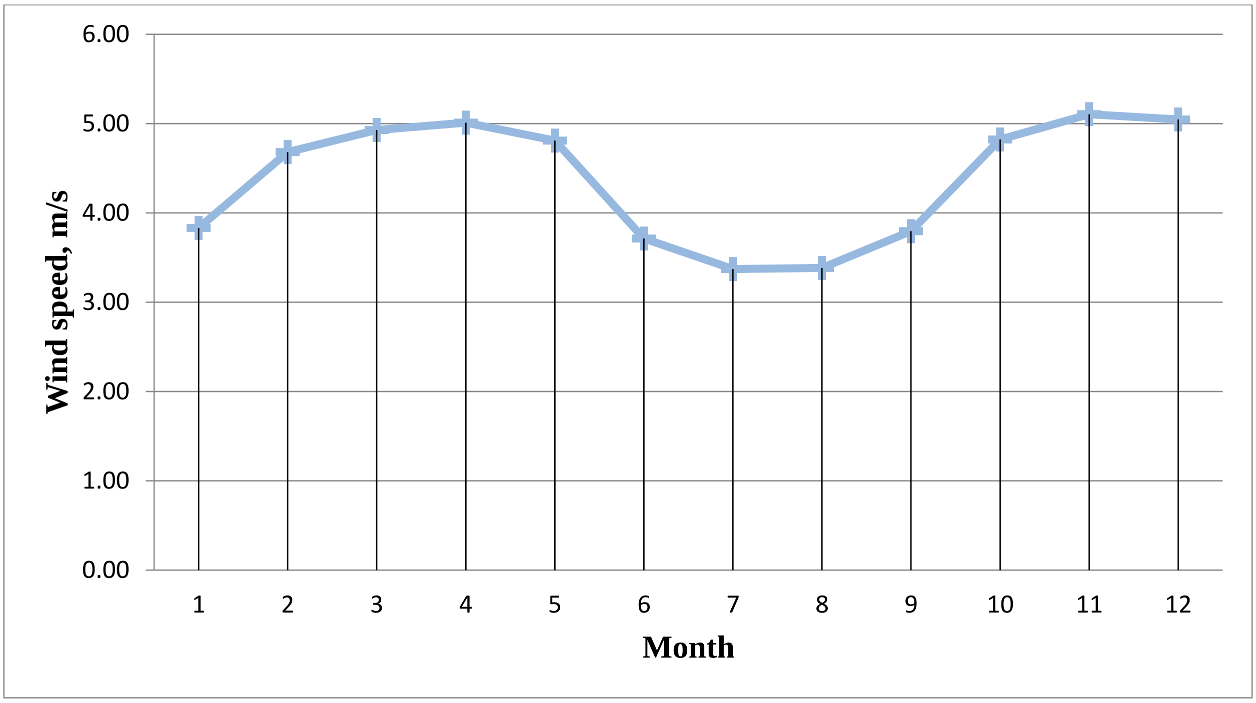

Figure 5. Wind speed at a height of 20m for 12 months

According to the obtained figure, I can conclude that the maximum wind speeds correspond to winter, autumn and spring season, with a minimum in the summer period.

In addition to calculations, it is necessary to depict a wind rose for the study area in order to know the prevailing wind direction.

Wind rose - is a graphical representation of the repeatability of wind directions. It is of great practical importance when using large-capacity wind turbines, where instead of slip rings, a power cable laid in a cable channel is used. In the process of operation, the gondola of such a wind turbine rotates around its axis, thereby unwinding the cable. The wind rose allows you to set the duration of the interservice period when maintenance personnel need to unwind and lay the cable.

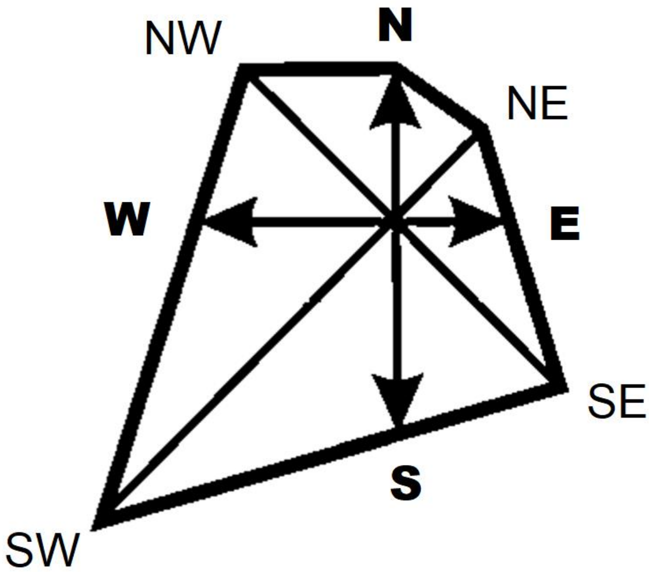

Figure 6. Wind rose for the Tomsk region. [7]

Correct accounting of wind directions allows you to most effectively locate wind turbines on the ground.

Analyzing wind repeatability, it must be remembered that from an energy point of view, it is much more important to know the energy characteristic (maximum possible output) of the wind in the selected directions than in which direction the wind prevails.

2.2. Solar insolation analysis

Since ancient times, main source of energy for our planet was the Sun. Solar energy produces the energy of wind, water, heat, biomass, as well as the use of rough and hard coal, oil and natural gas, but this is indirect energy and accumulated over thousands of years and millions of years. The energy of the Sun can be used directly as a source of electricity and heat.

Insolation - is the quantity of potentially useful solar radiation, which falls on an illuminated surface. Solar insolation varies greatly from one point of the earth's surface to another. To calculate insolation of an area, several factors should be taken into account: influence of seasons, for instance, in winter light level is lower and daylight hours are shorter; characteristics of illuminated terrain (some relief features may prevent illumination); local weather conditions (frequent cloudy weather, fogs and rains), etc. [10]

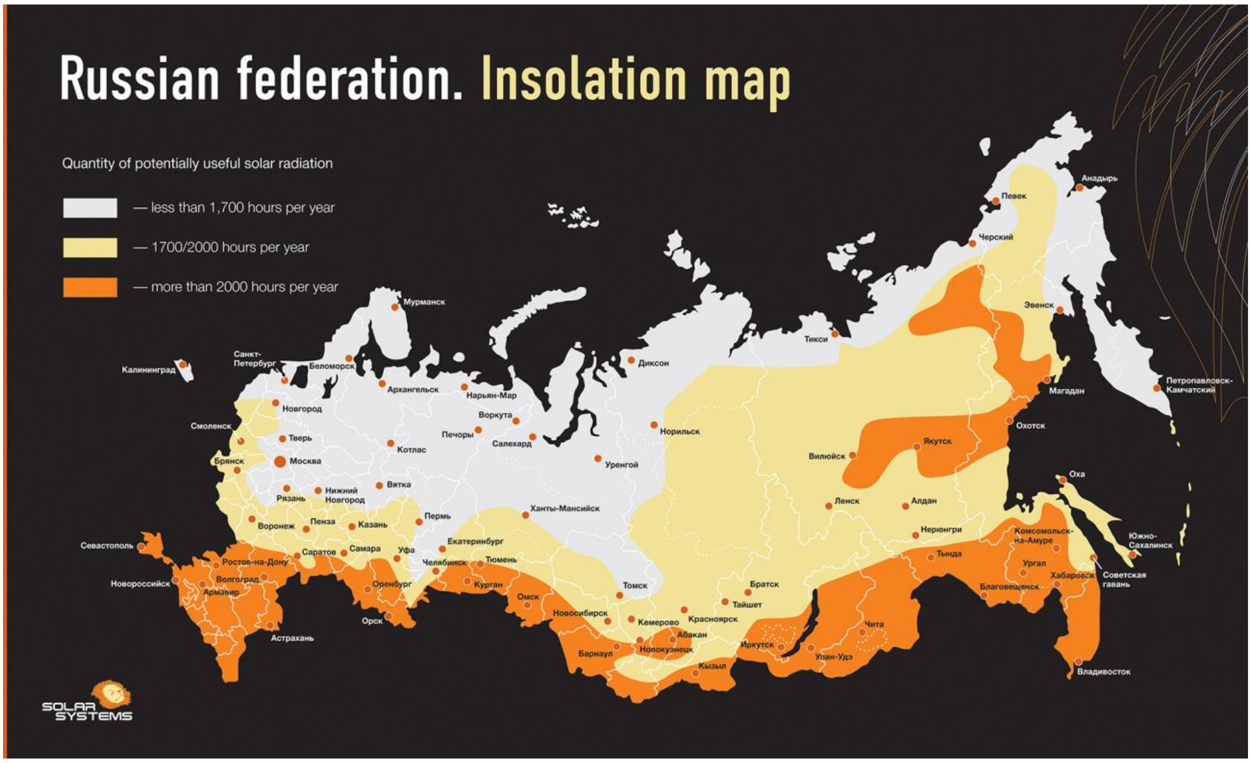

Figure 7. Russian Federation insolation map. [10]

Solar insolation is characterized by a wide spectral range - from radio waves to gamma radiation. At a distance of 1 AU from the Sun, the density of its radiation flux is 1360 W / m^2.

Also often is used definition of the solar constant on the surface of the Earth, which is equal to the value of insolation on the surface, located at the sea level and oriented on the Sun. [11]

It is convenient to define a surface solar constant—that is, a value of insolation on a surface that, at sea level, faces the vertical sun on a clear day. This “constant” has the convenient value of about 1000W / m^2 or “one sun.” At other than vertical, owing to the larger air mass through which the rays have to pass, the insolation is correspondingly smaller. [12]

In order to assess the renewable energy potential of solar energy, it is necessary to determine the energy potential of solar insolation in a given region. The assessment is based on the data of the National Aeronautics and Space Administration (NASA). NASA data is used in the processed form in the RETScreen software. The data provided below is valid for facility located at coordinates latitude 56,5102, longitude 84,9546.

To determine the solar radiation incident on an oblique the investigated flat area in cloudy conditions, I use the expression [7]:

$$Q_{sl} = Q_{dir} + Q_{dif} \cdot [1 - (a + bn) \cdot n], \quad (4)$$

Where, Q_{dir} – direct solar energy incident on a sloped surface, [W/m^2],

Q_{dif} – diffused solar energy incident on a sloped surface, [W/m^2],

a – coefficient depending on the environment (land or sea) and the latitude of the place, a = 0,383 for Tomsk [relative units], according to [7];

b – coefficient, which in this case can be considered constant and equal to 0,38 [relative units], according to [7];

n – relative cloudiness (0 for cloudless weather, 1 for fully cloud weather) [relative units];

$$Q_{dir} = Q_{ort} \cdot cos\,\theta, \quad (5)$$

Where, Q_{ort} – direct solar energy incident on a surface orthogonal to beams of light, [W/m^2],

θ – direct sunglight incidence angle [degrees], figure 8.

$$Q_{ort} = \frac{Q_0 \cdot sin\,\alpha}{sin\,\alpha + c}, \quad (6)$$

Where, Q_0 – surface solar constant [W/m^2], Q_0 = 1000 W/m^2, according to [12],

sin α – the angle between the vertical axis and the incident beams of light [relative units], figure 8

c – degree of transparency of the atmosphere [relative units], c = 0,32 [7]

$$Q_{dif} = Q_{dif\,hor} \cdot [0{,}55 + 0{,}434 \cdot cos\,\theta + 0{,}313(cos\,\theta)^2], \quad (7)$$

Where, $Q_{dif\,hor}$ – diffused solar energy incident on a horizontal surface, [W/m^2],

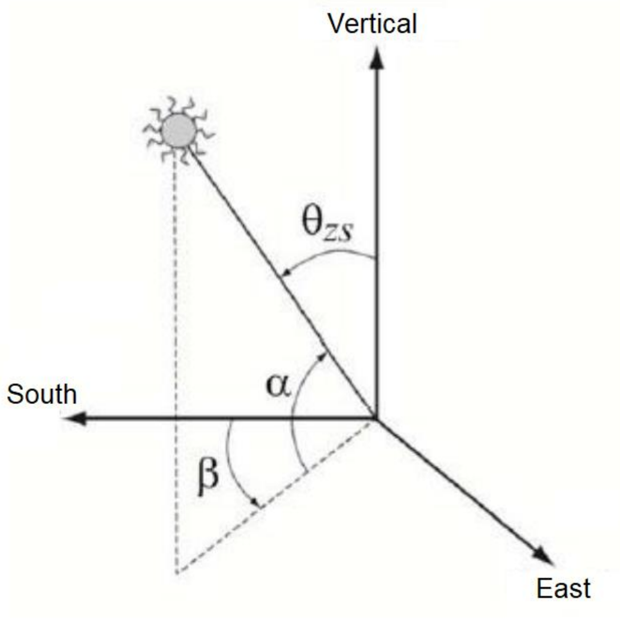

Figure 8. The coordinates of the Sun relative to a geographically oriented coordinate system [7].

$$Q_{ort} = \frac{1 \cdot sin(35°)}{sin(35°) + 0{,}32} = 0{,}642\ [\text{kW/m}^2],$$
$$Q_{dir} = 0{,}642 \cdot cos\,45° = 0{,}4539\ [\text{kW/m}^2],$$
$$Q_{dif} = 0{,}69 \cdot [0{,}55 + 0{,}434 \cdot cos(45°) + 0{,}313(cos\,45°)^2] = 0{,}6992\ [\text{kW/m}^2],$$
$$Q_{sl} = 0{,}4539 + 0{,}6992 \cdot [1 - (0{,}383 + 0{,}38 \cdot 0) \cdot 0] = 1{,}1531\ [\text{kW/m}^2]$$

Other months are provided in the table below. Data in table 4, column 2 provided by NASA database in software RETScreen, next columns are calculated by formulas above.

Table 4 – Values of solar radiation in Tomsk. Based on data from RETScreen software.

Month	Daily average solar radiation, horizontal, [kWh/m^2/day]	Daily average solar radiation, sloped, [kWh/m^2/day]	Monthly solar radiation, horizontal, [kWh/m^2/ month]	Monthly solar radiation, sloped, [kWh/m^2/ month]
December	0,46	0,92	14,26	28,52
January	0,69	1,15	21,39	35,75
February	1,59	2,07	44,52	57,82
Average value per winter season	0,91	1,38	26,72	40,70
March	2,94	3,43	91,14	106,43
April	4,29	4,80	128,7	144,04
May	5,48	6,01	169,88	186,22
Average value per spring season	4,24	4,75	129,91	145,56
June	5,79	6,32	173,7	189,64
July	5,8	6,33	179,8	196,28
August	4,55	5,06	141,05	157,01
Average value per summer season	5,38	5,91	164,85	180,98
September	2,83	3,32	84,9	99,65
October	1,58	2,06	48,98	63,71
November	0,83	1,29	24,9	38,85
Average value per autumn season	1,75	2,22	52,93	67,40

As you can see in the table 4, the maximum values of solar energy correspond to the spring and summer season. In order to plot the values of solar energy, it is necessary to know daylight duration, which is provided in table 5.

Table 5 – The average monthly daylight duration based on data from [13].

Month	Sunrise	Sunset	Daylength
December	9:29	16:48	7:19
January	9:54	16:52	6:58
February	9:17	17:50	8:33
Average per winter season	9:33	17:10	7:36
March	8:13	18:52	10:39
April	6:51	19:58	13:07
May	5:35	21:00	15:25
Average per spring season	6:53	19:56	13:03
June	4:39	21:57	17:18
July	4:34	22:12	17:38
August	5:21	21:30	16:09
Month	Sunrise	Sunset	Daylength
Average per summer season	4:51	21:53	17:01
September	6:22	20:16	13:54
October	7:22	18:56	11:34
November	8:28	17:38	9:10
Average per autumn season	7:24	18:56	11:32

It is necessary to build sinusoidal plot, in the range of angles from 0 º to180 º (sunrise = 0 º, sunset = 180 º), so for each hour of solar activity I have to calculate the angle, in accordance with the number of hours of the day. To calculate the power of the proposed photovoltaic installation (PMT), I use the formula:

$$P_{PV} = \eta \cdot \lambda \cdot S, \text{[kW]} \tag{8}$$

Where η – efficiency of PV installation [relative units], let assume η = 0,15;
λ – solar radiation, [kW/m^2];
S – area of solar panel, [m^2], let assume S = 1m^2;

Average winter daylength is 7 hours 36 minutes, when divided into equal intervals, I obtain that every minute the angle of the sun changes by 0,3939 degrees. The same way I can calculate generated power for each season. Let us build the tables and provide them in appendices.

According to the data in appendices 1 - 4, I build seasonal plots of the generated active power, figure 9.

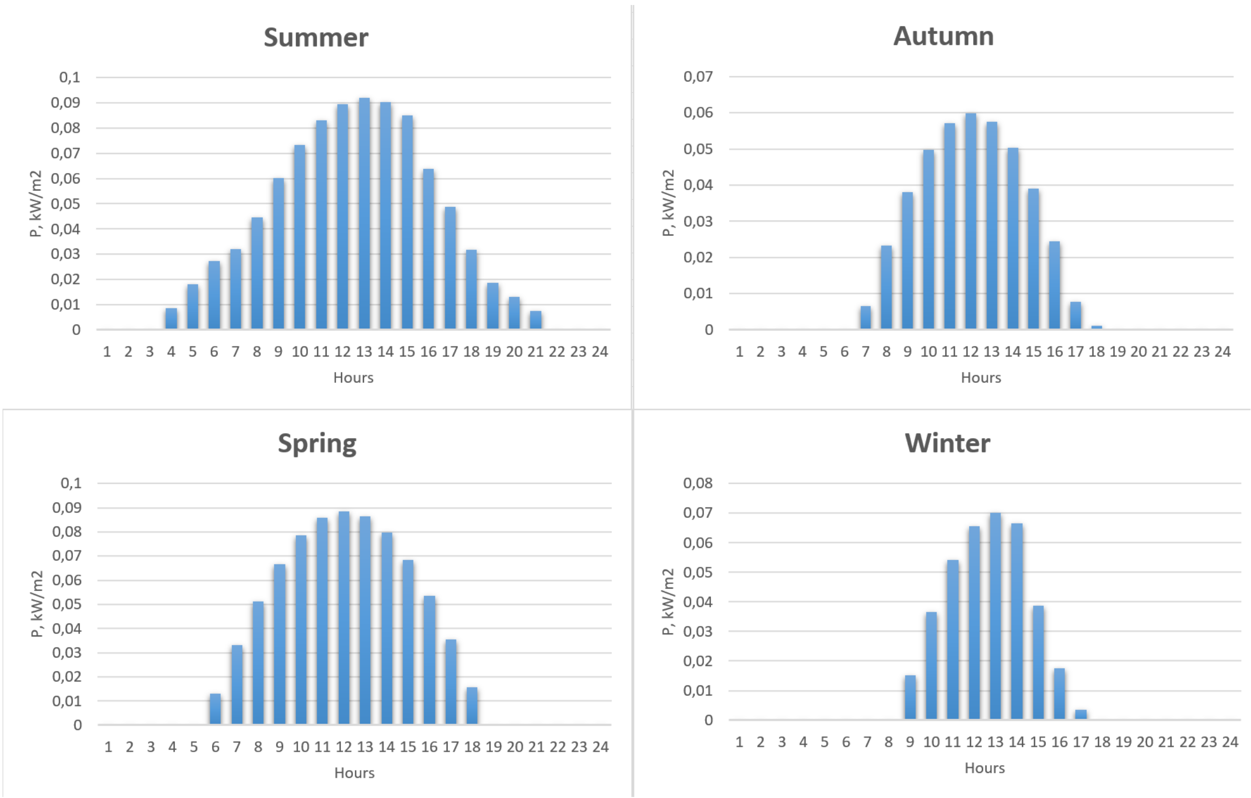

Figure 9. Seasonal plots of the generated active power

2.3. Other renewable sources analysis

Hydropower is the most used form of renewable energy in Russia, and there is large potential in Russia for more use of hydropower. Russia has 102 hydropower plants with capacities of over 100 MW, making it fifth in the world for hydropower production. It is also second in the world for hydro potential, yet only 20% of this potential is developed. Russia is home to 9% of the world's hydro resources, [16] mostly in Siberia and the country's far east. At the end of 2005, the generating capacity from hydroelectric sources in Russia was 45,700 MW, and an additional 5,648 MW was under construction.

The World Energy Council believes that Russia has much potential for using its hydro resources, with a theoretical potential of about 2,295 TWh/yr, with 852 TWh being economically feasible. [17]

Although hydropower is widespread in Russia and climatic condition suit to build hydropower plant, but the main problem that this is not reasonable to construct whole power plant in order to supply single house. Thus I will not consider this option in the future.

3. Description of the consumer

In order to define exact structural scheme, I have to first describe the consumer. Let assume that I supply cottage house with total area 150 m^2. Also, I have to design table with installed electrical appliances and their nominal power in order to find consumed power. To do that I use common appliances for such area provided by Schneider Electric in [19]

Table 6 – Initial data about the supplied cottage house, from [19]

Room	Area, [m^2]	Installed electrical appliances	Nominal power, [kW]
Kitchen	18	Electric stove	10,5
		Fridge	1,2
		Dishwasher	2,2
		Lighting	0,8
		1 Socket x 16 A; 4 Sockets x 6 A	0,5
Living room	48	Electric fireplace	2
		Air conditioning	4
		TV	0,6
		Lighting	2,2
		10 Sockets x 6 A	1
Bedroom 1	20	Floor heater(12m^2)	1
		Air conditioning	1,5
		Lighting	0,5
		Computer	1
		4 Sockets x 6 A	0,4
Bedroom 2	20	Floor heater(12m^2)	1
		Air conditioning	1,5
		Lighting	0,5
		Computer	1
		4 Sockets x 6 A	0,4
Children's room	22	Floor heater(18 m^2)	1,6
		Air conditioning	2,2
		Computer	1
		Stereo system	0,7
		Lighting	0,4
		4 Sockets x 6 A	0,4
Bathroom 1	14	Heated shower	3
		Jacuzzi	2,5
		Floor heater(6m^2)	0,4
		Fan	0,5
		Lighting	0,3
		4 Sockets x 6 A	0,4
Bathroom 2	8	Washing machine	2,2
		Fan	0,5
		Lighting	0,3
		4 Sockets x 6 A	0,4
Total	150		50,6

Now, when I defined total nominal power, I can calculate design power using formulas from [19]

$$P_D = \sum P_{nom} \cdot K_D \cdot K_U, \quad (9)$$

Where P_D – design power, [kW]

P_{nom} – nominal power, [kW]

K_D – coefficient of demand, [relative units]

K_U – coefficient of usage. [relative units]

Also I need to find apparent power for each group of consumer, using formula [19]

$$S = \frac{P_D}{\cos\varphi}, \text{[kVA]} \quad (10)$$

Where cos φ – power factor, [relative units].

cos φ for the whole building could be found as ratio [19]

$$\cos\varphi = \frac{\sum P_D}{\sum S}, \quad (11)$$

Table 7 – Results of the calculations, using coefficients from [19]

Consumer type	Nominal power	Calculated coefficients			Design power	
	P_{nom}	K_D	K_U	cos φ	Active power, [kW]	Apparent power, [kVA]
Lighting	5	0,8	0,6	1	2,4	2,4
Socket network	3,5		0,7	0,9	2,45	2,72
Electric stove	10,5	0,8	1	1	8,4	8,4
Fridge	1,2	1	0,5	0,95	0,6	0,63
Dishwasher	2,2	0,8	0,8	0,8	1,408	1,76
Air conditioning	9,2	0,7	0,8	0,8	5,152	6,44
Electric fireplace	2	0,4	1	0,9	0,8	0,89
TV	0,6	0,6	1	0,8	0,36	0,45
Floor heaters	4	0,5	1	1	2	2
Computers	3	0,6	1	0,65	1,8	2,77
Stereo system	0,7	0,6	1	0,8	0,42	0,53
Jacuzzi	2,5	0,8	0,8	0,8	1,6	2
Heated shower	3	0,6	0,8	1	1,44	1,44
Fans	1	0,6	0,6	0,8	0,36	0,45
Washing machine	2,2	1	0,6	0,8	1,32	1,65
Total	50,6	-	-	0,884	30,51	34,53

As you can see from the table 7, total design power is 30,51 kW. This means that I should choose source of power with at least 30,51 kW capacity.

Now I should build load schedule of the house for winter and summer season in order to define load peaks and falls.

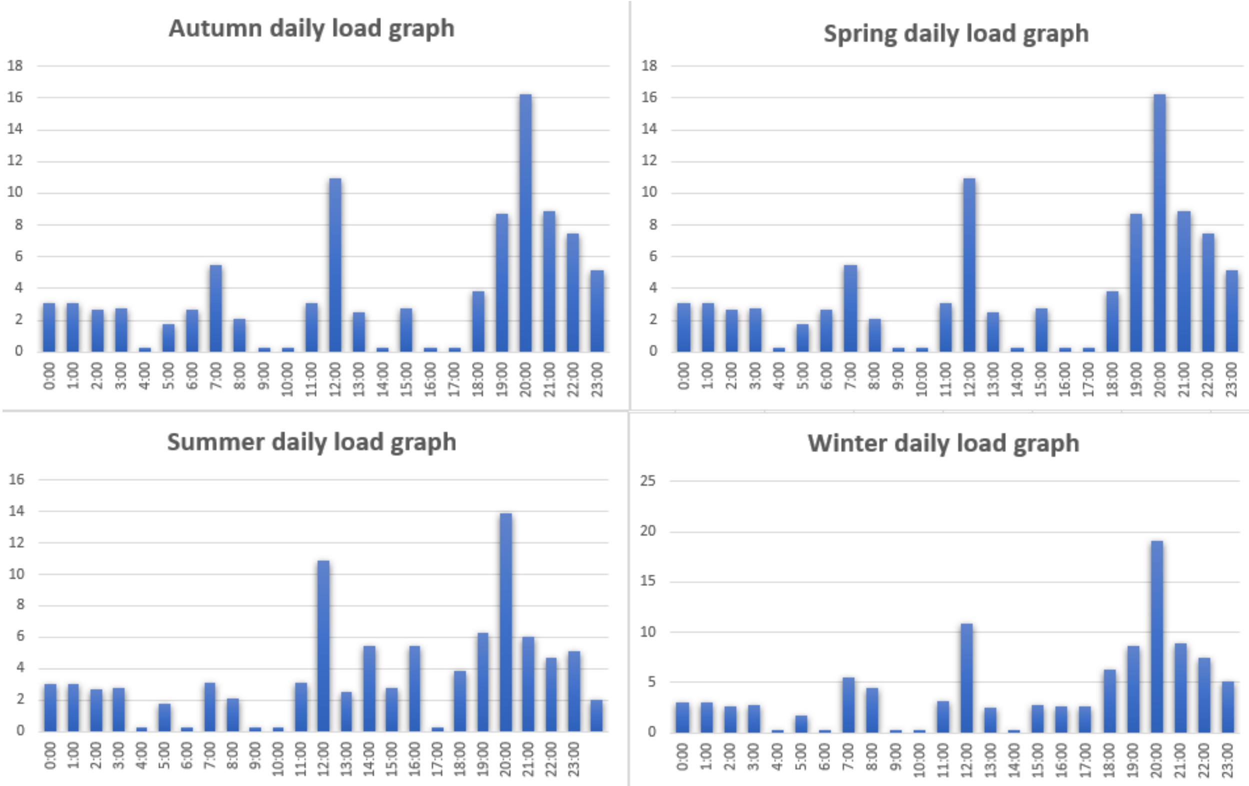

Figure 10. Cottage house season daily load schedule based on data from [19], coefficients are provided in appendix 6.

Obtained load schedule shows us that during some hours the power supply system will be overloaded and underloaded sometimes. This fact means that I need to consider variant with integrated battery storage system or backup power supply system, in order to cover all the graph with energy. Also you might note, that in summer period our house consumes less, than in winter but the system can produce more, that means, that I should store the energy.

4. Analysis of the possible configurations of hybrid power supply

Since the nearest electric power line is at a distance of about 30 km, the variant of electric supply from grid is excluded, due to its high cost and landscape features.

So thus, there are several configurations of hybrid power supply with renewable energy source. Most of them are a combination of renewable energy source and gasoline generator. The gasoline generator provides consumers with energy when there is lack of energy from RES (for example the wind is weak for wind power plant or at night for photovoltaic power plant). Also, the configurations include storage battery. It keeps energy in case when the power plant generates more power than consumer needs.

Stand-alone wind generator

Wind generator is an installation that uses wind power to produce electrical energy. Usually, wind generators are made of tower and blades.

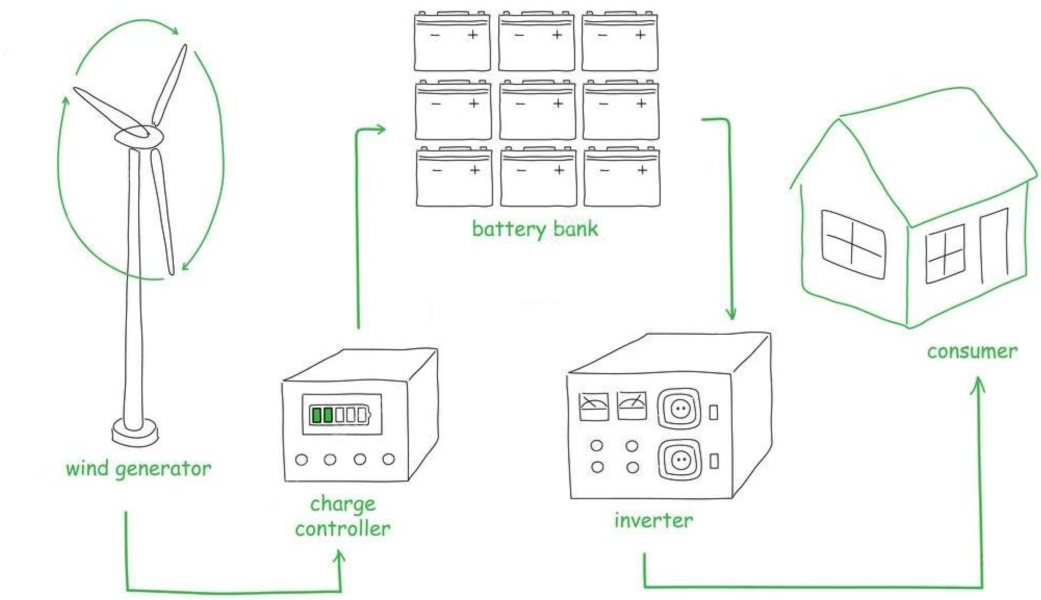

Figure 11. Stand-alone wind generator [20]

Due to the climate characteristics of Western Siberia, and in particular the Tomsk Region, it will be advisable to consider low-speed wind generators. Low-speed generator is considered to be powered by wind if the blades rotate along the vertical axis. Achieving low speed contributes to a high number of wings.

In order to operation of the rotor of a vertical windmill, the effect of magnetic levitation is used, which allows it to actually soar in the air. The use of rare earth magnets allows us to compensate the force of gravity, and special automated systems hold the mechanism at the desired position. This approach makes it possible to start spinning the rotor with very low wind gusts (from 0,17 m / s). Reducing the number of mechanical parts significantly increases the reliability and durability of the entire structure, and also positively affects acoustic comfort (noise level up to 20 dB). [20]

Vertical type wind turbines require almost no maintenance. In comparison with the classic horizontal generator, which will require maintenance every six months, this is a significant advantage.

The requirements for installing a vertical wind turbine do not contain statements on noise insulation or the minimum distance to residential buildings. Silent operation is achieved through the use of the effect of magnetic levitation, which allows to nullify almost all vibrations and achieve a noise load of less than 20 dB. The tower of the windmill can even be installed on the roof of the house, as the generator is almost silent.

One of the main disadvantages of a vertical wind turbine is its low efficiency in comparison with a horizontal wind generator. Efficiency is in the range 15-25%, but it is lower than horizontal wind turbines, which efficiency is 25-35%. [20]

The vertical wind generator is a rather complicated design, which negatively affects the weight, and this, in turn, makes it difficult to lift the device to a great height. Because of this, problems arise when it is catching the wind, since strong wind gusts are most often observed at high altitudes.

Hybrid wind and solar power supply

This type of generation is a hybrid system of accumulator inverter type, operating in the complex as on renewable natural energy resources, which for mankind are wind and solar radiation energy.

Combined power systems that use wind and solar energy at the same time have several advantages over stand-alone wind or solar installations.

For conditions, for example, in Russia, and especially in its middle lane, wind speed in summer is relatively small, but there is a lot of sun and long daylight hours. While in winter, on the contrary, there are a lot of strong winds and less sunlight. Since the peak of electricity generation in wind and solar systems occurs at different times of the day and year, such a combined system, accordingly, produces more energy.

Such a hybrid electrical installation for generating electricity is capable of ensuring the stability of its supply to the network of small cottage villages, country houses and a small private business.

The main element in the system is a wind generator that produces electrical energy and charges batteries. To avoid the dependence of the system on the absence or availability of energy resources and to ensure its greatest efficiency and stability, we supplemented the system with photovoltaic modules that generate solar energy and charge its batteries.

This hybrid installation is able to function without an electrical network. In the absence of sun and wind, the system will supply energy from the batteries.

The system should have several controllers - for PV modules, and for a wind generator - electrical devices for monitoring and controlling the battery charge, and inverters - for providing 220 V AC for consumers of electric energy from direct current batteries.

MPPT charge controller for PV modules increases by more than 30% the energy flow from PV modules to the battery, and performs the tasks of 2 devices: battery charge control and power amplifier of PV modules. [21]

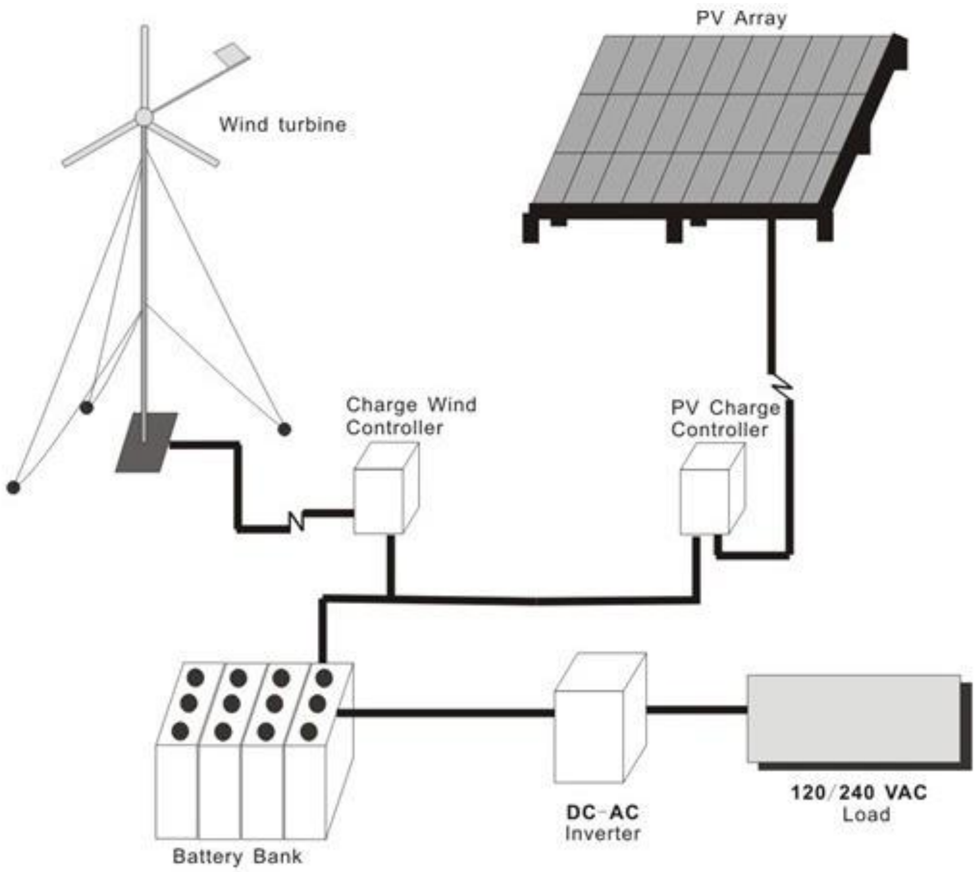

Figure 12. Wind and solar hybrid power supply system [22]

Wind, solar and gasoline generator

This is also hybrid type of power supply, working almost the same way as previous one, but at the time when there is no wind, sun and batteries are empty, gasoline generator starts to operate. Such time calls “Deficit time”, when power I need to consume are higher, than power the system can produce, without gasoline generator. Period of time, when wind turbine and PV arrays can cover all the consumption, calls “Normal time”. In this scheme specialized ATS controller is used, that monitors under / over voltage, under / over frequency and voltage unbalance and forward a start command on gasoline generator, if it is necessary.

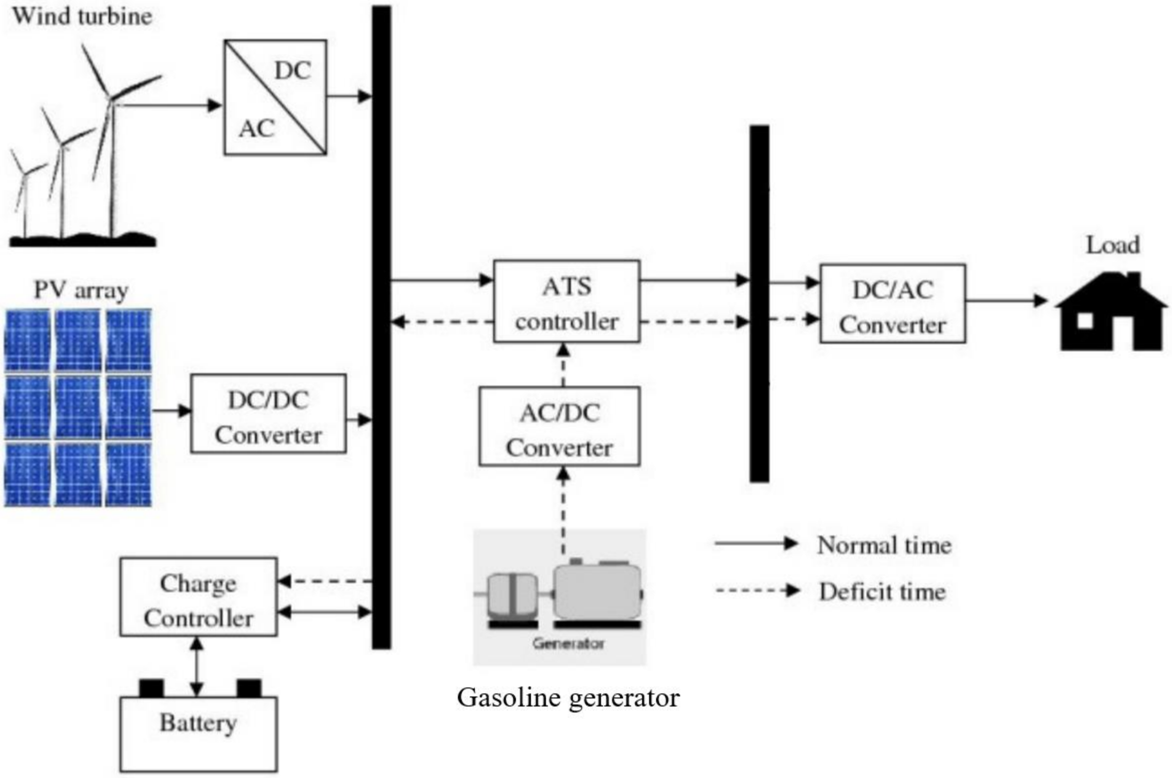

Figure 13. PV, wind and gasoline hybrid power supply system [23]

Due to the load is residential house, with permanently working appliances (not all of them, but part), it is very important to have backup generator, because in sharply continental climate zone often occurs windless and cloudy weather and batteries could not cover this period. It is obvious, that for this purpose the best option is third system, since it is the most reliable one, but for completeness it is necessary to consider all these options in simulation.

5. Mathematical simulation

The effectiveness of the projected object directly depends on the correct choice of equipment. Features of the facility location impose additional requirements for the operation of equipment. Harsh climatic conditions, a large amount of precipitation, and a significant temperature difference make the use of conventional equipment ineffective and impossible. Thus, before make simulations, I have to select suitable equipment, which can operate in such severe weather.

Description of the equipment

Wind generator

First of all, I choose wind generator. Since I have to cover load of 30,51 kW, capacity of the generator must be higher or equal. Due to the low wind speed, the best solution would be to use “Condor Air” 30 kW wind generator. The low starting speed of wind of 2,5 m/s and the low nominal speed of wind of 8 m/s, the most fully corresponds to the wind potential in the considered region.

Condor Air is a high-tech horizontal type wind generator developed by the “Energy Decision” company and adapted to work in Russian climatic conditions. Operational temperature range: from -40 to +50 degrees in the normal version and up to -55 in the version for low temperatures. The price of the wind generator includes a **charge controller** and a **mast**. [24]

Short description of the generator is provided in table below; full description is in the Appendix 7.

Table 8 – Short description of the wind generator [24].

Wind wheel diameter	13 m
Blade height	6 m
Nominal RPM	35-40
Output voltage	170-240 V
Nominal power	30 kW
Maximum power	32 kW
Starting wind speed	2,5 m/s
Nominal wind speed	9 m/s
Operational wind speed	3 – 20 m/s
Generator type	Three phase permanent-magnet generator
Generator frequency	0 - 50 Hz
Output current	Alternating
Nominal current	100 A
Maximum current	110 A
Cost	26000 EUR

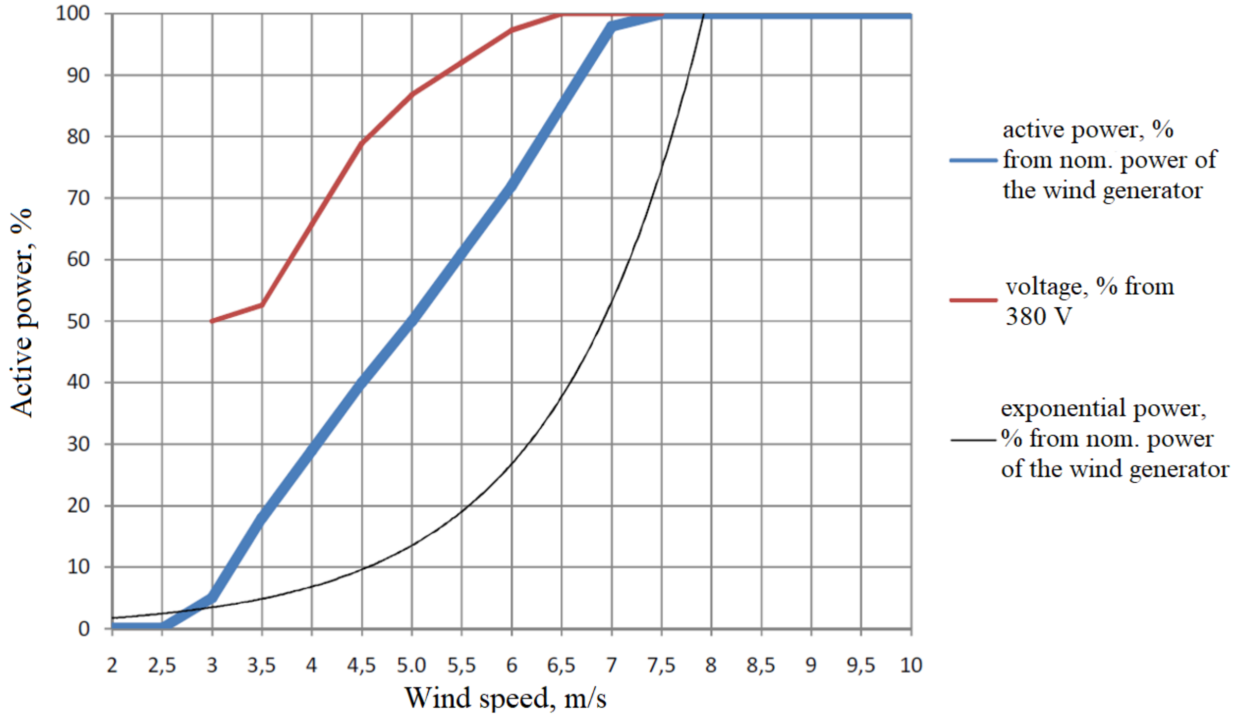

Figure 14. Dependence of active power on wind speed [5]

$$P = \xi \cdot \pi \cdot R^2 \cdot 0{,}5 \cdot V^3 \cdot \rho \cdot \eta_{rg} \cdot \eta_{gen} \quad (12)$$

Where ξ – wind energy using coefficient,

R – rotor radius, [m]

V – wind speed, [m/s]

ρ – air density, [kg/m^3]

η_{rg} – reduction gear efficiency

η_{gen} – generator efficiency

Let's calculate the amount of energy generated by a single wind generator over a period of months to a month, using formula 12 [7].

Table 9 – Amount of generated energy per month for the whole year

Month	W, [kWh/month]
January	980,35
February	1786,91
March	2085,73
April	2192,28
May	1939,59
June	892,61
July	668,08
August	675,11
September	953,45
October	1953,89
November	2318,43
December	2239,04
Total	18685,48

I present the obtained results as a histogram to visualize them.

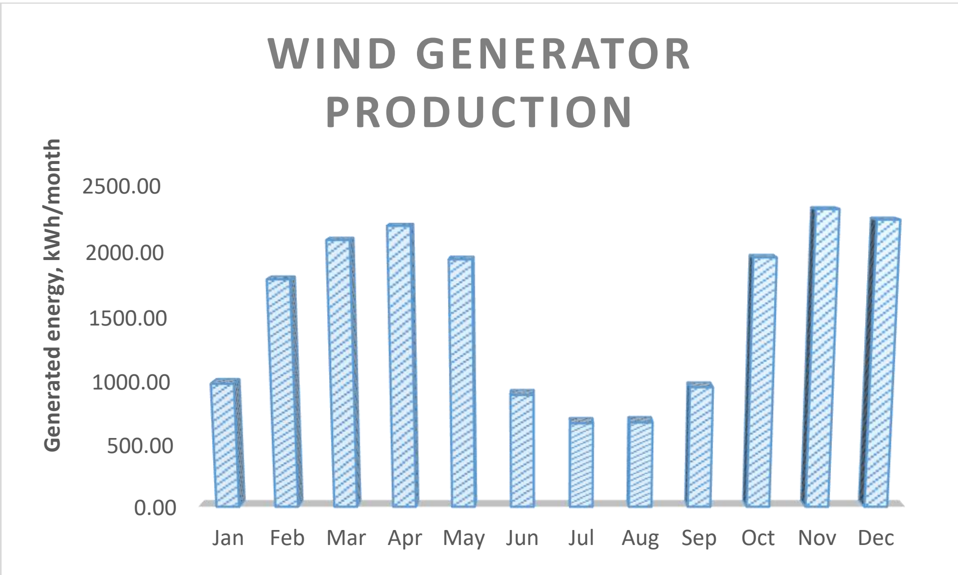

Figure 15. Amount of generated energy per month for the whole year

Let's calculate the balance of generated and consumed energy for the whole year using formula (13) in order to determine deficiency of energy in system.

$$\Delta W = W_g - W_c, \quad (13)$$

Where, W_g – Generated energy, [kWh/month]
W_c – Consumed energy [kWh/month]

Table 10 – Balance of generated and consumed energy for the whole year

Month	W_g, [kWh/month]	W_c, [kWh/month]	W_{5xg}, [kWh/month]	ΔW, [kWh/month]
January	980,35	3254,938	4901,74	1646,80
February	1786,91	2966,1935	8934,53	5968,34
March	2085,73	2944,938	10428,67	7483,73
April	2192,28	2849,94	10961,42	8111,48
May	1939,59	2944,938	9697,97	6753,03
June	892,61	2764,56	4463,05	1698,49
July	668,08	2856,712	3340,40	483,69
August	675,11	2856,712	3375,56	518,85
September	953,45	2849,94	4767,25	1917,31
October	1953,89	2944,938	9769,45	6824,51
November	2318,43	2849,94	11592,15	8742,21
December	2239,04	3254,938	11195,19	7940,25
Total	18685,48	35338,6875	93427,38	58088,69

* Where consumed power was obtained using data from figure 10.

Let's build the graph to visualize the deficiency of energy in system.

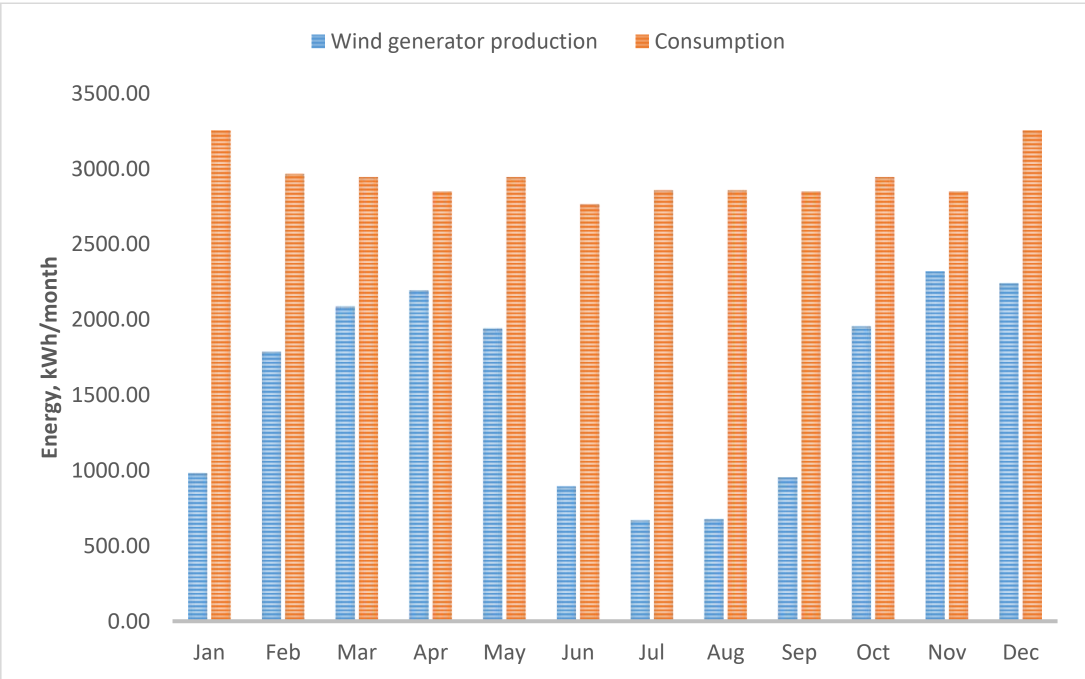

Figure 16. Balance of the energy per month for the whole year

As you may see from the figure 16, not all months' loads are covered by wind generator. Deficiency of energy is especially high in summer months. In case with stand-alone wind generators to cover this deficiency, I have to install at least 5x 30 kW wind generators.

Solar modules

As PV modules, I choose "Exmork FSM-300M". Main characteristics are provided in table below.

Table 11 – Solar module "Exmork FSM-300M" main characteristics [25]

Electrical parameters	
Maximum power, W	300
Nominal voltage, V	24 V
On-load voltage, V	36
Off-load voltage, V	43,15
On-load current, V	8,33
Short circuit current, A	9,14
Maximum off-load voltage of PV array, V	1000
Efficiency, %	17,4
Cost	256 EUR

Also, PV charge controllers are included. The full specification provided in appendix 8.

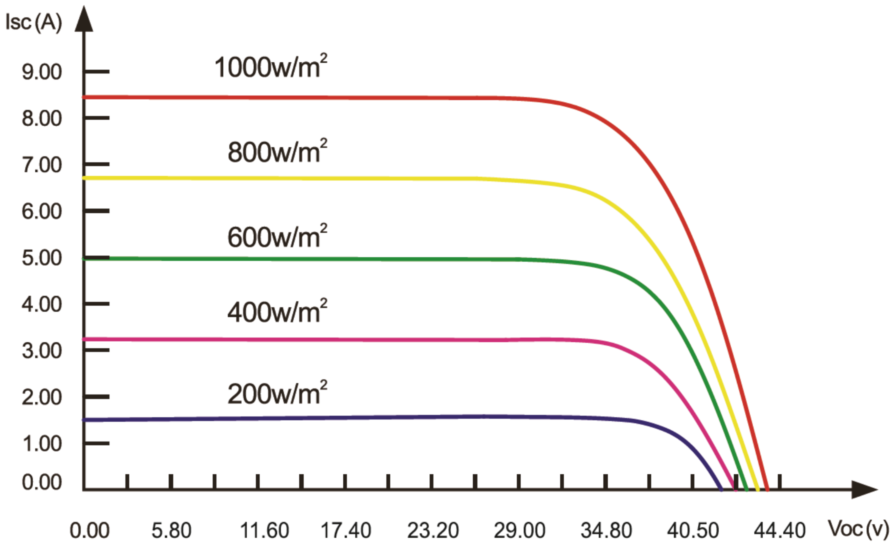

Figure 17. Current and voltage dependences on the intensity of solar radiation

Now I calculate amount of energy generated by one solar module during one year month by month using methodic
[Лукутин Б.В., Суржикова О.А., Шандарова Е.Б. Возобновляемая энергетика в децентрализованном электроснабжении.- Москва: Энергоатомиздат, 2008. - 231 с.]

Solar module with nominal power P_{SM} generates such amount of energy:

$$W_{SM} = \frac{P_{SM} \cdot \lambda}{1000}\ [kWh]; \quad (13)$$

where, λ - insolation during the chosen period, [kWh/m^2];

Example of calculations for January:

$$W_{SM} = \frac{300 \cdot 28{,}52}{1000} = 8{,}556\ [kWh]$$

Table 12 – Amount of energy generated by solar module "Exmork FSM-300M"

Month	Energy generated by 1 solar module, $W_{1SM}, [kWh]$	Energy consumptions, $W_C, [kWh]$	Necessary quantity of solar modules, N_{SM}	Energy generated by 70 solar modules, W_{70SM}
January	8,556	3254,938	380	598,92
February	10,725	2966,1935	277	750,75
March	17,346	2944,938	170	1214,22
April	31,929	2849,94	89	2235,03
May	43,212	2944,938	68	3024,84
June	55,866	2764,56	49	3910,62
July	56,892	2856,712	50	3982,44
August	58,884	2856,712	49	4121,88
September	47,103	2849,94	61	3297,21
October	29,895	2944,938	99	2092,65
November	19,113	2849,94	149	1337,91
December	11,655	3254,938	279	815,85
Total	391,176	35338,6875	-	27382,32

As you can note from the table 12, in order to cover energy consumptions, we need to install more than 300 solar modules, that is literally impossible. Furthermore, all we need is to cover deficiency. The highest deficiency of energy is in winter season. The most reasonable quantity of solar modules is 70, it allows us to cover summer season, May and June.

Let us build the plot of energy generated by solar modules.

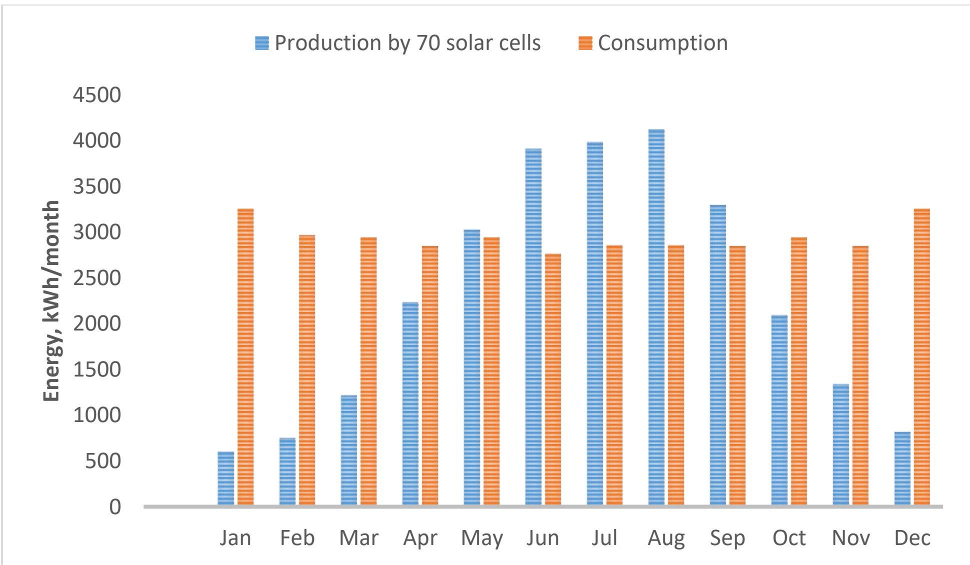

Figure 18. PV power plant energy balance per month for the whole year

Two solutions are possible to cover the current energy deficit. First is to install additional gasoline generator, the second is to install wind generators. From the previous calculation, I can note that to cover all the load I have to install at least **3x30kW wind generators** and **70 solar cells**.

Table 13 – Amount of energy generated by hybrid wind-solar power plant

Month	Energy consumption, [kWh]	Energy generated by 70 solar modules, [kWh]	Energy generated by 3x30kW wind generators, [kWh]	Total energy generated, [kWh]
January	3254.938	598.92	2941.044	3539.964
February	2966.1935	750.75	5360.718	6111.468
March	2944.938	1214.22	6257.204	7471.424
April	2849.94	2235.03	6576.854	8811.884
May	2944.938	3024.84	5818.780	8843.620
June	2764.56	3910.62	2677.831	6588.451
July	2856.712	3982.44	2004.239	5986.679
August	2856.712	4121.88	2025.336	6147.216
September	2849.94	3297.21	2860.349	6157.559
October	2944.938	2092.65	5861.670	7954.320
November	2849.94	1337.91	6955.288	8293.198
December	3254.938	815.85	6717.114	7532.964
Total	35338.6875	27382.32	56056.428	83438.748

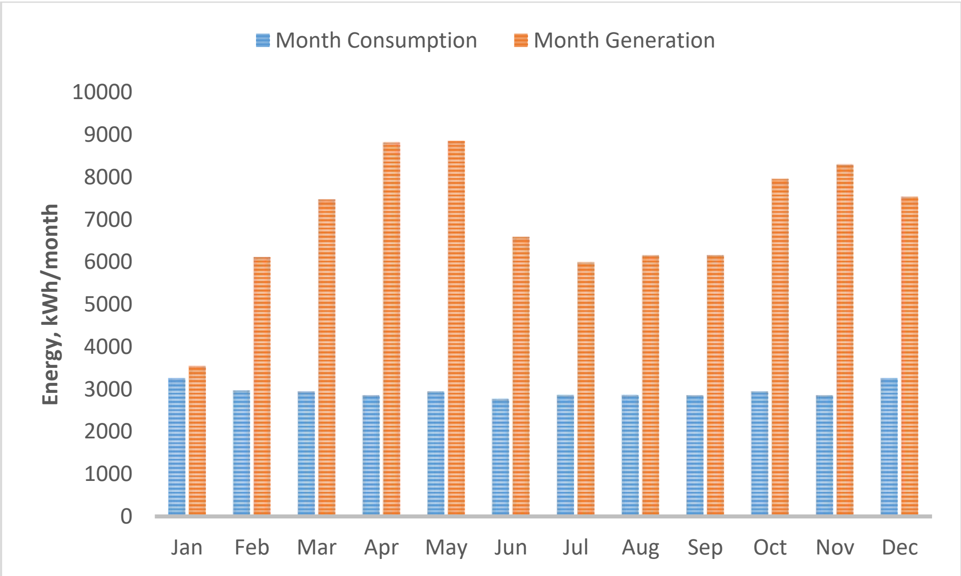

Figure 19. Wind-solar power plant monthly energy balance for the whole year

Gasoline generator

As gasoline generator I choose “EUROPOWER EP20000TE”. Brief description of main characteristics is provided in table below.

Table 14 – “EUROPOWER EP20000TE” generator main characteristics [26]

Nominal power, kW	16
Frequency, Hz	50
Dimensions l x w x h	100 x 64 x 72cm
Maximum apparent power, kVA	20
Nominal voltage, V	380/220
Cost	6000 EUR

The cost also includes ATS controller and AC/DC converter. The full specification is provided in the appendix 9.

Table 15 – approximate calculation of annual gasoline consumption for different structures of power plant

Month	Gasoline consumption, l/h		
	1 WT + GG	70 PV + GG	1 WT + 70 PV + GG
January	1327	1549	977
February	688	1292	250
March	501	1010	0
April	384	359	0
May	586	0	0
June	1092	0	0
July	1277	0	0
August	1273	0	0
September	1106	0	0
October	578	497	0
November	310	882	0
December	593	1423	117
Total	9714	7012	1344

* 1 WT + GG – Combination of 30 kW “Condor Air” wind generator + Gasoline generator “EUROPOWER EP20000TE”

* 70 PV + GG – Combination of 70 x 0.3 kW “Exmork FSM-300M” solar cells + Gasoline generator “EUROPOWER EP20000TE

* 1 WT + 70 PV + GG – Combination of 70 x 0.3kW “Exmork FSM-300M” solar cells + 30 kW “Condor Air” wind generator + Gasoline generator “EUROPOWER EP20000TE”

Inverter

The next device I have to install is inverter. Inverter is a device which converts DC voltage to AC voltage. The form of voltage can be sinusoidal, close to sinusoidal or pulsed. Inverters are used as stand-alone devices and as a part of uninterruptible power supply systems.

As inverter I choose "**GoodWe DT series 25 kW inverter**". Brief description of main characteristics is provided in table below.

GoodWe smart DT series inverter is typically designed for the home solar systems, covering 4kW/5kW/6kW. By adopting cutting-edge technology of photovoltaic field, it provides three phase AC output, making home system connection well balanced, safer and more convenient. The integrated two MPPTs allow two-array inputs from different roof orientations. And the combination of both RS485 and Wi-Fi communication makes the system well interactive and extremely easy to monitor. [27]

Table 16 – Brief description of main characteristics of the inverter [27]

Input Data(DC)	
Max. DC Power	32.5 kW
Max. DC Voltage	1000 V
Nominal DC Voltage	620 V
Min. DC Voltage to Start Feed In	250 V
Output Data (AC)	
Max. AC Power	25 kW
Nominal AC Power	25 kW
Nominal AC Voltage	400 V
Max. AC Current	37 A
Frequency	50, 60 Hz
Cost	3500 EUR

The full specification is provided in the appendix 10.

Batteries

The battery is a consumable item in an autonomous or backup power system. The better you pick up the battery for your system, the longer it will work and the less will ultimately be the cost of electricity generated by your system.

The main parameter of any battery is its capacity. Depending on which system it will be used in, it is necessary to choose the required face value. In our case, batteries are going to use as backup for the main power sources. It means, that battery will be discharged quite rarely (in case of fault of the main source of electricity). I will consider the required capacity based on a 100% discharge cycle. I will design backup system for 1 day of normal house operating.

Maximum daily consumption according to figure 10 is 105 kWh in winter. To supply house with energy during the whole this day we need to 8,75 kA*h capacity. I will install "**Delta DTM 12250 L (12V / 250Ah)**" in the amount of 35 batteries. Description of technical characteristics is provided in table below.

Table 17 – Technical characteristics of battery “**Delta DTM 12250 L (12V / 250Ah)**” [28]

Technical characteristics:	
Voltage, V	12
Capacity, Ah	250
Length, mm	520
Width, mm	269
Heigth, mm	222
Height with terminal, mm	225
Weigth, kg	71.2
Lifetime, age	12
Cost, EUR	500

Summary

After calculation of energy balance, I decided to consider a few additional hybrid combinations of power plant structure and complement them. I provide all the considered structures below:

- 5x30 kW “Condor Air” wind generator
- 30 kW “Condor Air” wind generator + Gasoline generator “EUROPOWER EP20000TE”
- 70x0.3kW “Exmork FSM-300M” solar cells + 3x30 kW “Condor Air” wind generator
- 70x0.3kW “Exmork FSM-300M” solar cells + Gasoline generator “EUROPOWER EP20000TE”
- 70x0.3kW “Exmork FSM-300M” solar cells + 30 kW “Condor Air” wind generator + Gasoline generator “EUROPOWER EP20000TE”

All other equipment is the same for all these options.

6. Economic comparison of possible option of electric supply

To make the final decision, it is very important to assess the not only technical, but also economic component of the project. In this chapter I will evaluate all the structures of electric supply from previous chapter with different types of financing. In particular I will consider financing with own funds and with bank loan.

It is necessary to note, that all considered power supply structures do not have any opportunity to sell electricity, since they are off-grid. Also, I do not consider selling equipment and other sources of revenues. Hence, it will be "expenses-only" project. Also, since net cash flow always will be negative, it is not necessary to calculate depreciation, because I will not pay any taxes. For such projects it is impossible to calculate IRR or Payback period, thus, to evaluate the structures, I will use the NPV investment decision criteria, calculated by formula from [29]:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - INV, \tag{14}$$

where CF_t – net cash flow during t-period;

r – discount rate;

t – number of time period;

T – project lifetime;

INV – initial investments.

Table 18 – Asset prices and lifetime

	Cost [EUR]	Lifetime [years]
Wind generator	26000	20
PV Cell	256	20
Gasoline generator	6000	20
Inverter	3500	20
Battery	500	10
Delievery	500	-
Maintenance	1000	-
Installation	Depends on the scenario	-
Other	3000	-
Gasoline fuel (1 liter)	0.55	-

* All the prices provided in the table have shown per unit of the equipment or product
* Maintenance will be held every year
* Other – all the expenses, that was not included in previous paragraphs, including wiring, gearboxes, project expenses

As you can note from table 18, lifetime of batteries twice lower than other equipment, thus, I have to buy new batteries after 10th year.

Table 19 – Scenarios description

	Wind generators number	PV Cells number	Fuel consumption	Batteries number	Bank loan	Investment cost, EUR
Scenario 1	5	-	-	35	No	157 000
Scenario 2	5	-	-	35	Yes	0
Scenario 3	1	-	9714	35	No	57 500
Scenario 4	1	-	9714	35	Yes	0
Scenario 5	3	70	-	35	No	122 420
Scenario 6	3	70	-	35	Yes	0
Scenario 7	-	70	7012	35	No	49 420
Scenario 8	-	70	7012	35	Yes	0
Scenario 9	1	70	1344	35	No	76 420
Scenario 10	1	70	1344	35	Yes	0

* Scenarios without fuel consumption do not include gasoline generator

In order to calculate annuity payment for bank loan I will use formula [29]:

$$PMT = PVAF \cdot PV = \frac{1-(1+r)^{-T}}{r} \cdot PV, \quad (15)$$

where PMT – annual loan payment,
PVAF – Present Value Annuity Factor,
PV – present value,
r – interest rate,
T – number of periods

Economic characteristics

Inflation rate – a quantitative measure of the rate at which the average price level of a basket of selected goods and services in an economy increases over some period of time. It is the rise in the general level of prices where a unit of currency effectively buys less than it did in prior periods. [30]

Table 20 – Inflation data [31]

Year	Inflation, %	Average value, %
2019	3	6,7
2018	4,3	
2017	2,5	
2016	5,4	
2015	12,9	
2014	11,36	
2013	6,45	
2012	6,58	
2011	6,1	
2010	8,78	

So, as inflation rate, I will use average value for last 10 years.

Inflation rate = 6,7 %

Cost escalation can be 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 specific to an item or class of items (not as general in nature), 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. [29]

Table 21 – Gasoline price growth data [32]

Year	Gasoline price growth, %	Average value
2017	6,58	7,76%
2016	6,10	
2015	6,83	
2014	5,23	
2013	7,75	
2012	5,97	
2011	6,77	
2010	12,56	
2009	12,06	

Gasoline escalation = 7,76 %

Batteries escalation should be less than inflation due to obsolescence of this technology, but not zero, I assume

Batteries escalation = 2 %

Escalation for maintenance I assume to be equal to average inflation rate.

Maintenance escalation = 7,76 %

The interest rate is the amount a lender charges for the use of assets expressed as a percentage of the principal. The interest rate is typically noted on an annual basis known as the annual percentage rate. The assets borrowed could include cash, consumer goods, or large assets such as a vehicle or building. [33]

According to database [34] long term loans interest rates are from 8 to 19%. So, let us assume

Interest rate = 11 %

Discount rate is used in discounted cash flow analysis. DCF is a commonly followed valuation method used to estimate the value of an investment based on its expected future cash flows. Based on the concept of time value of money, the DCF analysis helps assess the viability of a project or an investment by calculating the present value of expected future cash flows using a discount rate. [35]

Also, I assume a discount rate to be a risk-free asset. It is can be taken at the level of governmental bonds [36]

Discount rate = 8 %

Table 22 – Obtained results

	NPV, EUR
Scenario 1	-183 427
Scenario 2	-218 928
Scenario 3	-174 628
Scenario 4	-188 021
Scenario 5	-148 847
Scenario 6	-177 361
Scenario 7	-141 319
Scenario 8	-152 830
Scenario 9	-115 396
Scenario 10	-133 196

As you can see from the table, the best scenario according to economic evaluation is 9th, but I will not rush to conclusions as this is not the only factor important for me. In order to make a final decision, I have to take into account cost of initial investment and technical parameters.

The full tables with calculations provided in appendices 11, 12 and 13.

Sensitivity analysis

Sensitivity analysis of an investment project (sensitivity analysis) is an assessment of the impact of changes in the initial parameters of an investment project (investment costs, cash inflows, discount rate, operating expenses, etc.) on its final characteristics, which are usually used as IRR or NPV.

To analyze the sensitivity of an investment project, the main thing is to assess the degree of influence of each (or a combination of) changes from the initial parameters in order to provide for the worst development of the situation in the investment project. [37]

In this part I will analyze sensitivity of all the scenarios to discount rate, interest rate, fuel escalation and fuel price in order to evaluate how input parameters affect the project.

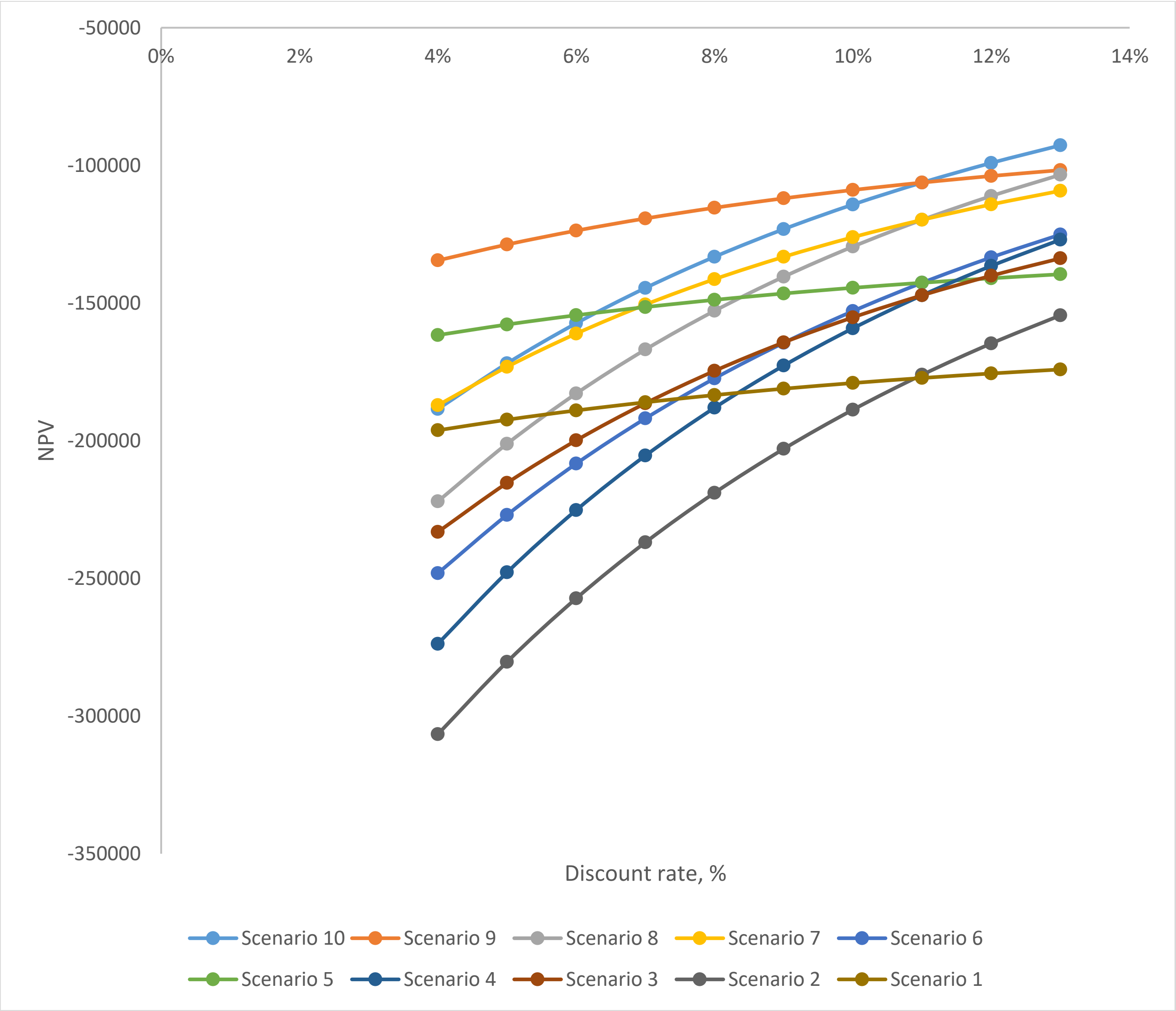

Figure 20. Sensitivity of NPV to discount rate

As you can see from the figure 20, the higher discount rate, the higher will be NPV for these scenarios. It can be explained by type of the projects, due to there are no cash inflows, increase of discounting leads to increase of NPV.

If you compare two best scenarios, 9 and 10, you can note, that scenario with bank loan become more advantageous when discount rate becomes higher than interest rate.

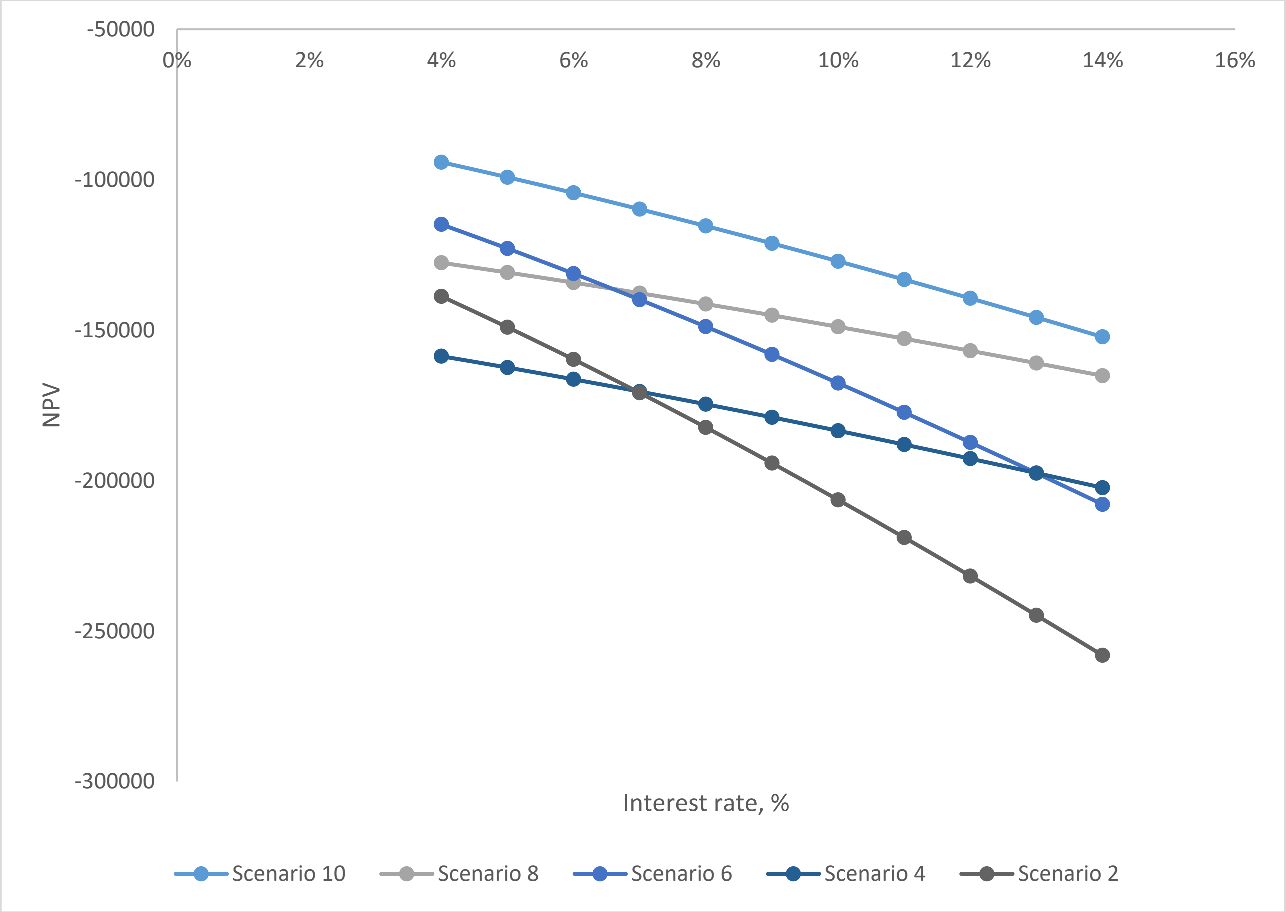

Figure 21. Sensitivity of NPV to interest rate

On this figure I have shown only these scenarios, which include bank loan. As you can see here, the higher loan amount of the scenario, the more sensitive NPV will be to interest rate. In any case, scenario 10 has the best NPV comparing with other scenarios, financed by bank loan.

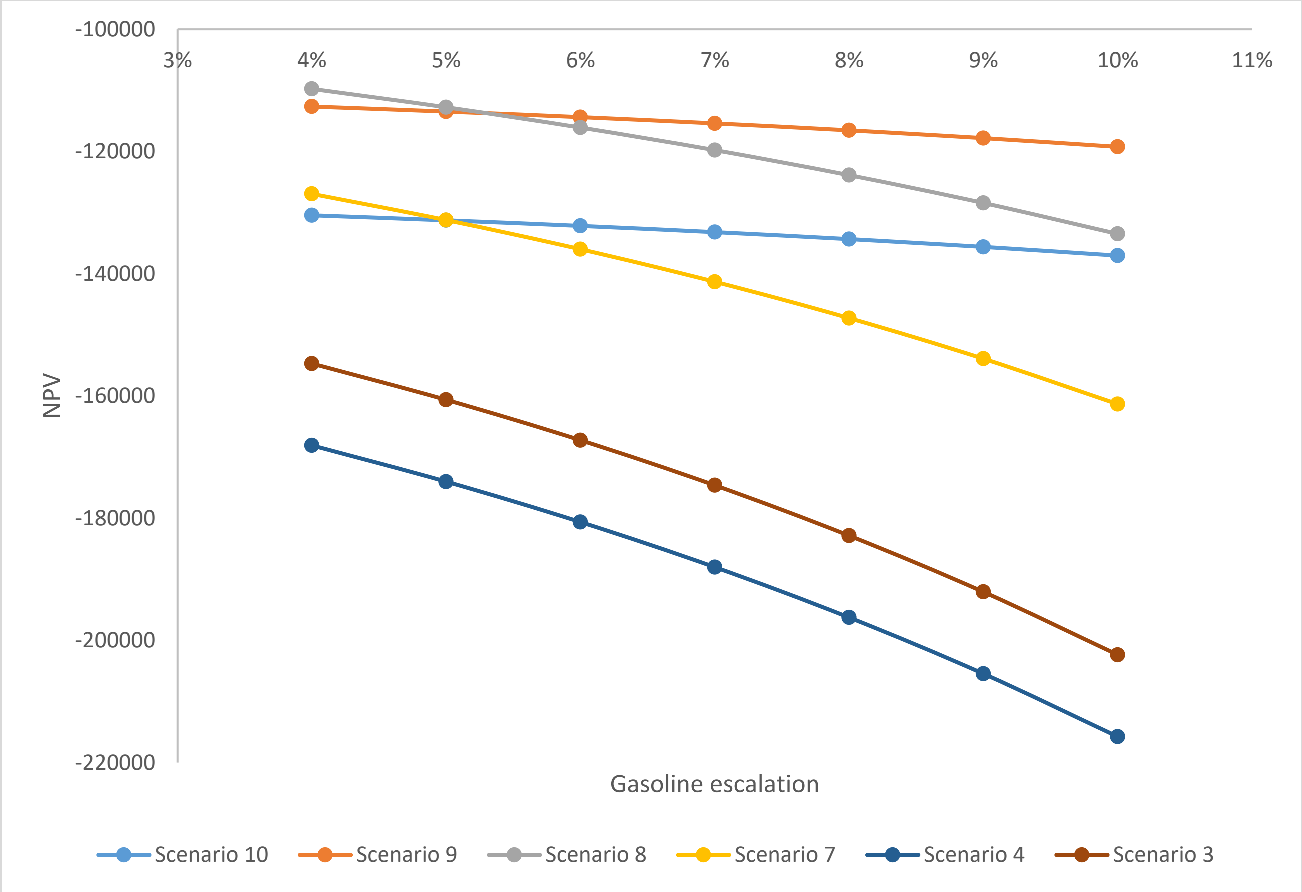

Figure 22. Sensitivity of NPV to gasoline escalation

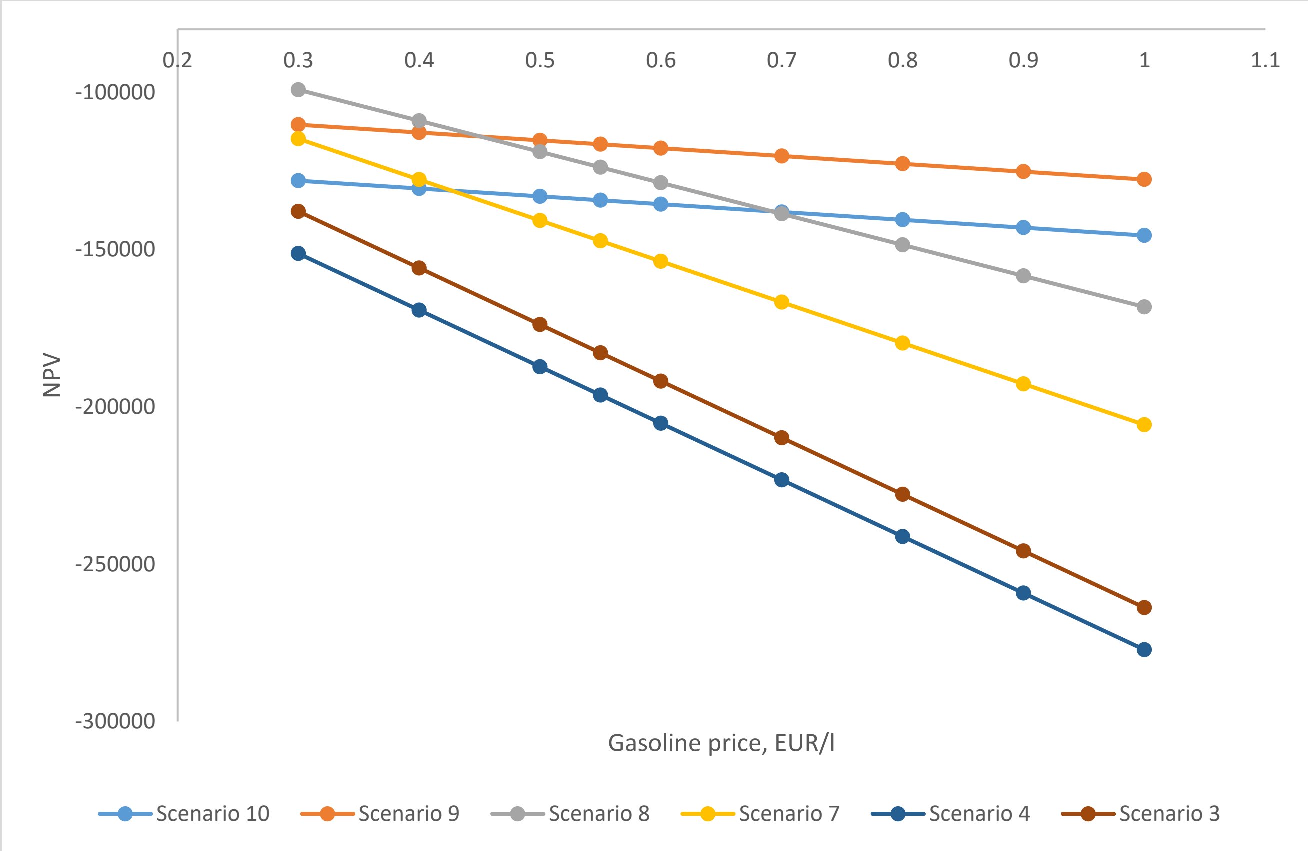

Figure 23. Sensitivity of NPV to gasoline price

I include to both this and previous figure only scenarios, including gasoline generator. As you can see, dependence for same project, but with different initial financing are same. However, it is necessary to note, projects with higher consumption of fuel more sensitive to fuel price/escalation.

7. Final decision making

Now, as rational decision maker, I should make the most suitable decision for me. Almost everything is ready for a final decision, however, to make a decision, it is only necessary to introduce criteria for evaluation and evaluate each scenario according to the entered criteria so that the solution is the most suitable for me.

Among the criteria, one should take into account not only the NPV of each scenario, but also other aspects, such as Investment cost and Reliability, etc. The final list of criteria will be given in the table below, with explanations.

Table 23 – Scenarios evaluation according to specified criteria

	Reliability [C1]	Convenience [C2]	NPV [C3]	Investment cost [C4]	Fuel dependence [C5]
Type	max	max	max	min	min
Scale	ordinal [1 to 5]	ordinal [1 to 5]	interval	interval	ordinal [0 to 3]
Scenario 1	2.000	3.000	-1.834	1.57	0.000
Scenario 2	2.000	3.000	-2.189	0	0.000
Scenario 3	4.000	5.000	-1.746	0.575	3.000
Scenario 4	4.000	5.000	-1.880	0	3.000
Scenario 5	1.000	4.000	-1.488	1.2242	0.000
Scenario 6	1.000	4.000	-1.774	0	0.000
Scenario 7	3.000	2.000	-1.413	0.4942	2.000
Scenario 8	3.000	2.000	-1.528	0	2.000
Scenario 9	5.000	1.000	-1.154	0.7642	1.000
Scenario 10	5.000	1.000	-1.332	0	1.000
Weight	0.200	0.150	0.300	0.250	0.100

Here I would like to clarify that from customer point of view, the value of the initial investment has almost the same value as NPV. Since we are talking about large amounts of money, an individual may simply not have that kind of money. As for the other scales, they are intuitively arranged and displays what interests me more among these scenarios.

There are two types of scale – ordinal and inverval. An ordinal scale is one where the order matters but not the difference between values. An interval scale is one where there is order and the difference between two values is meaningful. [38]

In order to find the optimal solution, I use Global Criterion Method. [39] According to this method, I have to recalculate values from initial scale, to relative scale. In order to do that I should use formulas (16) for “min” and (17) for “max”:

$$f = \frac{f_W - f_i}{f_W - f_B} \tag{16}$$

$$f = \frac{f_i - f_W}{f_B - f_W}, \quad (17)$$

Where f_W – the worst scenario rating of the criteria,

f_B – the best scenario rating of the criteria,

f_i – current scenario rating of the criteria,

f – relative rating of the criteria

Table 24 – Results of calculation according to global criterion method

	Reliability [C1]	Convenience [C2]	NPV [C3]	Investment cost [C4]	Fuel dependence [C5]	$\sum w_i f_i$
Scenario 1	0.250	0.500	0.343	0.000	1.000	0.328
Scenario 2	0.250	0.500	0.000	1.000	1.000	0.475
Scenario 3	0.750	1.000	0.428	0.634	0.000	0.587
Scenario 4	0.750	1.000	0.299	1.000	0.000	0.640
Scenario 5	0.000	0.750	0.677	0.220	1.000	0.471
Scenario 6	0.000	0.750	0.401	1.000	1.000	0.583
Scenario 7	0.500	0.250	0.750	0.685	0.333	0.567
Scenario 8	0.500	0.250	0.638	1.000	0.333	0.612
Scenario 9	1.000	0.000	1.000	0.513	0.667	0.695
Scenario 10	1.000	0.000	0.828	1.000	0.667	0.765

According to global criterion methodic, the obtained value the better solution will be.

So, as you can see, from the table 23, the best solution will be “Scenario 10”. This scenario includes hybrid power supply, financing by bank loan. More precisely, there will be installed 70 PV Cells, 1 Gasoline generator and 1 Wind generator.

It is necessary to note, although scenario 10 has close value to scenario 9, obtained scenario is more suitable decision. Since the value of initial investment is significant factor, especially from customer point view, although as a result I choose scenario with lower NPV. Between these two scenarios this criterion is decisive.

Conclusion

The main goal of my work was to provide electricity to a house inaccessible to the central power supply system. The objectives of this work were the design of various power supply options and the choice of the optimal one. Also, my goals were to reduce environmental impact factors and to calculate the economic efficiency of the cottage's electricity supply using renewable energy sources.

The main result of this work is a developed algorithm for the optimal design of a decentralized power supply system. The created model takes into account a very wide range of factors, trying to assess the main possible risks and problems associated with the problem of building a power supply system. However, this complexity is close to real situations when the designer is faced not only with technical obstacles when creating a new generating unit.

I looked at five different scenarios with different financing options. 5 wind generators; 3 wind generators and 70 solar panels; 1 wind generator and 1 gasoline generator; 70 solar panels and a gasoline generator; 1 wind generator, 70 solar panels and one gasoline generator. Among these options, from my point of view, it was necessary to choose an option that is reliable enough, but at the same time the most economically profitable, with minimal dependence on the price of fuel.

The result of the presented algorithm is a project ready for implementation, with economic indicators calculated for it and an analysis of possible risks, such as changes in fuel prices, changes in interest rates on loans, etc. The resulting project consists of one wind generator “Condor Air” 30 kW, 70 PV cells “Exmork FSM-300M” and one gasoline generator “EUROPOWER EP20000TE” 16 kW. From the decision-making part, I would note that the most suitable financing option for me is a bank loan. The decisive factor for me, from a consumer point of view, was the value of the initial investment cost.

It should be noted that all the work I have done is based on statistical data, such as wind speeds, solar radiation, electricity consumption. All these data will be well suited for the average cottage, in weather conditions that do not deviate from the norm. However, if against the weather anomalies there is an energy source independent of the weather conditions, as well as rechargeable batteries, in order to store energy, then no one is safe from force majeure situations, such as the financial and economic crisis, the epidemic, the sledges against the state, which is very strongly affects inflation, component prices, interest rates, gasoline prices, etc.

The last, but not least factor is the subsidization of alternative energy by the government. Unfortunately, currently in Russia there are no such subsidies and there are no prerequisites for them to appear. It only remains to hope for an improvement in the situation regarding alternative energy, because for many people this will be the decisive factor.

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Appendices

Appendix 1 – Winter solar radiation values for 1 m^2 based on data from [14]

Time	Sun angle, φ, deg	λ, kW/m^2	P, kW/m^2
9:00 – 9:33	0	0	0
9:33 – 10:00	10,6346	0,1005	0,0151
10:00 – 11:00	34,2670	0,2444	0,0367
11:00 – 12:00	57,8993	0,3612	0,0542
12:00 – 13:00	81,5317	0,4381	0,0657
13:00 – 14:00	105,1641	0,4666	0,0700
14:00 – 15:00	128,7965	0,4434	0,0665
15:00 – 16:00	152,4289	0,2581	0,0387
16:00 – 17:00	176,0613	0,1164	0,0175
17:00 – 17:10	180	0,0234	0,0035
17:10 – 18:00	0	0	0
Total			0,3678

Appendix 2 – Spring solar radiation values for 1 m^2 based on data from [14]

Time	Sun angle, φ, deg	λ, kW/m^2	P, kW/m^2
6:00-6:53	0	0	0
6:53-7:00	1,6092	0,0875	0,0131
7:00-8:00	15,4023	0,2209	0,0331
8:00-9:00	29,1954	0,3422	0,0513
9:00-10:00	42,9885	0,4448	0,0667
10:00 - 11:00	56,7816	0,5230	0,0785
11:00 - 12:00	70,5747	0,5725	0,0859
12:00 - 13:00	84,3678	0,5908	0,0886
13:00 - 14:00	98,1609	0,5766	0,0865
14:00 - 15:00	111,9540	0,5309	0,0796
15:00 - 16:00	125,7471	0,4561	0,0684
16:00 - 17:00	139,5402	0,3563	0,0534
17:00-18:00	153,3333	0,2370	0,0356
18:00-19:00	167,1264	0,1047	0,0157
19:00-19:56	180	0	0
Total			0,7565

Appendix 3 – Summer solar radiation values for 1 m^2 based on data from [14]

Time	Sun angle, φ, deg	λ, kW/m^2	P, kW/m^2
4:00-4:51	0,0000	0,0000	0,0000
4:51 - 5:00	1,5851	0,0571	0,0086
5:00 - 6:00	12,1526	0,1213	0,0182
6:00 - 7:00	22,7202	0,1815	0,0272
7:00-8:00	33,2877	0,2142	0,0321
8:00-9:00	43,8552	0,2981	0,0447
9:00-10:00	54,4227	0,4020	0,0603
10:00 - 11:00	64,9902	0,4886	0,0733
11:00 - 12:00	75,5577	0,5543	0,0831
12:00 - 13:00	86,1252	0,5963	0,0894
13:00 - 14:00	96,6928	0,6127	0,0919
14:00 - 15:00	107,2603	0,6029	0,0904
15:00 - 16:00	117,8278	0,5672	0,0851
16:00 - 17:00	128,3953	0,4256	0,0638
17:00-18:00	138,9628	0,3257	0,0489
18:00-19:00	149,5303	0,2118	0,0318
19:00 - 20:00	160,0978	0,1240	0,0186
20:00 - 21:00	170,6654	0,0880	0,0132
21:00 - 21:53	180,0000	0,0500	0,0075
Total			0,8882

Appendix 4 – Autumn solar radiation values for 1 m^2 based on data from [14]

Time	Sun angle, φ, deg	λ, kW/m^2	P, kW/m^2
7:00-7:24	0,0000	0,0000	0,0000
7:24-8:00	9,3642	0,0443	0,0066
8:00-9:00	24,9711	0,1553	0,0233
9:00-10:00	40,5780	0,2543	0,0381
10:00 - 11:00	56,1850	0,3315	0,0497
11:00 - 12:00	71,7919	0,3811	0,0572
12:00 - 13:00	87,3988	0,3988	0,0598
13:00 - 14:00	103,0058	0,3832	0,0575
14:00 - 15:00	118,6127	0,3356	0,0503
15:00 - 16:00	134,2197	0,2599	0,0390
16:00 - 17:00	149,8266	0,1625	0,0244
17:00-18:00	165,4335	0,0516	0,0077
18:00-18:56	180,0000	0,0070	0,0011
Total			0,4148

Appendix 5 – Hour coefficient for winter and summer season [19]

Hour	Season	
	Winter	Summer
1	0,25	0,15
2	0,25	0,15
3	0,25	0,15
4	0,25	0,15
5	0,25	0,175
6	0,35	0,21
7	0,50	0,28
8	0,60	0,31
9	0,40	0,28
10	0,30	0,21
11	0,35	0,21
12	0,40	0,21
13	0,30	0,24
14	0,30	0,21
15	0,30	0,21
16	0,30	0,21
17	0,40	0,21
18	0,70	0,21
19	1,00	0,25
20	0,95	0,28
21	0,70	0,5
22	0,50	0,7
23	0,35	0,42
24	0,30	0,18

Appendix 6 – Hour coefficient for winter and summer period

Hour	1	2	3	4	5	6	7	8
Winter	0,25	0,25	0,25	0,25	0,25	0,35	0,5	0,6
Summer	0,15	0,15	0,15	0,15	0,175	0,21	0,28	0,31
Hour	9	10	11	12	13	14	15	16
Winter	0,4	0,3	0,3	0,35	0,4	0,3	0,3	0,3
Summer	0,28	0,21	0,21	0,21	0,24	0,21	0,21	0,21
Hour	17	18	19	20	21	22	23	24
Winter	0,4	0,7	1	0,95	0,7	0,5	0,35	0,3
Summer	0,21	0,21	0,25	0,28	0,5	0,7	0,42	0,18

Appendix 7 – Wind generator “Condor Air” 30 kW [24]

Wind wheel diameter	13 m
Blade height	6 m
Nominal RPM	35-40
Output voltage	170-240 V
Nominal power	30 kW
Maximum power	32 kW
Starting wind speed	2,5 m/sec
Nominal wind speed	9 m/sec
Operational wind speed	3 - 20 m/sec
Hurricane protection	Automatic
Automatic wind orientation	Yes
Tower height	20 m
Weight without tower	1730 kg
Blades quantity	3
Wind energy utilization	>0,42
Generator type	Three phase permanent-magnet generator
Generator frequency	0 - 50 Hz
Output current	Alternating
Nominal current	100 A
Maximum current	110 A
Inverter type	Optional
Recommended Battery Quantity	20/40
Recommended Battery Capacity	150/200 A*hour
Conversion system efficiency	>0,85
Noise level	45 dB
Wind speed limit	35 m/sec
Basic equipment	
Tower	1 unit
Generator	1 unit
Rotor	1 unit
Blades	Set
Fasteners	Set
Controller	1 unit
Technical certificate	1 unit
Cost	26000 EUR
Lifetime	20 years

Appendix 8 – Solar module “Exmork FSM-300M” technical specification [25]

Electrical parameters	
Maximum power, W	300
On-load voltage, V	36
Off-load voltage, V	43,15
On-load current, V	8,33
Short circuit current, A	9,14
Maximum off-load voltage of PV array, V	1000
Efficiency, %	17,4
Operational parameters	
Sizes (LxWxH), mm	1956x992x45
Weight, kg	23
Quantity of elements	72 (12x6)
Solar cells	Grade A, monocrystal
Cell size, mm	156x156
Type of cable connectors	MC4
Shell protection	Anodized aluminum frame, tempered anti-reflective glass
Operating and storage temperature, ° C	-40 +80 ℃
Protection level	IP 65
Cost	256 EUR
Lifetime	20 years

Appendix 9 – Gasoline generator “EUROPOWER EP20000TE” technical specification [26]

Generator	
kVA max.	20
kVA cont.	18
kVA @ 1~230V	6
kVA @ 3~400V	18
kW max.	16
Amps cont. @ 1~230V	26A
Amps cont. @ 3~400V	26A
Dimensions l x w x h	100 x 64 x 72cm
Weight incl. oil (+ coolant if water-cooled), excl. fuel	213kg
Weight incl. oil (+ coolant if water-cooled) + fuel	244kg
Engine	
Brand/Type	B&S Vanguard 543477 1142 J1-14051512
HP max.	28
kW max.	21
rpm	3000
Cylinder	2
Fuel	Gasoline
EU Emission norm	Stage V
Cooling	Air-cooled
Displacement	895cm3
Consumption @75% load	7 litres/hour
Tank	41 litres
Autonomy @75% load	5.9 hours
Noise level	79 dB(A)@7m
Alternator	
Brand/Type	Sincro GT2MAS ˜ with brushes
Nominal voltage	3~400V and 1~230V
Frequency	50Hz
Protection degree	IP23
Lifetime	20 years

Appendix 10 – Inverter “**GoodWe DT series 25 kW” technical specification** [27]

Input Data(DC)	
Max. DC Power	32.5 kW
Max. DC Voltage	1000 V
Nominal DC Voltage	620 V
Min. DC Voltage to Start Feed In	250 V
Max. DC Current	27 A
MPP(T) Voltage Range	260~850 V
No of MPP Trackers	2
DC Inputs	6
Output Data (AC)	
Max. AC Power	25 kW
Nominal AC Power	25 kW
Nominal AC Voltage	400 V
Max. AC Current	37 A
Frequency	50, 60 Hz
Power Factor (cosθ)	1
Distortion (THD)	< 1.5 %
No of feed-in phases	3
Max. Efficiency	98.40%
Euro Efficiency	98.10%
General Data	
Dimensions (H/W/D)	650x516x203 mm
Weight	40 kg
Power Consumption at Night	< 1 W
Noise Level	< 45 dB(A)
Operating Temperature	-25 ~ +60 ℃
Transformer	Transformerless
Humidity	0-100 %
Cooling	Fan
Max. Altitude	4000 m
Interface	RS 485, WLAN
Display	LCD, LED
Protection Features	
Protection Features	Anti Island Protection(ENS), Overvoltage Protection, Overcurrent Protection, Residual Current Device (RCD), Reverse Polarity Protection
Lifetime	20 years

Appendix 11 – NPV Calculations for Scenarios 1 – 4

Scenario 1																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Investment																						
Wind gene	130000																					
Inverter	3500																					
Batteries	17500										21332.4											
Delivery	500																					
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Installatio	2500																					
Other	3000																					
CF	-157000	-1000	-1067	-1138.49	-1214.77	-1296.16	-1383	-1475.66	-1574.53	-1680.02	-23125	-1912.69	-2040.84	-2177.57	-2323.47	-2479.14	-2645.25	-2822.48	-3011.59	-3213.36	-3428.66	NPV
DCF	-157000	-925.926	-914.781	-903.769	-892.891	-882.143	-871.524	-861.034	-850.67	-840.43	-10711.3	-820.319	-810.445	-800.69	-791.052	-781.53	-772.122	-762.828	-753.646	-744.575	-735.612	-183427.33

Scenario 2																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Loan payment		19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	19715.37	
Batteries													22194.23									
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
CF		-20715.4	-20782.4	-20853.9	-20930.1	-21011.5	-21098.4	-21191	-21289.9	-21395.4	-21508	-21628.1	-43950.4	-21892.9	-22038.8	-22194.5	-22360.6	-22537.9	-22727	-22928.7	-23144	NPV
DCF		-19180.9	-17817.5	-16554.5	-15384.3	-14300.1	-13295.6	-12364.8	-11502.3	-10703	-9962.35	-9275.91	-17453.3	-8049.99	-7503.37	-6996.64	-6526.85	-6091.28	-5687.4	-5312.86	-4965.51	-218928.39

Scenario 3																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Wind gene	26000																					
Gasoline g	6000																					
Inverter	3500																					
Batteries	17500										21332.4											
Delivery	500																					
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Installatio	1000																					
Fuel		5342.7	5716.689	6116.857	6545.037	7003.19	7493.413	8017.952	8579.209	9179.753	9822.336	10509.9	11245.59	12032.78	12875.08	13776.33	14740.68	15772.53	16876.6	18057.96	19322.02	
Other	3000																					
CF	-57500	-6342.7	-6783.69	-7255.35	-7759.8	-8299.35	-8876.41	-9493.61	-10153.7	-10859.8	-32947.3	-12422.6	-13286.4	-14210.4	-15198.6	-16255.5	-17385.9	-18595	-19888.2	-21271.3	-22750.7	NPV
DCF	-57500	-5872.87	-5815.92	-5759.53	-5703.69	-5648.4	-5593.65	-5539.43	-5485.75	-5432.59	-15261	-5327.83	-5276.22	-5225.12	-5174.51	-5124.4	-5074.79	-5025.65	-4977	-4928.82	-4881.12	-174628.28

Scenario 4																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Loan payment		7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	7220.599	
Batteries											21332.4											
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Fuel		5342.7	5716.689	6116.857	6545.037	7003.19	7493.413	8017.952	8579.209	9179.753	9822.336	10509.9	11245.59	12032.78	12875.08	13776.33	14740.68	15772.53	16876.6	18057.96	19322.02	
CF		-13563.3	-14004.3	-14475.9	-14980.4	-15519.9	-16097	-16714.2	-17374.3	-18080.4	-40167.9	-19643.2	-20507	-21431	-22419.2	-23476.1	-24606.5	-25815.6	-27108.8	-28491.9	-29971.3	NPV
DCF		-12558.6	-12006.4	-11491.5	-11011	-10562.6	-10143.8	-9752.58	-9386.81	-9044.69	-18605.5	-8424.63	-8143.62	-7880.12	-7632.85	-7400.64	-7182.41	-6977.16	-6783.95	-6601.92	-6430.28	-188021.19

Appendix 12 – NPV Calculations for Scenarios 5 – 8

Scenario 5																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Wind gene	78000																					
PV cells	17920																					
Inverter	3500																					
Batteries	17500										21332.4											
Delivery	500																					
Installatio	2000																					
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Other	3000																					
CF	-122420	-1000	-1067	-1138.49	-1214.77	-1296.16	-1383	-1475.66	-1574.53	-1680.02	-23125	-1912.69	-2040.84	-2177.57	-2323.47	-2479.14	-2645.25	-2822.48	-3011.59	-3213.36	-3428.66	NPV
DCF	-122420	-925.926	-914.781	-903.769	-892.891	-882.143	-871.524	-861.034	-850.67	-840.43	-10711.3	-820.319	-810.445	-800.69	-791.052	-781.53	-772.122	-762.828	-753.646	-744.575	-735.612	-148847.33

Scenario 6																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Loan payment		15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	15372.97	
Batteries											21332.4											
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
CF		-16373	-16440	-16511.5	-16587.7	-16669.1	-16756	-16848.6	-16947.5	-17053	-38498	-17285.7	-17413.8	-17550.5	-17696.4	-17852.1	-18018.2	-18195.4	-18384.6	-18586.3	-18801.6	NPV
DCF		-15160.2	-14094.6	-13107.3	-12192.5	-11344.7	-10559.1	-9831.01	-9156.21	-8530.74	-17832	-7413.52	-6915.26	-6453.3	-6024.95	-5627.73	-5259.35	-4917.66	-4600.72	-4306.68	-4033.86	-177361.41

Scenario 7																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
PV cells	17920																					
Gasoline g	6000																					
Inverter	3500																					
Batteries	17500										21332.4											
Delivery	500																					
Installatio	1000																					
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Fuel		3856.6	4126.562	4415.421	4724.501	5055.216	5409.081	5787.717	6192.857	6626.357	7090.202	7586.516	8117.572	8685.802	9293.808	9944.375	10640.48	11385.31	12182.29	13035.05	13947.5	
Other	3000																					
CF	-49420	-4856.6	-5193.56	-5553.91	-5939.27	-6351.37	-6792.08	-7263.38	-7767.39	-8306.38	-30215.2	-9499.2	-10158.4	-10863.4	-11617.3	-12423.5	-13285.7	-14207.8	-15193.9	-16248.4	-17376.2	NPV
DCF	-49420	-4496.85	-4452.64	-4408.87	-4365.54	-4322.64	-4280.16	-4238.11	-4196.48	-4155.26	-13995.5	-4074.05	-4034.04	-3994.44	-3955.23	-3916.41	-3877.98	-3839.93	-3802.25	-3764.95	-3728.02	-141319.34

Scenario 8																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Loan payment		6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	6205.948	
Batteries											21332.4											
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Fuel		3856.6	4126.562	4415.421	4724.501	5055.216	5409.081	5787.717	6192.857	6626.357	7090.202	7586.516	8117.572	8685.802	9293.808	9944.375	10640.48	11385.31	12182.29	13035.05	13947.5	
CF		-11062.5	-11399.5	-11759.9	-12145.2	-12557.3	-12998	-13469.3	-13973.3	-14512.3	-36421.1	-15705.2	-16364.4	-17069.3	-17823.2	-18629.5	-19491.7	-20413.7	-21399.8	-22454.4	-23582.1	NPV
DCF		-10243.1	-9773.24	-9335.35	-8927.1	-8546.3	-8190.96	-7859.22	-7549.36	-7259.78	-16870	-6735.67	-6498.51	-6276.36	-6068.11	-5872.79	-5689.43	-5517.2	-5355.28	-5202.95	-5059.5	-152830.25

Appendix 12 – NPV Calculations for Scenarios 9 and 10

Scenario 9																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Wind gene	26000																					
PV cells	17920																					
Gasoline g	6000																					
Inverter	3500																					
Batteries	17500										21332.4											
Delivery	500																					
Installatio	2000																					
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Fuel		739.2	790.944	846.3101	905.5518	968.9404	1036.766	1109.34	1186.994	1270.083	1358.989	1454.118	1555.907	1664.82	1781.357	1906.052	2039.476	2182.239	2334.996	2498.446	2673.337	
Other	3000																					
CF	-76420	-1739.2	-1857.94	-1984.8	-2120.32	-2265.1	-2419.77	-2585	-2761.52	-2950.11	-24484	-3366.81	-3596.74	-3842.39	-4104.83	-4385.2	-4684.72	-5004.72	-5346.58	-5711.81	-6101.99	NPV
DCF	-76420	-1610.37	-1592.89	-1575.6	-1558.5	-1541.59	-1524.86	-1508.32	-1491.97	-1475.79	-11340.8	-1443.97	-1428.32	-1412.84	-1397.53	-1382.4	-1367.43	-1352.62	-1337.98	-1323.49	-1309.17	-115396.44

Scenario 10																						
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Loan payment		9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	9596.49	
Maintenance		1000	1067	1138.489	1214.768	1296.157	1383	1475.661	1574.53	1680.023	1792.585	1912.688	2040.838	2177.575	2323.472	2479.145	2645.247	2822.479	3011.585	3213.361	3428.656	
Fuel		739.2	790.944	846.3101	905.5518	968.9404	1036.766	1109.34	1186.994	1270.083	1358.989	1454.118	1555.907	1664.82	1781.357	1906.052	2039.476	2182.239	2334.996	2498.446	2673.337	
Batteries											21332.4											
CF		-11335.7	-11454.4	-11581.3	-11716.8	-11861.6	-12016.3	-12181.5	-12358	-12546.6	-34080.5	-12963.3	-13193.2	-13438.9	-13701.3	-13981.7	-14281.2	-14601.2	-14943.1	-15308.3	-15698.5	NPV
DCF		-10496	-9820.33	-9193.6	-8612.2	-8072.8	-7572.28	-7107.78	-6676.65	-6276.42	-15785.9	-5559.74	-5239.22	-4941.45	-4664.77	-4407.61	-4168.55	-3946.25	-3739.49	-3547.12	-3368.08	-133196.2