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

Application of stand-alone photovoltaic system

Master's thesis

Study program: Electrical Engineering, Power Engineering and Management

Field of study: Economy and Management of power engineering

Scientific adviser: Martin Beneš

Timofei Abramov

Prague 2019

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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

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

Branch of study: **Economy and Management of Power Engineering**

II. Master's thesis details

Master's thesis title in English:

Application of Standalone Photovoltaic System.

Master's thesis title in Czech:

Application of Standalone Photovoltaic System.

Guidelines:

1. Describe use of solar energy in Russian Federation. 2. Create design of PV power source and implementation of PV system for supplying a public building. 3. Calculate technical properties and characteristics of the source. 4. Evaluate economic effectiveness of the source, make the electricity price comparison of variants.

Bibliography / sources:

1. Editor(s): Reinders A., Verlinden P., van Sark W., Freundlich A.: Photovoltaic Solar Energy – From Fundamentals to Applications, John Wiley & Sons, Ltd., 2017 2. Brealey R. A., Myers S. C., Allen F.:Principles of Corporate Finance, 10th edition, McGraw-Hill, 2011

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Date of master's thesis assignment: **31.01.2019** Deadline for master's thesis submission: __________

Assignment valid until: **20.09.2020**

Ing. Martin Beneš, Ph.D. Supervisor's signature	Head of department's signature	prof. Ing. Pavel Ripka, CSc. 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".

Date Signature

Abstract

The purpose of the master thesis is estimation of effectiveness of photovoltaic system implementation. In the thesis two approaches are investigated. In the first approach firm-owner of PV system covers their own demand, in other words it substitutes power supply from centralized network by RES. In the second approach firm-owner sell power energy on retail market, receiving profit. This two approaches are estimated by such investment criteria as NPV, IRR, PP. PV system consists solar modules, inverters, solar trackers. Storage battery are eliminated because the consumption is much higher than generation in all points of time for both approaches. Assessment of power production forecast is providing in the MatLab Simulink. All components of PV system and external factors (wind speed, daily temperature, solar irradiation) are simulated with capability to change inputs in order to provide simulations for different areas, different designs of renewable systems, and different days of the year.

The results obtained in the project shows an efficiency of PV system implementation in Russian Federation.

Key words: PV system, economic evaluation, renewables.

Contents

List of abbreviations

PV - photovoltaic

NPV – net present value

IRR – internal rate of return

PP – payback period

DPP – discounted payback period

RES – renewable energy system

ct/kWh – cent per kilowatt in hour

ROI – return on investments

Introduction

The conventional fossil fuel energy sources such as petroleum, natural gas, and coal which meet most of the world's energy demand today are being depleted rapidly. Also, their combustion products are causing global problems such as the greenhouse effect and pollution which are posing great danger for our environment and eventually for the entire life on our planet [1]. Solar photovoltaic technology is one of the most rapidly growing renewable sources of electricity that has practical application in various fields of human activity due to its high availability, huge potential and environmental compatibility [2]. Renewable energy can't substitute conventional energy, so it is combined for receiving maximum effectiveness.

So far fields of applicability of PV systems are needed to be investigated. In this thesis will be researched the feasibility of applying standalone photovoltaic systems in the area of the Russian Federation. In order to achieve this goal will be chosen a location of installation, chosen equipment of the system and found out predicted output power. The forecast of power production is the most complicated event, because it depends on unpredictable stochastic factors, such as outside temperature, wind speed, cloudiness. In the current thesis, methods of mathematical and computer simulations will be applied simultaneously for achieving high accuracy of the forecast by considering total impact from stochastic parameters. The model of PV system will be created in MatLab Simulink. The result of the thesis will be evaluation of economic effectiveness of a standalone PV system by such investments criteria as net present value, internal rate of return, payback period and discounted payback period.

In the guideline is mentioned that designed renewable system will supply public building, but after launch of the thesis's writing, appeared an idea of researching two approaches, that will demonstrate two opposite results concerning different fields of renewable energy implementation: selling power energy in network and supply the demand of consumer. Was decided, that the PV system would be created by an industrial enterprise and it would generate power energy to cover the firm's demand and save money on electricity bills in the first approach, and in the second approach produced energy will sell in the network. This changes are approved by the scientific advisor.

Throughout the work a reader will face the following structure. The master thesis starts with providing information about solar energy in the area of Russian Federation. The chapter two is devoted to design of PV system, simulation of its components and external parameters and their integration in one model. After that is necessary to choose the equipment (solar modules, solar trackers etc) and a consumer, that will build RES and further define the approach of it's application. In the third chapter are provided simulations for each month under certain conditions and received all necessary output values. The last but not least chapter four is devoted to financial assessment. There are estimated all parameters for financial model (value of investments, operation costs, the source of revenue and discount rate), made cash flow statements, a decision regard the approach and sensitivity analysis for the most profitable case in order to evaluate a stability of the project.

The results will be summarized in the conclusion.

Chapter 1. Renewable energy in the Russian Federation

1.1.Renewable energy

Conventional energy sources such as oil, gas and coal, which are used to convert energy in electricity all around the world, are rapidly depleted. In addition, combustion products are the cause of global problems: the greenhouse effect and pollution, which poison and cause huge damage to all life on the planet. Environment conditions – one of the most important social-ecological problem, that influences at the all citizens. Pleasant environment is necessary condition for state development and citizens health [3]. In this regard, renewable energy sources (solar, wind, geothermal) have been developing rapidly over the past decade. The great potential of solar energy is attractive to be used. United Nations Organization evaluates annual potential of solar energy is 1,575 – 49,837 EJ. It exceeds total world consumption, that was equal 567 EJ in 2012 [4]. The potential of solar energy that can be used by humans is distinguished from the amount of solar energy present near the planet's surface, as factors such as geography, the time of day changing, cloudiness, earth's availability to humans - constraint the amount of solar energy we could take [5].

Since its first application in space missions in 1958, solar photovoltaics technology has come a long way. The photovoltaic systems programme (PVPS) of the International Energy Agency (IEA) was established in 1993 and is one of the IEA's research and development cooperation agreements. At the moment there are 32 countries-participants. The program exists to "coordinate international collaborative efforts that enhance the role of photovoltaic solar energy in the transition to sustainable energy systems." In PVPS's snapshot mentioned that about 97.9 GW of the capacity installed in the countries-participants of the Program in 2018 and in total all over the world with 99.8 GW. At the end of 2018, the installed capacity of the world solar energy exceeded 500 GW.

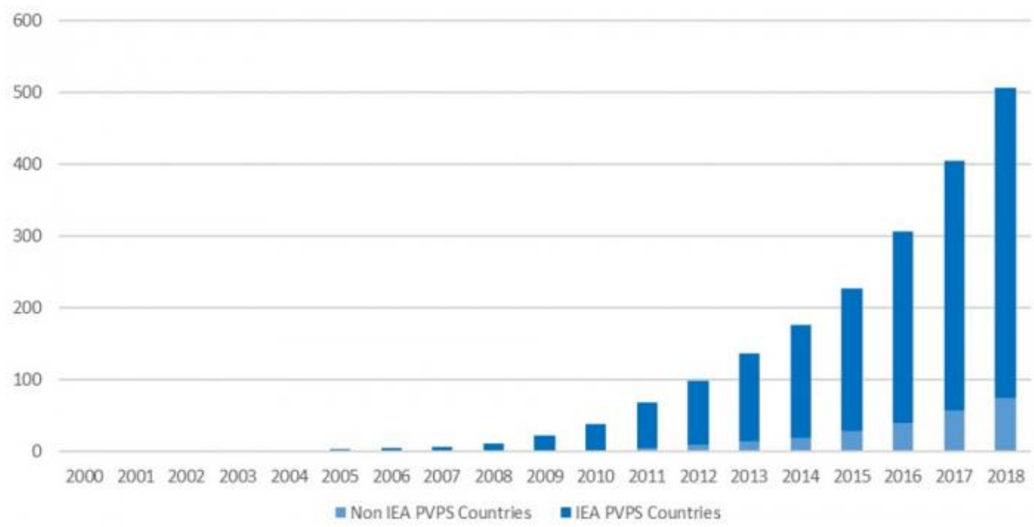

Figure 1. Growth of the PV system's install capacity [6]

Table 1. Top 10 countries for total install capacity in 2018

	Country	Cumulative capacity, GW
1	China	176.1
2	USA	62.2
3	Japan	56.0
4	Germany	45.4
5	India	32.9
6	Italy	20.1
7	UK	13.0
8	Australia	11.3
9	France	9.0
10	Korea	7.9
	EU	115.0

There is highlighted that there are already 32 countries on the planet, each of which has more than 1 GW of solar power. The IEA PVPS report estimates that solar energy produced approximately 2.6% of the world's electricity consumption and 4.3% of European in 2018. Of course, in some countries the share of the sun is higher. For instance, in Germany, which is not the sunniest place on the planet, photovoltaics produced about 7.9% of electricity. [6]

In Germany, a breakthrough in costs was observed over the last years, following a decade of massive investment in research and deployment. New solar photovoltaic power plants in Germany today cost almost 80 percent less than those built several years ago. Solar photovoltaics is already today a low-cost renewable energy technology. Cost of power from large scale photovoltaic installations in Germany fell from over 40 ct/kWh in 2005 to 9ct/kWh in 2014. Even lower prices have been reported in sunnier regions of the world, since a major share of cost components is traded on global markets. Solar power will soon be the cheapest form of electricity in many regions of the world. Even in conservative scenarios and assuming no major technological breakthroughs, an end to cost reduction is not in sight. Depending on annual sunshine, power cost of 4-6 ct/kWh are expected by 2025, reaching 2-4 ct/kWh by 2050 (conservative estimate).[7]

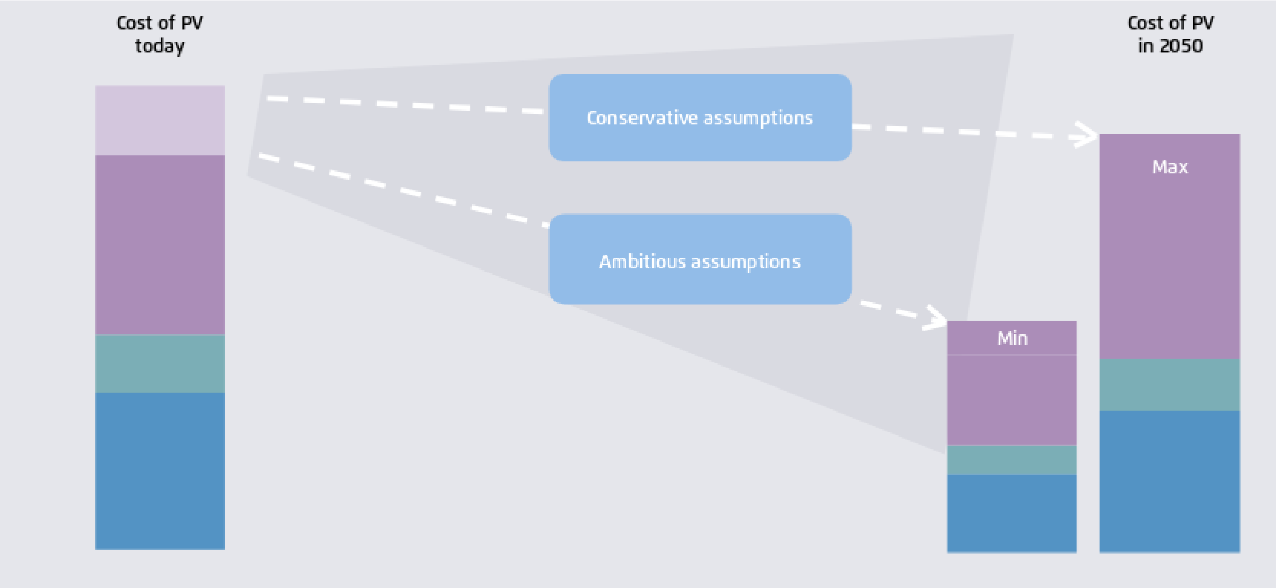

Figure 2. Cost of PV forecast

The analysis of [7] of different scenarios concludes that an end to cost reduction for power from solar photovoltaics is not in sight. Even in the most conservative scenarios for market development, without considering technology breakthroughs, significant further cost reductions are expected.

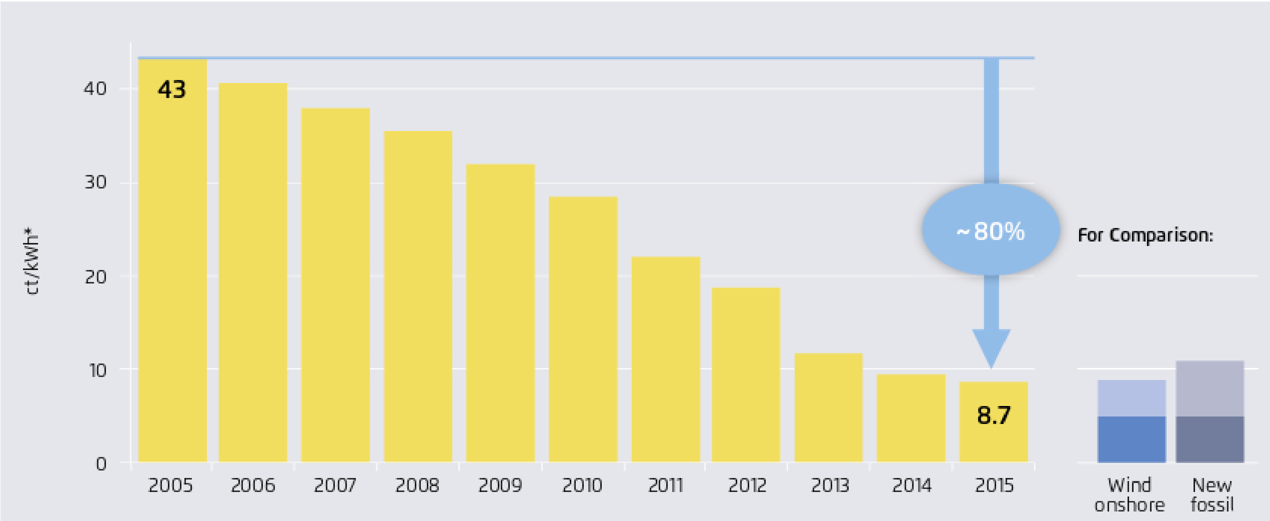

Figure 3. Feed-in tariff for new large-scale solar photovoltaic in Germany (in nominal values)

The following methodology in [7] was used to reach this conclusion: the starting point of the analysis was to derive consistent scenarios for the global photovoltaics market development between 2015 and 2050. These scenarios were discussed and revised in expert workshops and represent a range from “very pessimistic” to “very optimistic” in terms of global photovoltaics market developments. In the most pessimistic scenario, annual additional photovoltaic installations would increase from to 175 GW in 2050 (cumulated produced capacity until 2050 of ~6000 GW).

In the most optimistic scenario (“breakthrough scenario”), 1780 GW of photovoltaic systems will be installed per year by 2050 (cumulated produced capacity by 2050: ~36000 GW).

1.2.Development in the Russian Federation

If look at the global trends, possible to see the boom of solar energy growth. In just a few years, in many countries price per kWh has come close to the price of electricity from coal and gas plants. The question is: what place does our country take in these processes? Maybe solar energy is not for Russia? After all, Russia is located in the North, but stereotypes connect solar energy with those countries where it is hot all year round. However, scientific evidence refutes this view. Thus, according to the Institute of energy strategy, the potential of solar energy entering the territory of Russia in just three days exceeds the energy of the total annual electricity production in the country. The amount of solar radiation varies from 810 kWh per square meter per year in remote Northern areas to 1,400 kWh in the South. And in general, the idea that Russia is a sunless country is fundamentally wrong. In many regions, including Zabaikalsky region and Yakutia, solar energy is much higher than in the Krasnodar region. There are more sunny days and solar radiation than in the southern areas.

It is not surprising that solar energy is today one of the leading areas of renewable energy. Only in 2017, the installed capacity of solar generation, operating in the Russian wholesale electricity market and capacity, reached 224 MW. The largest of the solar power plants built in Russia are located in the Orenburg region and in the republics of Bashkortostan and Altai. In the period from 2018 to 2023, another 1.5 GW of solar generation will be built in Russia.

For Russia, with its huge reserves of natural resources, the development of alternative energy is also considered very important, because of the big size and difficult climatic conditions in most of the territory. On 70% of the territory of Russia there is no centralized power supply. About 20 million people live in this territory. High transport costs and a steady rise in motor fuel prices determine high tariffs for electricity production in decentralized power supply systems (up to 50-60 rubles per kWh), as in remote areas electricity is produced by diesel generators, because of the high cost or inability to connect consumers to a centralized power supply system. Cheap natural resources are the main reason why the scale of the Russian solar energy a negligible in comparison, for instance, with China, where its capacity is higher by almost 200 times. However, it cannot be denied that solar energy has good outlook in the country. The country has a number of enterprises producing components for solar power plants – from silicon wafers, supporting structures and all types of cable and wire products to the full cycle of production of solar modules. In particular, Russia has mastered the creation of one of the key components – inverters (current converters for PV modules and wind generators), increased the necessary competence in the design, engineering and construction of solar power plants.

Renewable energy (solar, wind and small hydropower) has being developed in Russia during 6 years. There were build more than 130 MW of renewable sources (almost all capacity is photovoltaic plants) in 2014-2016 years, 140 MW (100 MW – photovoltaic plants) in 2017. The average capital cost was reduced on 10,7% in solar energy in 2017. Even nowadays economically reasonable to use RES in remote and inaccessible areas on the Far East. Except the improving of power supply reliability in remote areas, the priority direction of RES development in Russia is producing of advanced technologies for export. In solar energy was created a cycle – from the science and production of photovoltaic modules to the construction and operation of PV systems. On July 3, 2017, the production of solar panels based on domestic heterostructure technology was established in Novocheboksarsk. The modules have an efficiency higher than 22% and among the world there are three leaders in efficiency in mass production. 19 September 2017 put into operation the first solar power plant, built using heterogeneous modules, the Mayminsky SES in the Republic of Altai. [8]

The highest value of solar radiation is in the Krasnodar region and Khabarovsk region, so the solar energy application is much profitable there. The cost of electricity on the Far East is significantly higher average value in Russia (in some regions in 5 times). But according the law in 2017 (it was confirmed in order to support development of this region) price for electricity was restricted by 4 rub for 1kWh, and 24 mlrd rub should be paid by the rest Russian regions, so the tariff was increased on 1,8% [9]. In 2018 price for electricity was restricted by 4,3 rub per 1kWh [10]. Renewable energy implements in Far East (Respublica Saha, Chykotskaya oblast, Khabarovskaya oblast') for supplying rural areas and enterprises [11]. Plans of Russian governments: “Microgeneration will appear in construction, especially in "smart homes". Built-in technology will be used. This is the next stage of development of the "sun", when solar panels will be insert into the building. Another idea — transportable — window that is not darkened and at the same time is a solar battery, generates electricity. All these wonderful prospects, which I am talking about, are not 2018, but 2020-2025”.

Chapter 2. Photovoltaic system

2.1. Design of PV system

The purpose of this item is determine the output power of PV system. The main components of stand-alone PV system are: solar battery, with a series-parallel set of photovoltaic cells; DC-DC converter, which is operated by maximum power point tracking controller; storage system is based on storage battery; inventor. Frequently, solar track is applied for efficiency increasing. In this case PV system include operational block and executive mechanism of the tracking system, which based on engines and gears.

For this thesis PV system doesn't require storage battery, because of the specific of project. In the both approaches in each point of time consumption exceeds the demand, and this power generating supplement just reduce a little bit the base load. PV system structure submitted in the Appendix A, figure A.1

Solar battery – the main component of PV system. The principle of operation of the solar panel based on the physical properties of semiconductors with the ability to create, under the influence of sunlight, electronic conductivity "p-n" type. Between the electrodes of the device, a potential difference is created, and when the load is connected, an electric current flows in the circuit.

DC-DC converter with MPPT controller allows to increase output power of solar modules without changing their number. If you look at the typical current-voltage characteristic of the solar battery, you can observe the power output can be increased if the controller will monitor the point of maximum power of the solar battery.

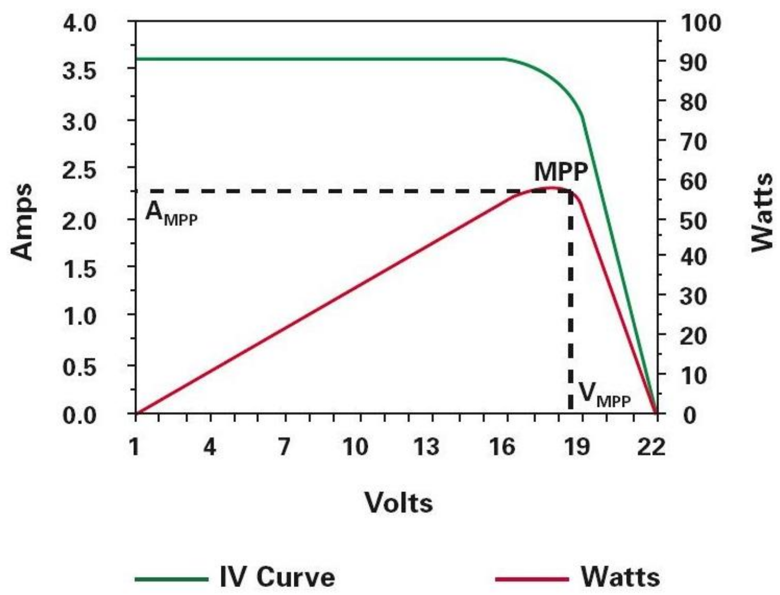

Figure 4. Volt-amps diagram[12]

MPPT controller tracks current and voltage on solar battery and multiplies them to determine the current and the voltage which lead to maximum output power. The approach consists power point changes and compares differences between new and previous outputs.

Solar tracker is a device for orienting a solar photovoltaic panel or concentrating solar reflector or lens toward the sun. The sun's position in the sky varies both with the seasons and time of day as the sun moves across the sky. Solar powered equipment works best when pointed at or near the sun, so a solar tracker can increase the effectiveness of such equipment over any fixed position, at the cost of additional system complexity. There are many types of solar trackers, of varying costs, sophistication, and performance.

2.2. Simulation of PV system

PV system's install capacity will be calculated in the created model in MatLAb Simulink. To determine the output power for one day with high accuracy it is necessary to consider all significant influences. Model is applied for accuracy increasing. Each average day of months will be simulated and then multiplied on number of days to define monthly generation. Assumed that during the month output power increases or decreases homogeneous, so the error of this approach is minimum.

Simulation of stand-alone PV system includes the 4 main components: model of solar radiation, model of solar battery, daily temperature model, model of temperature of photovoltaic sell surface. The particularity of this model is taking into the account external climatic features on the energy characteristics of the solar battery, which provides an increase in the accuracy of predicate power generation.

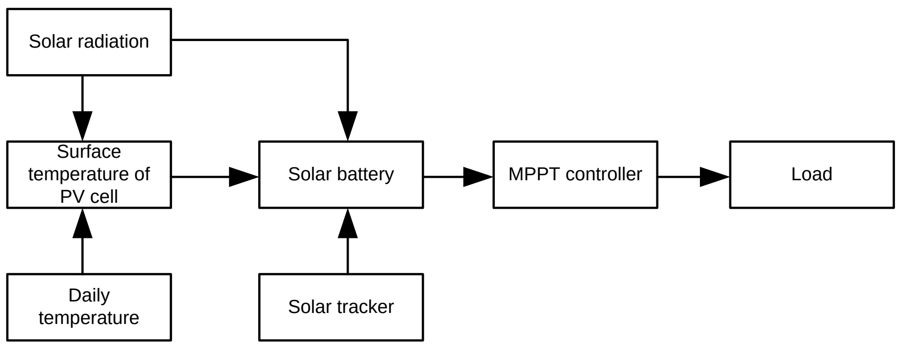

Figure 5. Standalone photovoltaic system's block diagram

2.2.1. Solar radiation

The intensity of solar radiation outside the earth's atmosphere is almost constant and is equal to 1367W/m^2. However, there are stochastic factors that influence the intensity of radiation on the

Earth's surface - the state of the atmosphere and the orientation of the receiving surface. The ultimate task of solar radiation modeling is to determine the magnitude of incoming solar radiation for any day of the year in an arbitrary geographical location of the PV system, which leads to simulation of all factors that affect on solar radiation. Block diagram of solar radiation is attached in Appendix A, Figure A.2.

Total solar radiation on an arbitrarily oriented surface on the Earth's surface is calculated by the formula [13]:

$$I_{total}^{\beta\gamma} = I_{beam}^{\beta\gamma} + I_{dif}^{\beta\gamma} + I_{refl}^{\beta\gamma} = I_{beam}^{hor}\frac{\cos\theta}{\cos\theta_z} + I_{dif}^{hor}\cos^2\left(\frac{\beta}{2}\right) + \rho I_{total}^{hor}\sin^2\left(\frac{\beta}{2}\right) \quad (1)$$

$I_{total}^{\beta\gamma}, I_{beam}^{\beta\gamma}, I_{dif}^{\beta\gamma}, I_{refl}^{\beta\gamma}$ – values of the total, beam, diffuse and reflected solar radiations on the arbitrarily oriented surface, $\frac{W}{m^2}$;

$I_{beam}^{hor}, I_{dif}^{hor}, I_{refl}^{hor}$ – values of the total, beam, diffuse and reflected solar radiations on the horizontally oriented surface, $\frac{W}{m^2}$;

θ – angle of drop, angle between the beam radiation on a surface and the normal to that surface;

θ_z – zenith angle, the angle between the vertical and the line to the sun, that is, the angle of drop of beam radiation on a horizontal surface;

β – slope, the angle between the plane of the surface and the horizontal; $0 \le \beta \le 180^o$ ($\beta \ge 90^o$ means that the surface has a downward-facing component);

ρ – ground albedo.

Value θ is determined from the equation [14]:

$$\theta = \arccos\left(\begin{aligned}&(\sin\varphi\cos\beta - \cos\varphi\sin\beta\cos\gamma)\sin\delta + \\ &+\cos\delta(\sin\beta\sin\gamma\sin\omega + (\cos\varphi\cos\beta + \sin\beta\sin\varphi\cos\gamma)\cos\omega)\end{aligned}\right) \quad (2)$$

where:

φ – latitude, the angular location north or south of the equator;

γ – surface azimuth angle, the deviation of the projection on a horizontal plane o the normal to the surface from the local meridian, with zero due south, east negative, and west positive; $-180^o \le \gamma \le 180^o$ [14];

δ – declination, the angular position of the sun at solar moon with respect to the plane of the equator;

ω – hour angle, the angular displacement of the sin east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive [14].

Declination is calculated by:

$$\delta = 23.45\sin\left(0.9683\cdot\left(N+284\right)\right)\text{degree.} \qquad (3)$$

Sun azimuth angle is determined from:

$$\cos A_z = \frac{\sinh\sin\varphi - \sin\delta}{\cosh\cos\varphi} \qquad (4)$$

The height of the rise of the sun above the horizon $[h]$ (the angle in the vertical plane between the sun's beam and its projection on the horizontal plane) plus the zenith angle $[\theta_z]$ is 90^0, therefore:

$$h = 90^0 - \theta_z \text{ degree.} \qquad (5)$$

Zenith angle is:

$$\theta_z = \arccos\left(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega\right) \text{ degree.} \qquad (6)$$

Hour angle is:

$$\omega = 15\left(t - 12 - T_{ratio} - \Delta T_{UTC}\right) + \psi \text{ degree.} \qquad (7)$$

Where t – current official time, h; ΔT_{UTC} – offset between currency official time and Greenwich time, h; ψ – longitude of the receiving plane point, degree.

Time ration for the equation of time is determined by the formula:

$$T_{ratio} = \frac{1}{60}\left(9.87\sin\left(2B\right) - 7.53\cos\left(B\right) - 1.5\sin\left(B\right)\right) \text{ h;} \qquad (8)$$

Where:

$$B = 0.9683\cdot\left(N - 81\right) \text{ degree;} \qquad (9)$$

N – the calendar day number from the beginning of the year.

Extra-atmospheric radiation on a horizontal surface, which is determined by Spencer's formula [14]:

$$I_0 = 1367\left(1 + 0.33\cos\left(0.9863N\right)\right)\cos\left(\theta_z\right) \frac{W}{m^2} \qquad (10)$$

To take into account the real characteristics of solar radiation, the average values of the atmospheric transparency index K_T for a given month, obtained from the database of the NASA [15] for the 22-year period of observations from 1983 to 2004.

$$K_T = \frac{I_{beam}^{hor}}{I_0}. \quad (11)$$

The value of diffusing radiation is determined throw diffuse factor K_D:

$$K_D = \frac{I_{dis}^{hor}}{I_{beam}^{hor}}. \quad (12)$$

The block diagram of solar radiation calculation is attached in the appendix B, figure B.4.

There are 7 inputs determine the value of the final solar intensity:

1. Latitude;
2. Surface azimuth angle;
3. Slope;
4. Calendar day number;
5. Atmospheric transparency index;
6. Ground albedo;
7. Solar tracker presence.

The inputs are set via the parameter block Constant.

At the design stage of the PV, the issue of the solar tracker should be resolved. On the one hand, effectiveness increases on 40-45%, which allows to use fewer solar panels to cover the required load. On the other hand, the high cost may be an obstacle to the installation of the tracker.

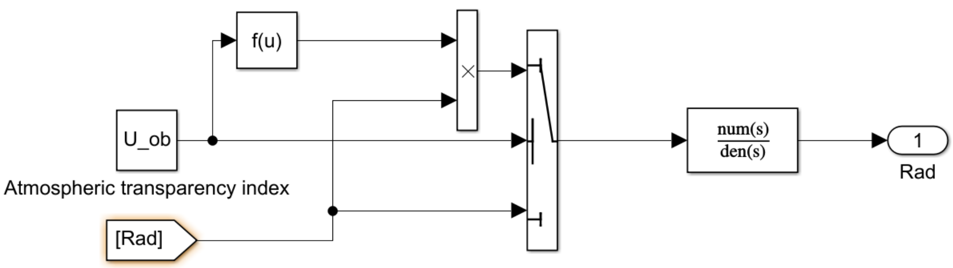

Figure 6. The output value of solar radiation

The model was transferred in subsystem with capability to change inputs for solar radiation simulation at any location, as well as for any day of the year.

Let’s check the adequacy of this model by providing simulation. Let’s choose the April, 13, point in Russia. Solar tracker is absent.

The result of the simulation is an oscillogram of the solar radiation. The presence of pulsations describes the possibility of clouds, as it is impossible to predict their presence. The figure is submitted in Appendix B Figure B.1. In order to observe solar tracker influence, the plot with solar tracker is submitted in Figure B.2.

As can be seen from the results, the output value of radiation took a flatter form, with the area under the radiation curve has increased significantly, which proves the effectiveness of the Sun tracking system.

Ripple describes cloud influence. Delete the random number generator to observe the waveform without ripple (Figure B.3.).

2.2.2. Daily temperature

The temperature changes has a daily character. The air temperature changes after the temperature of the earth's surface. As the air heats and cools from the earth's surface, the rise in air temperature begins with the rise in soil temperature (15 minutes later) in the morning, after sunrise. At 13-14 h (depends on latitude) soil temperature begins to decrease. In 14-15 hours begins to fall and the air temperature. Thus, the minimum in the daily course of the air temperature at the earth's surface falls on the time shortly after sunrise, and the maximum - 14-15 hours. In accordance with the process of changing the air temperature, it is obvious that the curve of the daily course of temperature has a form close to the sine wave.

For temperature calculation could be used the equation:

$$T(t) = \bar{T} + 0.5\Delta T \cos\left(2\pi \frac{t_{cur} - t_{\max}}{t_{per}}\right) \quad {}^{o}C \tag{13}$$

$\bar{T}$ – daily average air temperature, ${}^{o}C$;

ΔT – daily air temperature's amplitude, ${}^{o}C$;

t_{per} – the period of air temperature changing, h;

$t_{\max}$ – local temperature maximum time, h;

t_{cur} – local sun time, h.

The result of the simulation is to determine the change in air temperature during the day, which affects the generation of electricity. During the day, the air temperature changes along a sinusoidal curve. Block diagram of daily temperature is attached in Appendix A, Figure A.3.

The model of the daily temperature allows to determine the dynamics of temperature change during any day of the year by 3 input parameters:

1. daily average air temperature;
2. daily air temperature's amplitude;
3. local temperature maximum time.

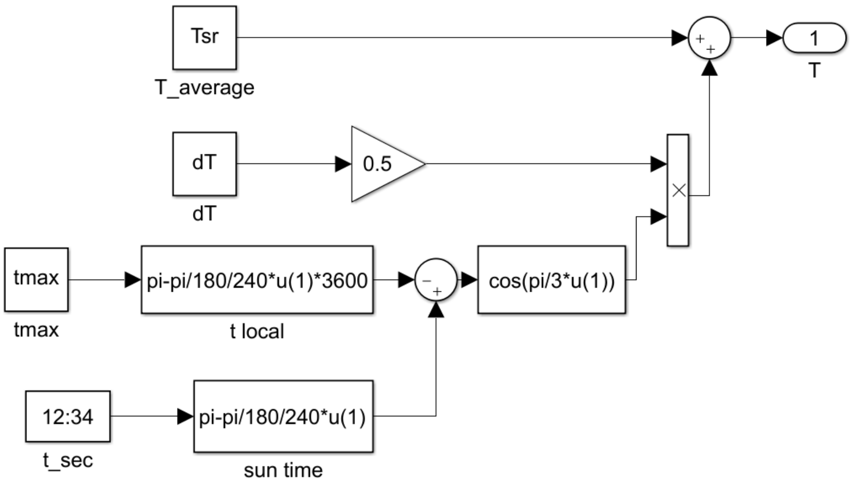

Figure 7. Daily temperature simulation

This model is applicable for any day of the year and any place using meteorological observations of the nearby weather station. The scope of curve is submitted in Appendix B, Figure B.4.

2.2.3. Surface temperature of photovoltaic module

Solar battery effectiveness depends on surface temperature of PV cell significantly. Solar batteries are tested at a standard temperature of 25ºC. The operating temperature is a result of heat exchange of its surface with the environment. Depending on the location, the increased temperature can reduce the efficiency of solar cells by 10% – 15%. When the temperature is exceeded by 1 degree above 25ºC, the efficiency is reduced by a value called "Temperature coefficient". As a result of operation, the temperature of the solar panel can exceed the ambient temperature by 30ºC, so the surface temperature is quite important parameter. To calculate the temperature, an empirical relationship is used [16]:

$$\Delta T_{FM} = 0.0283G - 0.0056GV + 0.0005GV^2 \;\; {}^{o}C \qquad (14)$$

where G – level of solar radiation, W/m^2, V – wind speed, m/s. The block diagram is submitted in Appendix A, Figure A.4.

The wind speed is assigned an average for the area, solar radiation level is obtained from solar radiation subsystem, air temperature – daily temperature subsystem.

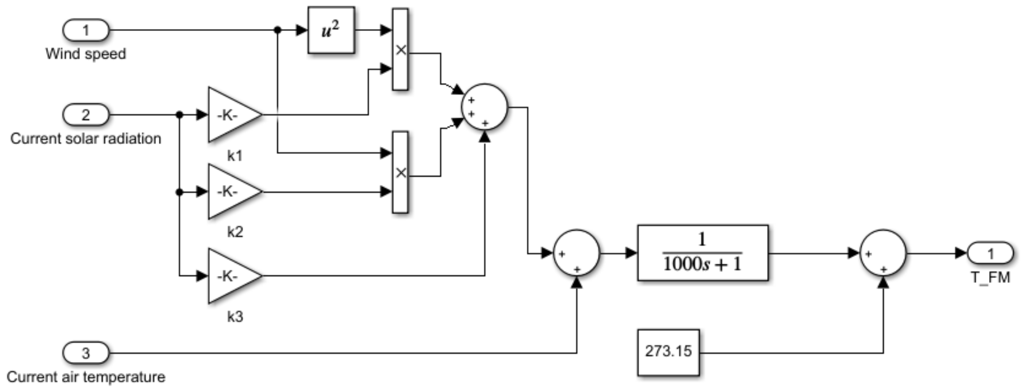

Figure 8. Surface temperature simulation

Wind speed is assigned by block “Constant” and assumed to be constant for each month of simulation. According [17] the average wind speed in Khabarovsk from 01.01.2016 to 05.05.2018 is 2.7 m/s. Transfer function describes inertia in thermal trainset processes. To observe results the following scheme is used:

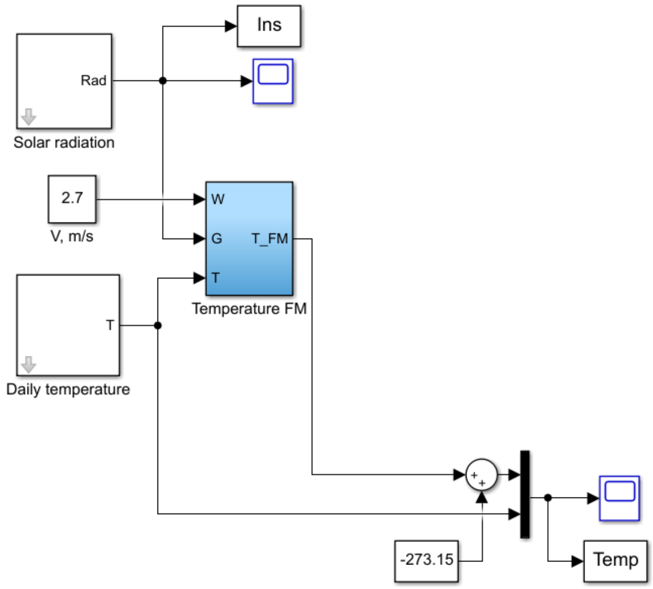

Figure 9. Scheme for daily temperature simulation

There are two diagrams on the oscillogram – daily temperature and surface temperature. See Appendix B, Figure B.5.

2.2.4. Solar battery

Output power is described by the equation [18]:

$$P_{VV} = \frac{C_{FF} N_{FM} \eta_{con} G \ln\left(G \cdot 10^6\right)}{T_{FM}} \; W \qquad (15)$$

where N_{FM} – number of photovoltaic modules; C_{FF} – solar battery ratio; η_{con} – effectiveness of converter with MPPT; G – current solar radiation, $\frac{W}{m^2}$; T_{FM} – current surface temperature, *K*.

Output power depends of environment conditions. Physic stochastic values (wind speed, solar radiation, air temperature) are included in current surface temperature.

Solar battery ratio depends on photovoltaic module's parameters:

$$C_{FF} = \frac{FF \cdot T_{ref}\left(I_{sc} + k_I\left(T_{FM} - T_{ref}\right)\right)\left(V_{oc} + k_V\left(T_{FM} - T_{ref}\right)\right)}{G_{ref}\ln\left(G_{ref} \cdot 10^6\right)} \qquad (16)$$

where, FF – filling factor of volt-ampere characteristic; T_{ref}, G_{ref} – temperature and illumination values of PV module under standard conditions; k_I, k_V – temperature's ratios of short-circuit current and open-circuit voltage. Filing factor describes nonlinearity of photovoltaic element.

$$FF = \frac{I_{MPP} V_{MPP}}{I_{sc} V_{oc}} \qquad (17)$$

where, I_{MPP}, V_{MPP} – certified values of current and voltage in maximum power point under standard conditions: I_{sc}, V_{oc} – certified values of short-circuit current and open-circuit voltage under standard conditions. The block diagram is submitted in Appendix A, Figure A.5.

The result of simulating is an output power, which solar battery generate under certain conditions. The model allows to evaluate the effectiveness and economic profit of different battery types (monocrystalline and polycrystalline), predict power generation and estimate operating modes of PV system.

Initial data are received from technical specification of a single panel:

1. temperature coefficient of open-circuit voltage;
2. temperature coefficient of short-circuit current;
3. number of PV modules;
4. voltage in maximum power point;

5. current in maximum power point;
6. open-circuit voltage;
7. short-circuit current.

Inputs from another blocks are solar radiation value and surface temperature. According the equation (16) the simulation is provided.

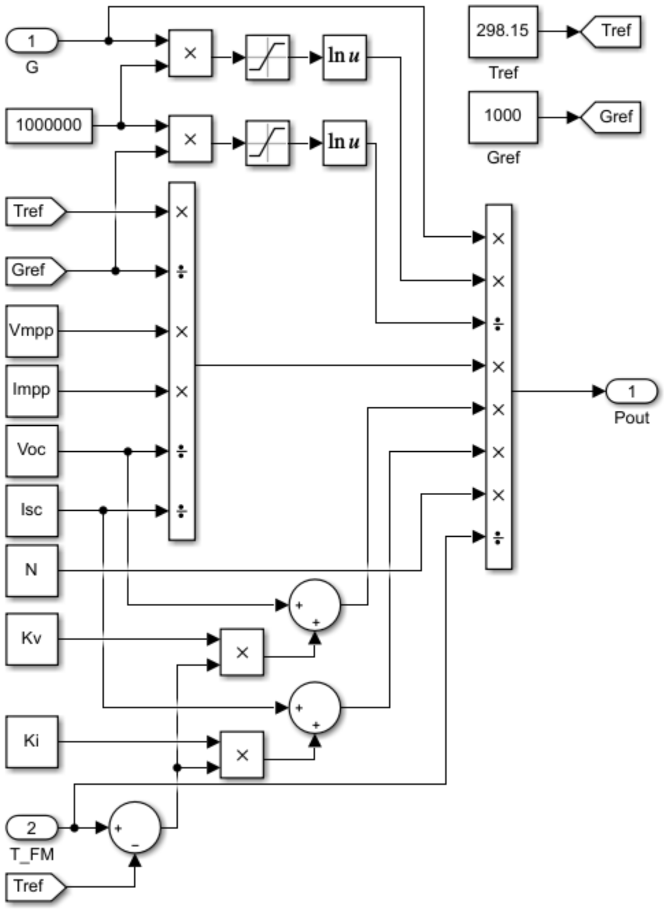

Figure 10. Solar battery simulation

2.3. Design of photovoltaic power plant

2.3.1. Solar modules

There was chosen 72-cell mono PERC Double Glass Module JAM72D00-380/PR of the firm JA Solar. These double-glass modules are powered by PERC cells to provide high power output with higher energy generation at low-irradiance conditions and better temperature-dependent performance, as well as excellent reliability and durability during the lifespan of their deployment in the field [19]. Double-glass modules work better in aggressive environment conditions – not only in deserts with sand but and in typical Russian conditions with snow and frequently passing 0 value. The great advantage is a prolongation of operating time until 30 years with 0.5 annually degradation [20]. Product datasheet is following in the table.

Table 2. Datasheet of JAM72D00-380/PR [21].

Rated Maximum Power	380 W
Maximum Power Voltage	40,27 V
Maximum Power Current	9,44 A
Open Circuit Voltage	49,03 V
Short Circuit Current	9,91 A
Temperature Coefficient of I_{sc} (α_I_{sc})	$+0,059\frac{\%}{K}$
Temperature Coefficient of V_{oc} (β_V_{oc})	$-0,380\frac{\%}{K}$
No. of cells	72 (6x12)
Dimensions with junction box	1968 x 992 x 25mm

This information is applied for simulation. The number of modules in battery is required too, in this step the consumer isn't chosen, so the allowed area for photovoltaic system is unknown, and it will be defined later. Beside this, in simulation the units of temperature coefficients are $\frac{V}{K}$ and $\frac{I}{K}$, so units from datasheet should be transformed.

$$\begin{aligned} \alpha\_I_{sc} &= 9,91 \cdot \frac{0,059}{100} = 0,00585\frac{A}{K}; \\ \beta\_V_{oc} &= 49,03 \cdot \left(-\frac{0,38}{100}\right) = -0,186\frac{V}{K}. \end{aligned} \quad (18)$$

2.3.2. Consumer

Russia is a very cold country. The sunniest regions are Krasnodarskiy region and Khabarovskiy region. In Khabarovsk the number of sunny days per year is much higher than in the biggest Russian cities (300 days versus near by 100 days in Moscow and Saint-Petersburg). This is due to the dominance of the Siberian winter anticyclone, thanks to which from November to March over the city is set very dry and frosty continental air with clear and sunny weather. Beside this, the average temperature is lower than in Krasnodar, so this is a natural cooling, that increases the efficiency of solar panels.

As a consumer is chosen the industrial enterprise of power engineering industry “Dal'nevostochnyj zavod ehnergeticheskogo mashinostroeniya” (PJSC Dalenergomash). It is located in Khabarovsk, Leningradskaya ulica, 28 (Latitude – 48,483765 degree, Longitude – 135,093890 degree.). It designs and manufactures industrial equipment.

Engineering

- upgrading designs of turbines and blowers for nitrogenous fertilizer production lines
- designs of new air blowers for aeration systems at sewerage facilities

Manufacture

- gas turbine equipment for weak nitric acid production lines
- overhead and gantry cranes including those for special uses
- installation and commissioning

In the annual report for 2015 on the page 36 [22] submits information about energy consumption.

Table 3. The information concerning power resources consumption (based on [22])

Items	Units	Value	Amount, mill. ru.
Water supply	m^3	31,309.4	0.79
Power energy	MWh	6,817.2	20.74
for power engines	MWh	3,370.0	10.15
economic needs (lighting of administrative buildings, computers)	MWh	3,139.3	9.55
losses in enterprise's network, transformation substations and converters	MWh	340.9	1

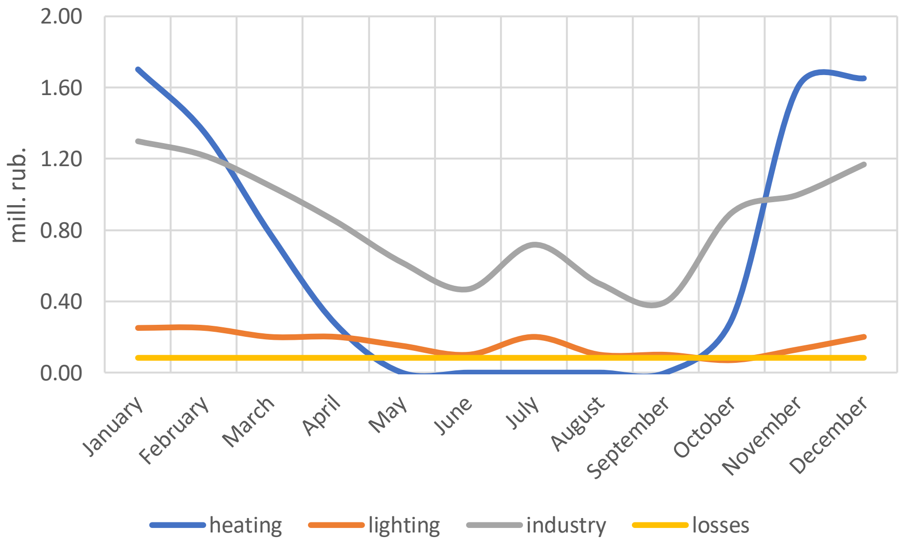

Figure 11. Data of energy consumption on PJSC “Dalenergomash”

After transforming the axis of money in the axis of power energy consumption:

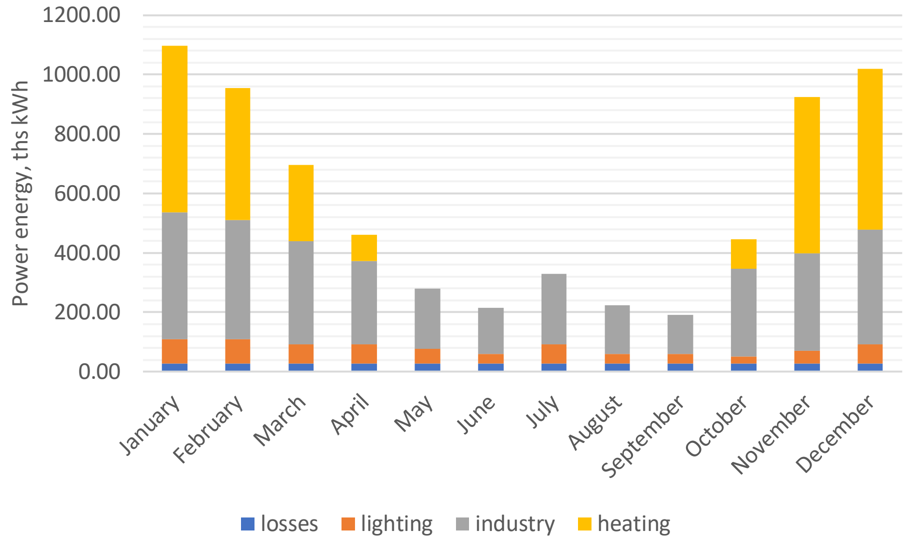

Figure 12. Monthly power energy consumption

This plot will be used in Chapter 3, in order to compare consumption of enterprise and production of PV system.

Table 4. Costs of power supply

	million rubles				
	heating	lighting	industry	losses	monthly
January	1.70	0.25	1.30	0.08	3.33
February	1.35	0.25	1.22	0.08	2.90
March	0.78	0.20	1.05	0.08	2.11
April	0.27	0.20	0.85	0.08	1.40
May	0.00	0.15	0.62	0.08	0.85
June	0.00	0.10	0.47	0.08	0.65
July	0.00	0.20	0.72	0.08	1.00
August	0.00	0.10	0.50	0.08	0.68
September	0.00	0.10	0.40	0.08	0.58
October	0.30	0.07	0.90	0.08	1.35
November	1.60	0.13	1.00	0.08	2.81
December	1.65	0.20	1.17	0.08	3.10
Annual	7.65	1.95	10.20		20.80

Table 5. Power energy demand

	thous. kWh				
	heating	lighting	industry	losses	monthly
January	558.79	82.17	427.31	27.39	1095.66
February	443.74	82.17	401.01	27.39	954.32
March	256.38	65.74	345.13	27.39	694.65
April	88.75	65.74	279.39	27.39	461.27
May	0.00	49.30	203.79	27.39	280.49
June	0.00	32.87	154.49	27.39	214.75

Table 5. Power energy demand (continuation)

July	0.00	65.74	236.66	27.39	329.79
August	0.00	32.87	164.35	27.39	224.61
September	0.00	32.87	131.48	27.39	191.74
October	98.61	23.01	295.83	27.39	444.84
November	525.92	42.73	328.70	27.39	924.74
December	542.35	65.74	384.58	27.39	1020.06
Annual	2514.54	640.96	3352.72	328.70	6836.92

2.3.3. Solar tracker

The effectiveness of applying solar trackers in the model will be checked in the sensitivity analysis in the financial part of the project. Remind, that solar tracker was included in the model like an optional element. There was used solar tracker ED – 5000 of Russian producer "EDS Group". It's one-axe tracker (in the left-right plane from -75^0 to $+75^0$). Operation period is 25 years [23].

Table 6. Features of solar tracker

Number of modules	36
Rotor power	5 W x 1
Daily power consumption	≤0,01 kWh
Angle	Left-right: since -120° till 120°
Maximum wind load	170 km/h
Operation period	≥25 years
Cost	410 000 rub

36 modules is a capacity for this solar tracker. Was decided to purchase 10 solar trackers, that leads to 360 modules for this project.

2.3.4. Inverter

There was chosen an inverter MAP-HYBRID-48-15 x 3 of the producer MicroArt. Map HYBRID - a series of hybrid three-phase inverters, working with networks and solar power plants, converting single-phase voltage to three-phase with high efficiency. The output of the devices will always be synchronized 380 V network.

Table 7. Features of inverter MAP-HYBRID-48-20x3 [24]

Maximum power	15 x 3 kW
Peak power	54 kW
Rated power	30 kW
Input voltage	48 V
Output voltage	380 V
Frequency	50 Hz
Dimensions	720x410x560 mm
Weight	165 kg
Cost	488 400 rub
Lifetime period	10 years

Conclusion.

According the chosen design of PV system it consists of solar modules, inverters and solar trackers. Storage batteries were eliminated. Was developed a model of photovoltaic system, providing the study of its operating modes in real operating conditions. It takes into account the influence of external stochastic factors in order to increase the accuracy of the power generation forecast. The model is capable to provide simulation for appointed day of the year with a step 1s (86,400 sec in total), and each second the values of solar irradiation, daily temperature and location of the sun are recalculated. All these parameters are taken into account in the model of solar battery and have an impact on output power. Beside this, were included blocks for recording cumulated solar radiation and cumulated output power – the main parameter in the next Chapter. Were added three scopes for graphical illustration of processes during the simulation. Initial data for the model are: latitude, surface azimuth angle, slope, calendar day number, atmospheric transparency index, ground albedo, solar tracker presence, daily average air temperature, daily air temperature's amplitude, local temperature maximum time and technical properties of PV module. In the second chapter was chosen equipment and attached properties of each device.

Chapter 3. Technical calculations

The output power will be defined for each month via created model.

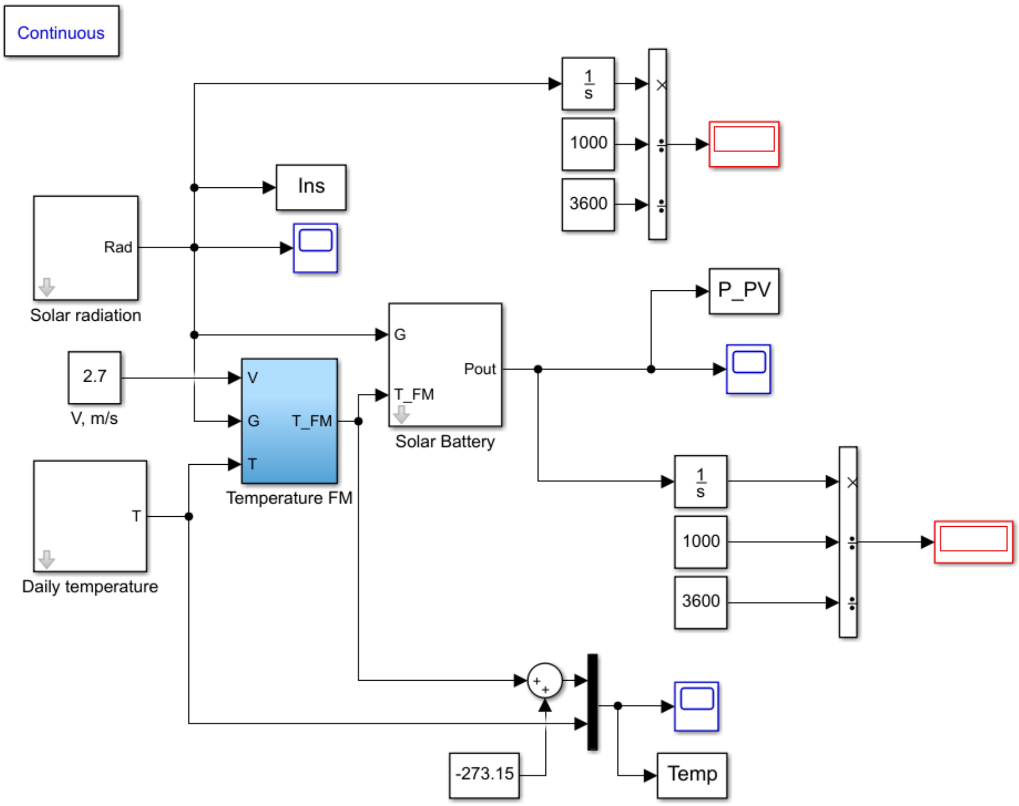

Figure 13. Model in MatLab Simulink

There will be simulated the 15th day of each of 12 months in the year and then will be multiplied with the number of days. Assumed, that the output power increases/decreases homogeneously, so underestimation for the first part of month will be covered by overestimation for the second part of month. All of the 12 simulations have the same following inputs:

Table 8. Common inputs.

Latitude	48,483765 degree
Solar tracker	Azimuth tracking
Slope	48 degree
Open Circuit Voltage	49.03 V
Short Circuit Current	9.91 A
Number of solar modules	360
Temperature Coefficient of I_{sc} (α_I_{sc})	$+0.00585\frac{A}{K}$
Temperature Coefficient of V_{oc} (β_V_{oc})	$-0.186\frac{V}{K}$

Table 8. Common inputs (continuation)

Maximum Power Voltage	40,27 V
Maximum Power Current	9,44 A
Local temperature maximum time	16 h

The following data will be applied for specific month:

Table 9. Data for each month (part 1)

Input	January	February	March	April	May	June
The number of the day	15	46	74	104	134	165
Cloud(0–cloudless, 1–unbroken)	0.25	0.05	0.25	0.4	0.4	0.6
Albedo(0.2-grass,0.9-fresh snow)	0.7	0.7	0.7	0.5	0.2	0.2
Air average daily temperature	-14.6	-12.7	-4.8	6	15.5	16.3
Air av. daily temp. amplitude	2.9	6.4	4.6	9.6	14.4	8.3
Wind speed	2.7	2.5	2.5	2.8	2.5	2

Table 9. Data for each month (part 2)

Input	July	August	September	October	November	December
The number of the day	195	226	257	287	319	349
Cloud(0–cloudless, 1–unbroken)	0.5	0.5	0.4	0.25	0.25	0.25
Albedo(0.2-grass,0.9-fresh snow)	0.2	0.2	0.2	0.2	0.9	0.9
Air average daily temperature	22.2	19.1	15.7	6.6	-4.9	-16.2
Air av. daily temp. amplitude	8	3.4	13.3	6	1.4	5.8
Wind speed	1.8	1.8	2.1	2.5	2.9	3.1

Cloud level was taken from [17]. On this webpage is collected information about weather since the August of 2016. The average information for each month was taken, in order to reduce mistakes during multiplication on number of days in months.

In [17] was obtained information concerning the level of snow in the city. According this data were assigned albedo of the earth's surface. The average information for each month was taken.

Air average daily temperature and its amplitude was taken for the 15th day of each month. Wind speed was taken for each month.
All initial inputs in software for January are attached in Appendix C, Figure C.1.

The results of two simulations (15th of January and 15th of July) will be submitted. The rest results will consist in table. After simulation of the 15th of January the following scopes are received.

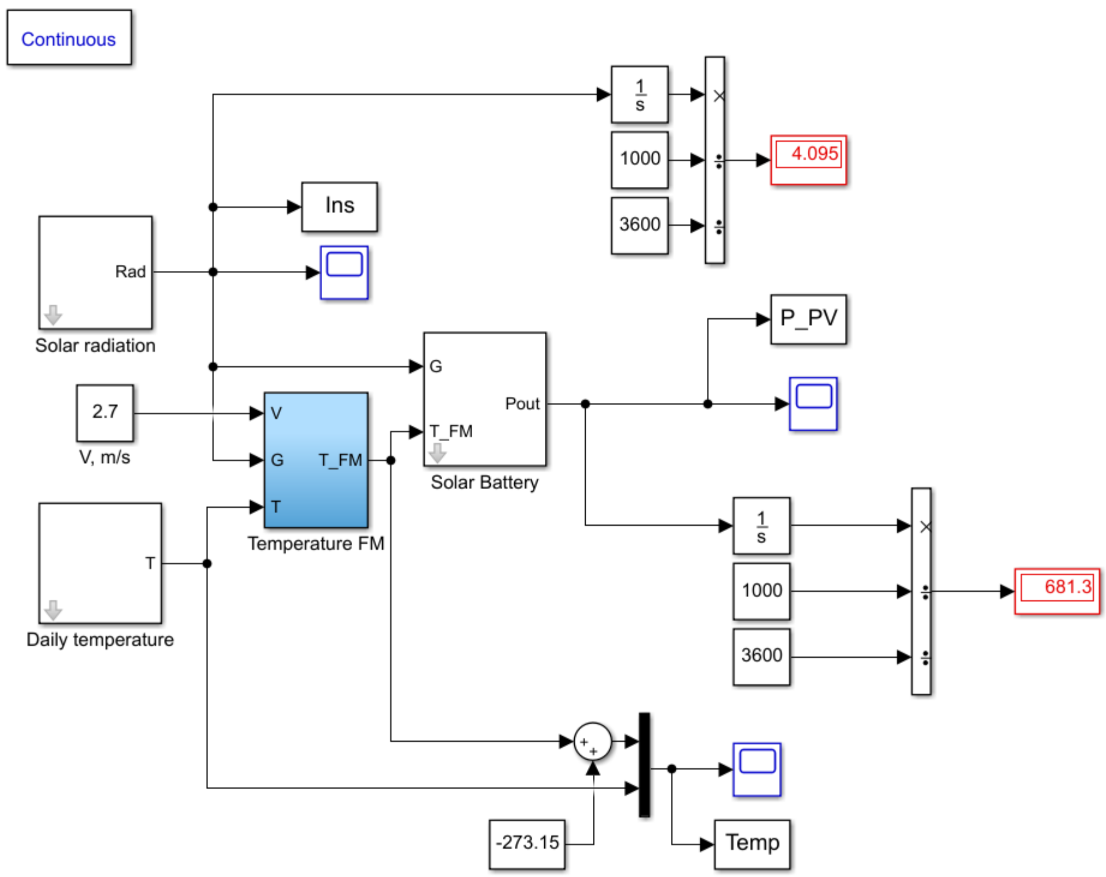

Figure 14. Simulation of the 15th of January.

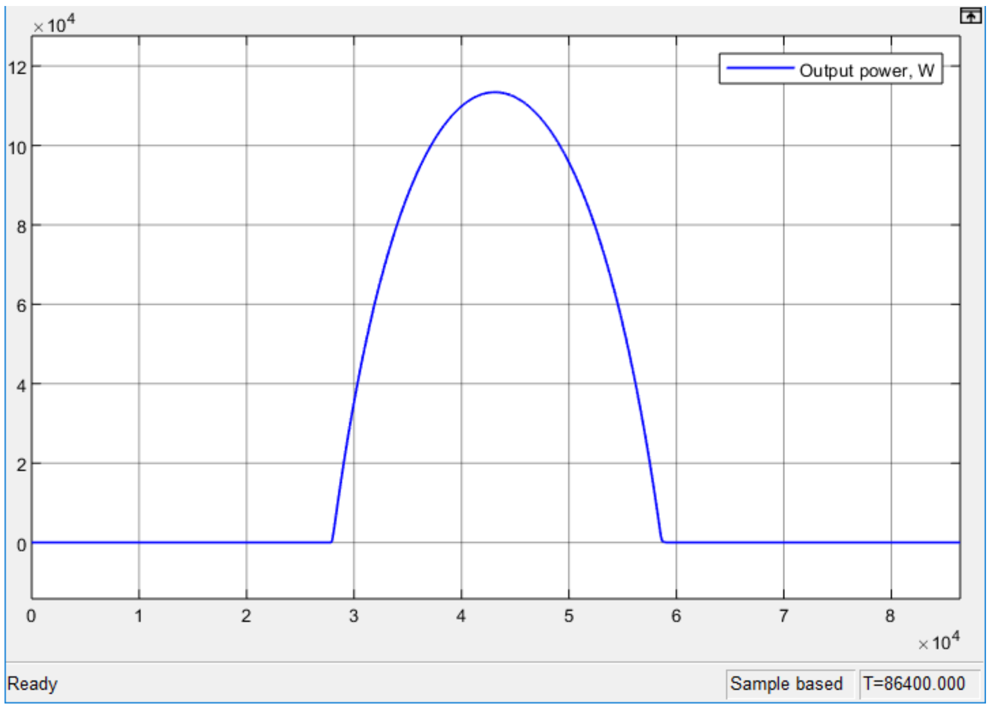

Figure 15. Daily output power plot for the 15th of January

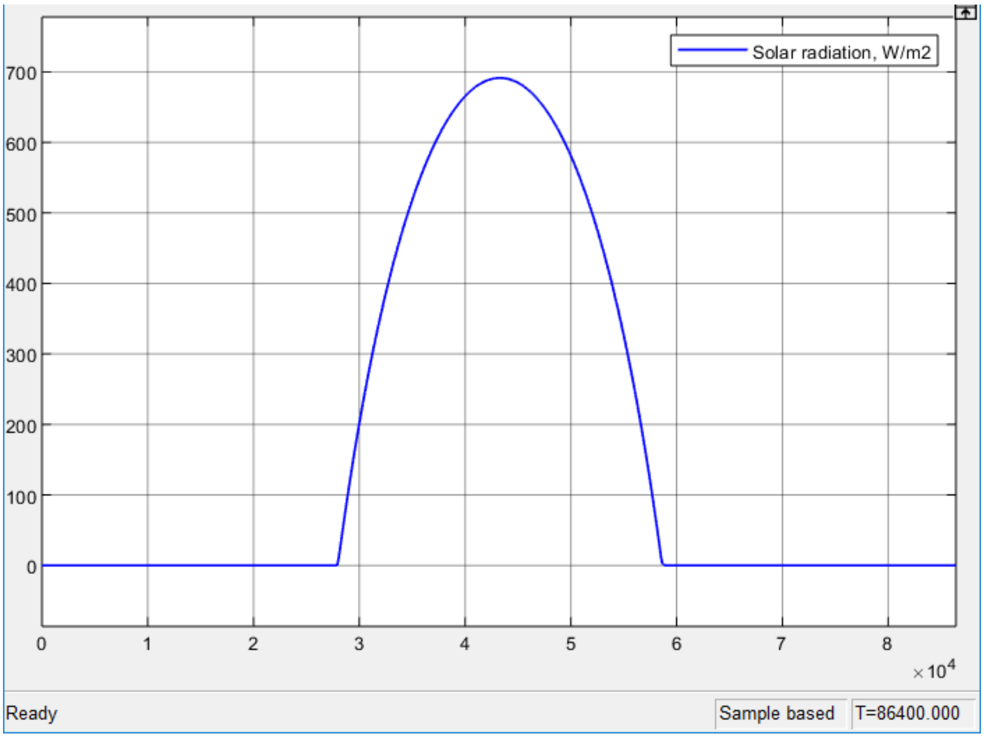

Figure 16. Solar radiation plot for the 15th of January

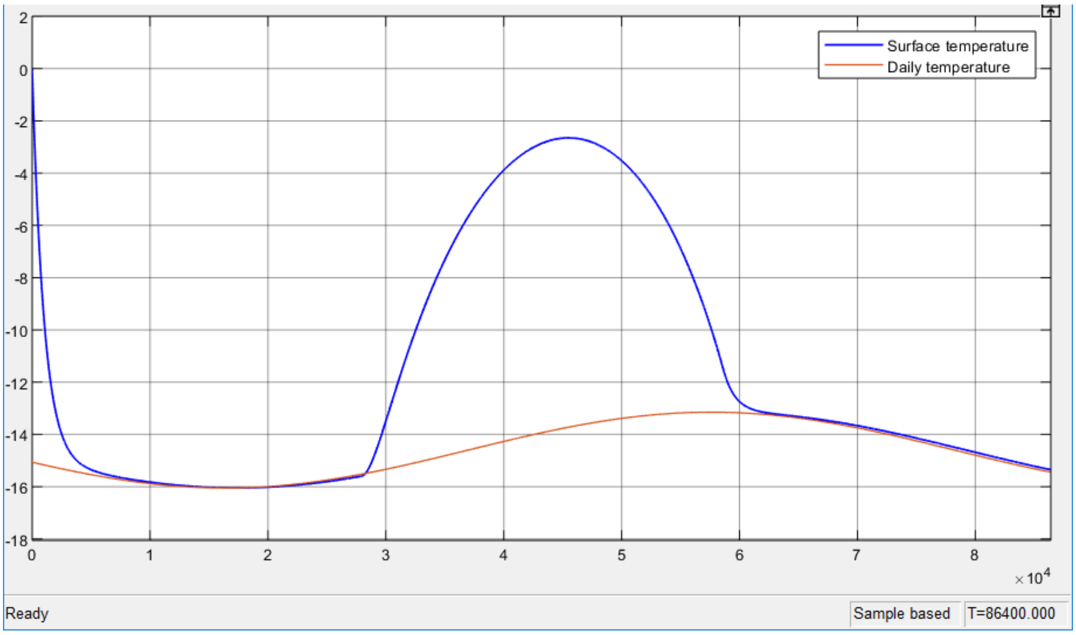

Figure 17. Temperatures behaviour plot for the 15th of January

It is possible to observe the cumulative solar irradiation (4.095 kWh/m^2) and cumulative output power (681.3 kWh) for specific day. For the whole month:

$$P_{January} = P_{15th} \cdot N_{days} = 681.3 \cdot 31 = 21.12 \ ths \ kWh;$$
$$I_{January} = I_{15th} \cdot N_{days} = 4.095 \cdot 31 = 126.95 \ \frac{kWh}{m^2}. \quad (19)$$

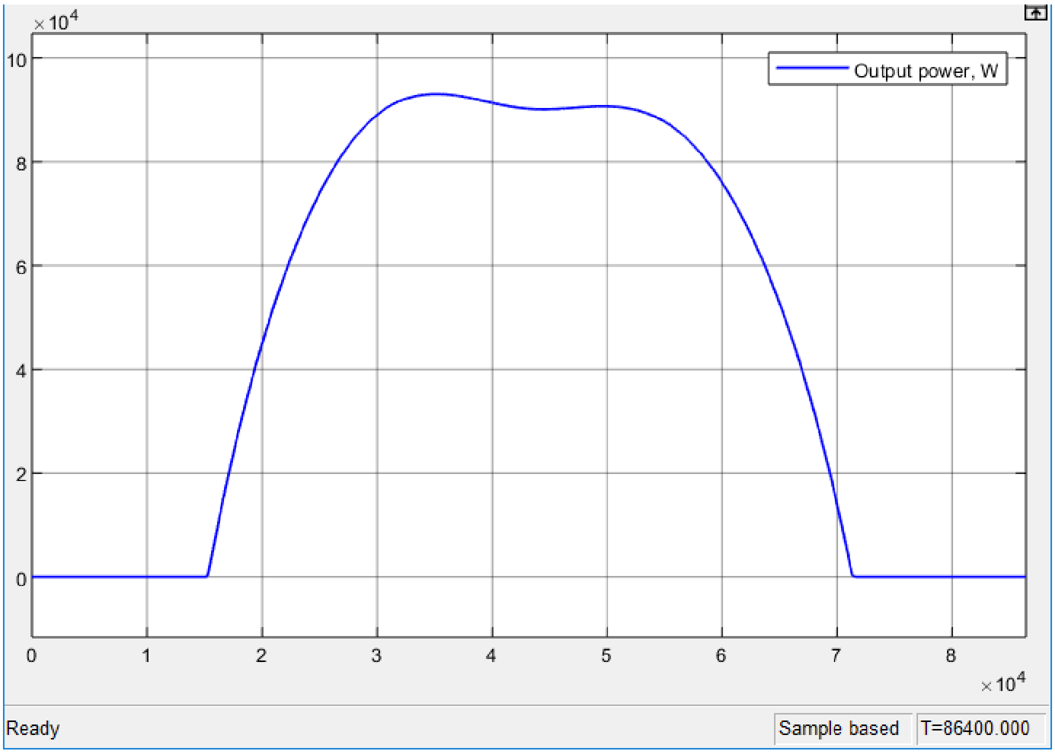

Figure 18. Daily output power plot for the 15th of July

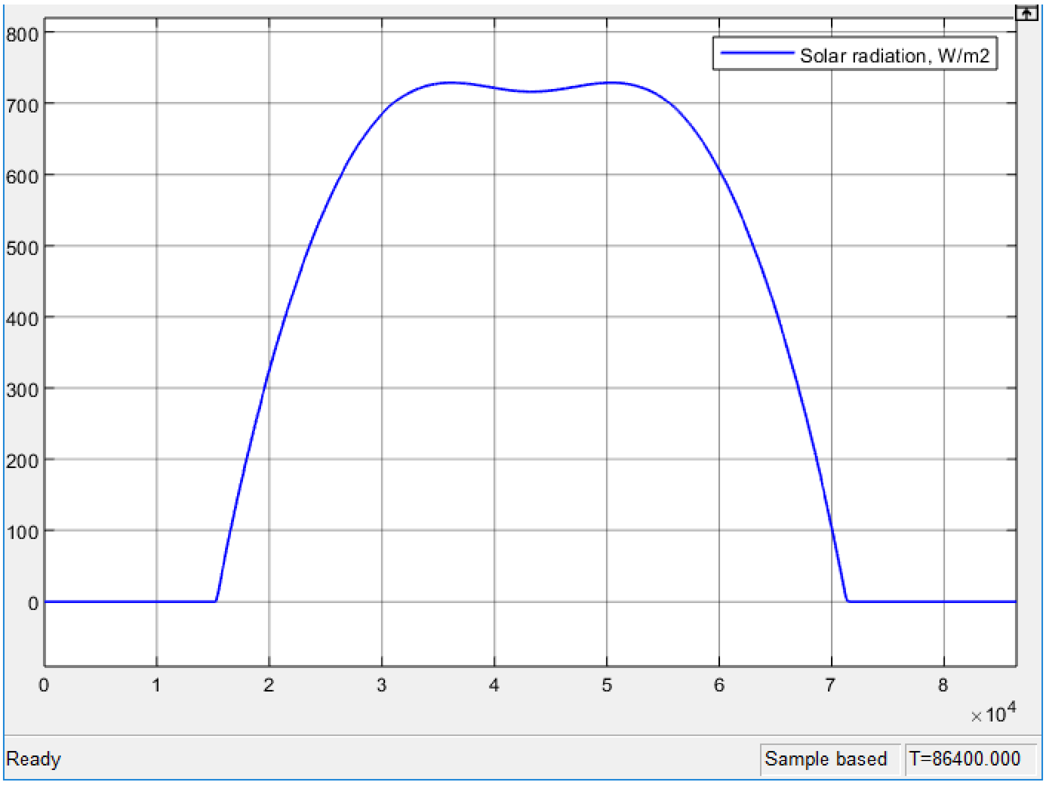

Figure 19. Solar radiation plot for the 15th of July

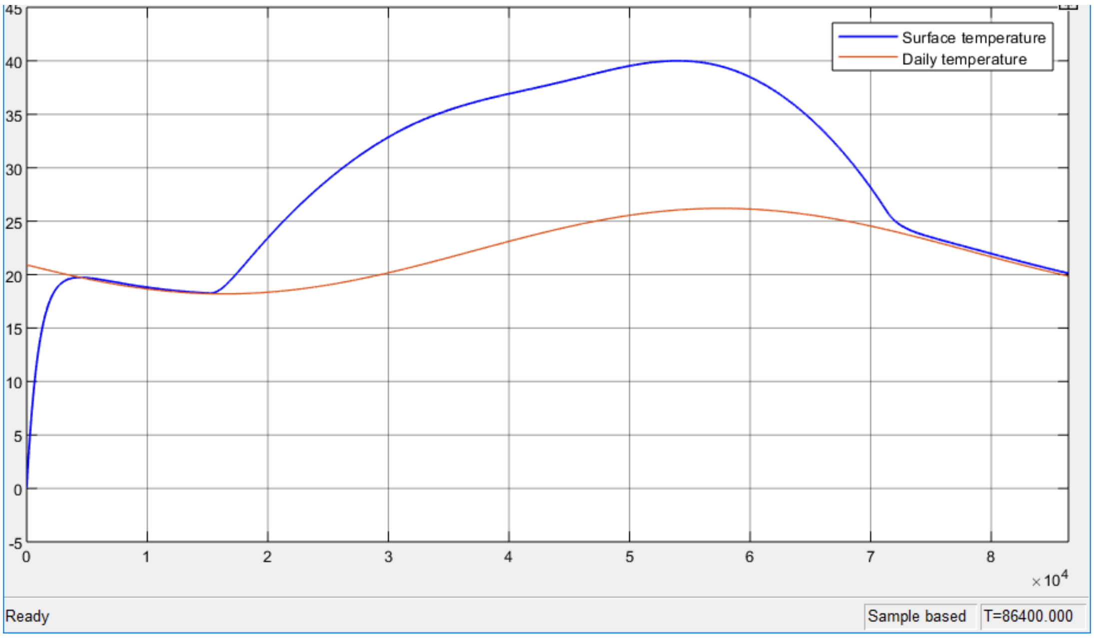

Figure 20. Temperatures behaviour plot for the 15th of July

The cumulative solar irradiation (8.756 kWh/m^2) and cumulative output power (1119 kWh) for the specific day. For the whole month:

$$P_{July} = P_{15th} \cdot N_{days} = 1119 \cdot 31 = 34.69 \ ths \ kWh;$$
$$I_{July} = I_{15th} \cdot N_{days} = 8.756 \cdot 31 = 271.44 \ \frac{kWh}{m^2}. \tag{20}$$

Table 10. Result of simulations and comparison with monthly consumptions

	Generated daily power,kWh	Generated monthly power,kWh	Monthly consumption,kWh	Deficit, kWh	Covered, %
January	681.3	21,120.3	1,095,660	1,074,540	2%
February	1063	29,764	954,320	924,556	3%
March	1,256	38,936	694,650	655,714	6%
April	1,258	37,740	461,270	423,530	8%
May	1,236	38,316	280,490	242,174	14%
June	1,066	31,980	214,750	182,770	15%
July	1,119	34,689	329,790	295,101	11%
August	1,035	32,085	224,610	192,525	14%
September	951.8	28,554	191,740	163,186	15%
October	850	26,350	444,840	418,490	6%
November	753.4	22,602	924,740	902,138	2%
December	636.7	19,737.7	1,020,060	1,000,322	2%

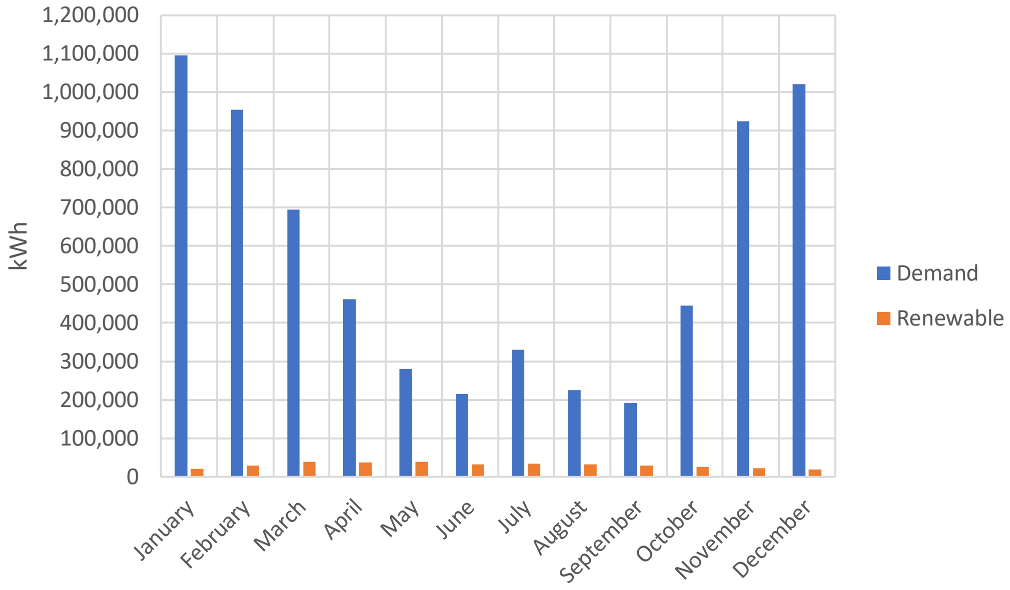

Figure 21. Load plot

Annual generation is a sum of monthly power column.

$$P_{gen}^{an} = \sum_{i=1}^{12} P_i^{mon} \approx 362 \ MWh \tag{21}$$

Conclusion.

The third Chapter is the practical part of the thesis. There were implemented background from the second Chapter and provided simulation with specific properties and under specific conditions. Were taken into account all inputs for appropriate months and done 12 simulation in order to define generated energy during the day. These data allowed to find out total generated power for the month and annual power as a result. It was the aim of this Chapter, because further P_{gen}^{an} will be used for the economic evaluation of the project and exactly it will define the revenue of a project.

According the Figure 20 is clear, that the assumption concerning exceeding of demand under production is verified because renewable covers 15% only in the best way. Submitted charts allow to observe internal processes of power production process and confirm the high accuracy of the approach and adequacy of the model.

Chapter 4. Financial evaluation

This chapter is devoted to financial evaluation of two projects:

- generated power energy from standalone system supply the demand of the enterprise;
- generated power traded on market and sailed in the network.

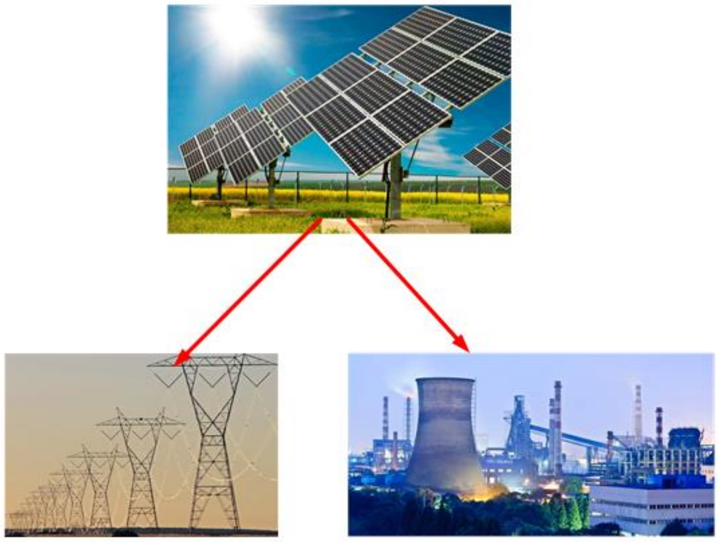

Figure 22. Two approaches

The purpose of this chapter is economical estimation of stand-alone photovoltaic system application. For the economic evaluation the net present value (NPV) tool will be used. NPV of the PV system's project will be find out. I'll find out annual output power, escalate the price of output energy corresponding electricity tariffs and this amount would be equal revenue. Revenue is equal an opportunity cost. CF statement consist of installation, connecting and operating costs, annual electricity tariff prices, degradation and annual output power for the 30 years, depreciation and tax payments. This approach allows do not consider a manufacture power consumption and estimate the price tariff for electricity only.

4.1. The projects' costs

Initial investments will be paid in the 0 year, so it will be included in CF beyond the operation time, except the maintenance. Investments cover expenditures on purchasing, transportation and installation of all equipment. Necessary investments and costs are shown below:

Table 11. Costs (discounted to 2019)

Item	Units	Cost per unit	Cost
Solar panels	360	15 000 rub	5 400 000 rub
Solar tracker	10	410 000 rub	4 100 000 rub
Inverter	3	488 400 rub	1 465 200 rub
Installation	0.35 of investment costs		3 837 800 rub
Shipping	0.05 of investment costs		548 300 rub
Maintenance	30 000 rub per year		333 000 rub
Total investment costs		15 684 300 rub	

Number of solar panels and trackers was explained in the Chapter 2. Number of inverters is chosen according their rated power, maximum power from solar panels, input and output voltage value. Will be considered, that the maximum power of inverters is 45 kW, and maximum output power appears just for a few minutes in the hottest days, which is not so much in those region. Beside this, the efficiency of inverters is lower, if the load is very low, so a big number of inverters are ineffective in the standpoint of efficiency and economy. Figure 15 shows the maximum output power equal almost 95 kW for the 15th of July, so the number of inverters is:

$$N_{inverters} = \frac{P_{max}}{P_{inv}} = \frac{95}{45} \approx 3 \qquad (22)$$

The price for 1 PV module of JA SOLAR JAM6(K)(DG)60-280/4BB is 15,000 rub, but 21 modules and more (360 for the project) cost 13,000 rub/unit [25]. In the project are applied more effective modules 72-cell mono PERC Double Glass Module JAM72D00-380/PR. Assumed, that the price is higher on 2,000 rub/unit, that is equal 15,000 rub/per unit.

There are no operation costs except the maintenance, that is estimated as 30,000 rub per year and escalated on 2% plus value inflation by fact minus predicted inflation.

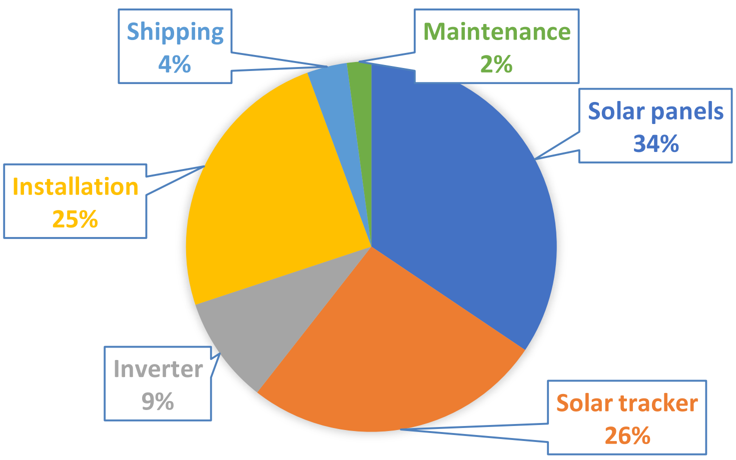

Figure 23. Pie of costs

Producer of solar panels guarantee 97% efficiency for the first 2 years, and then 14.5% degradation after 28 years of operation, that equal 0.518% per year. Higher lifetime and lower degradation allows solar modules with double-glasses generate on 25% more power during the whole operation time, that leads to reducing of internal rate of return.

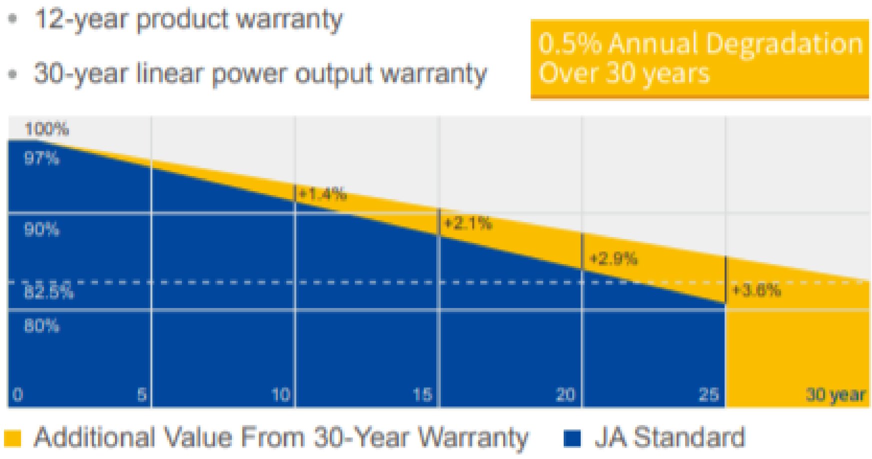

Figure 24. Degradation of JAM72D00 360-380/PR [21]

The highest cost during operation time is depreciation. Depreciation is a method of reallocating the cost of a tangible asset over its useful life span of it being in motion. Businesses depreciate long-term assets for both accounting and tax purposes. In the project depreciation is applied for tax purposes. There are two types of depreciation in Russian Federation: linear and non-linear. Linear depreciation is the highly recommended, since it is the easiest depreciation method to calculate. For financial accounting purposes, non-linear depreciation is expected to be much more productive during its early years, so that depreciation expense will more accurately represent how much of an asset's usefulness is being used up each year. Non-linear depreciation is divided on 3 approaches: method of reduced residue, write-off on the sum of the number of years of operation, proportional to the volume of production. In the thesis the second approach is applied, because its idea close to accelerated depreciation. Russian tax codecs defines 10 groups of depreciation by the lifetime of the asset. Solar panels with the 30 years lifetime is counted as ninth group of depreciation (25-30 years), solar trackers belongs to the eighths group (20-25 years) and inverters are the fifth group (7-10). According the tax law income tax payer is able to choose useful lifetime period in the range of the depreciation group. Obvious, that better would be use the lowest available value. The formula for the "write-off on the sum of the number of years of operation" approach is:

$$D_t = \frac{I(T+1-t)}{\sum(1+2+...+30)} \qquad (23)$$

Solar panels will be depreciated for 25 years, but will be used 30 years. Solar trackers will be depreciated for 20 years, and after 20 years the half of solar trackers are planning to be changed (5 trackers), because their lifetime period is 25 years and more. Inverters and installation with shipping will be depreciated during 7 years, but inverters are planning to be exchange by new ones at 10th and 20th years. At the end of the project solar trackers will be depreciated only for the first 10 years, that is why the rest (10 years) depreciation will be included in the last year.

Table 12. Costs including reinvestments (discounted to 2019)

Item	Units	Cost per unit	Cost
Solar panels	360	15 000 rub	5 400 000 rub
Solar tracker	10 + 5	410 000 rub	8 592 000 rub
Inverter	3 + 3 + 3	488 400 rub	6 844 000 rub
Installation	0.35 of investment costs		3 837 800 rub
Shipping	0.05 of investment costs		548 300 rub
Maintenance	30 000 rub per year		333 000 rub
Total investment costs		25 555 000 rub	

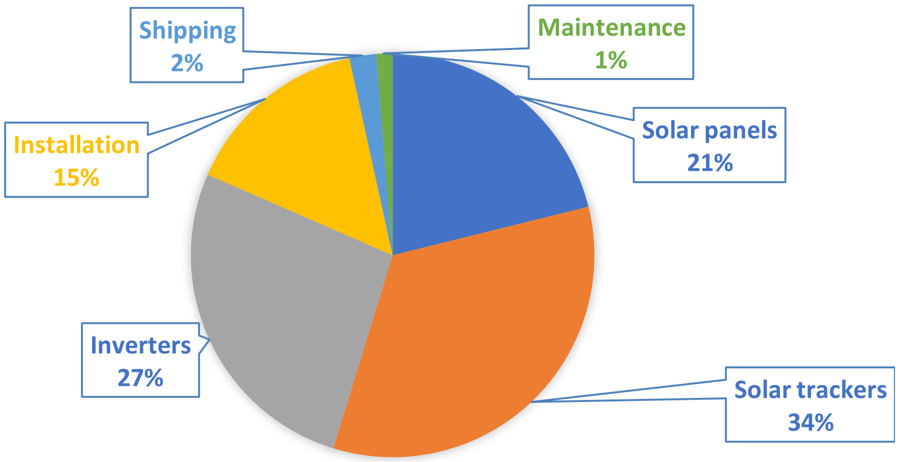

Figure 25. Pie of costs including reinvesting

Photovoltaic system is installed by industrial enterprise, and this project belongs to them, that leads to common tax base calculation. So, negative earnings before tax (EBT) are used to reduce tax payments of the enterprise in general.

4.2. Subsidies

Ministry of Energy of Russian Federation finalized the rules of granting money from the federal budget subsidies to compensate the cost of technological connection of generation facilities with total generated facilities with total generated capacity no more than 25 MW.

The subsidy is granted to the owner of the generating facility in an amount not exceeding 50% of the cost of technological connection of the generating facility, but not more than 30 million rouble on a single generating facility [26].

4.3. Electricity tariff and escalation rate

Nowadays in Russian Federation the biggest part of electricity costs are paid by firms, in order to reduce price for householders. That has a negative impact on the price of products, services, and people - instead of relevant price for electricity, they pay higher price for goods. In monetary units industries pay around 200 – 300 billions of roubles per year instead of householders. It needs to be changed and it happens. Ministry of Economic Development has started the reform of the Russian power sector. Was decided to bring the price of a 1 kWh for householders closer to market price. That is, how much electricity will cost in 2019 for householders will be 100% dependent on its owners. If they meet the social norm, the bill will be less.

There is the two-level electricity market in Russia - wholesale and retail. In the wholesale market buying and selling is carried out the subjects of the wholesale market - large power generating companies, guaranteed supply companies, independent energy retail companies, large consumers of electricity and Federal grid company of Unified Energy System. The wholesale market of electricity and power operates in most regions of the country united in price zones - the first and second. In non-price zones, market mechanisms for pricing electricity do not apply, and special pricing rules are used. The wholesale market is the space of circulation of two goods - electricity and power. Despite the fact that electricity and power consumption are interrelated, they are considered in the wholesale market as two separate products (power is the preparedness of the generating company at any time to provide the necessary amount of electricity to the consumer). Summarize, in wholesale markets producers sell energy and guaranteed supply companies purchase it.

Pricing in retail electricity markets varies depending on the tariff group of the consumer:

- householders and equivalent groups of consumers acquire electricity at regulated by governments tariff;
- For "other consumers" (industrial enterprises, legal entities, all who doesn’t belong to the tariff group of householders), the logic of pricing depends on their location: they are in the price or non-price zone of the wholesale market.

Pricing in retail markets depends on type of zone of wholesale market. In non-price zones of the wholesale market, the price of electricity is regulated by the state, guaranteed supply companies purchase electricity in the wholesale market at set prices and then transmit their costs to consumers in the retail market. In the price zones, the price of electricity in the retail market is not regulated by the state, guaranteed supply companies and independent energy retail companies purchase electricity in the wholesale market at free market prices. Subjects of the retail markets having generating capacities have the right to sell the electric power to consumers located in a zone of activity of the same guaranteeing supplier, as they. At the same time, generation facilities whose installed capacity is more than or equal to 25 MW are required to sell electricity only to the wholesale market. Summarize, in retail markets guaranteed supply companies purchase energy from local producers and with energy, purchased on wholesale market, sell it to consumers.

Tariffs in Russia are divided into 6 categories, and each consumer has the right to choose the category that will allow them to save more money, because the final price of electricity for the consumer depends significantly at the correctly chosen price category. In all price categories except the first and second, electricity is paid by the hour, in the electricity bill two rows – electricity and power. Electricity is charged every hour at a different price, so these price categories require hourly electricity measurement. There are some restrictions in each tariff. First and second tariffs are available only for consumers with maximum power less than 670 kW. The rest tariffs are charged by the hour and separated by different maximum powers: less than 670 kW, between 670 kW and 10 MW, higher than 10 MW. The fifth and sixth categories oblige to plan their consumption. Third and fifth categories are paid by single-rate tariff.

Local guaranteed supply company "Transneft'energo" delivers energy to local consumers. It purchases power energy on the wholesale market and on the retail market from PJSC "DEK". Each month the database with prices is published on the webpage [27] for each hour of the month, for each voltage level, each range of maximum power and category of tariff. Assumed, that PJSC "Dalenergomash" has a fourth tariff category, the maximum power belongs to the range 670 kW – 10 MW and purchase electricity on low voltage level. Databases of 2018 were analysed and relevant average monthly values are submitted in the Table 13.

Table 13. Average monthly values of T_m in 2018.

	Wholesale, $^{rub}/_{kWh}$	Retail, $^{rub}/_{kWh}$
January	1.626	2.222
February	1.646	2.238
March	1.551	2.154
April	1.499	2.099
May	1.430	2.025
June	1.423	2.047
July	1.429	1.989

Table 13. Average monthly values of T_m in 2018 (continuation)

August	1.367	1.870
September	1.430	1.980
October	1.550	2.080
November	1.632	2.160
December	1.691	2.218

The average and escalated to 2019 value of T_{annual} is:

$$T_{annual} = \frac{\sum_{i=1}^{12} T_{mi}}{12} \cdot 1.03 = 1.861 \ \frac{rub}{kWh} \qquad (24)$$

The tariff price for the householders according [28] is 4.53 rub/kWh with VAT.

Since 2019 tariffs for householders and firms are escalated twice per year, in the beginning of year and at the end. Tariffs for householders will grow by an average of 7-8% per year, while for enterprises this rate will be $g = 3\%$ per year [29], in order to eliminate the current inequality in the payment of electricity between them. This data are taken from the forecast of Ministry of Economic Development of Russian Federation, and it is valid until 2036 year, which corresponds the life time of the project.

4.4. Discount rate

The discount rate is the rate that is used to revalue the value of future capital at the current time. This is because one of the fundamental laws of Economics is the devaluation of the value of money. The discount rate is used in investment analysis when the investor decides on the prospect of investing in a particular object. To do this, it is converted from the future cash flows of the project to the present (current). By providing a comparative analysis, the attractiveness of the object could be estimated. Any value of the object is always relative, so the discount rate is the basic criterion for the comparison of investments effectiveness.

For this parameter defining the Weighted Average Cost of Capitals (WACC) tool is applied. The WACC represents the minimum return that a company must earn on an existing asset base to satisfy its creditors, owners, and other providers of capital, or they will invest elsewhere. It is an average discount rate for all sources of financing (internal and external) the company and the "weight" of the each source is consisting. Internal component represents as an equity, external – as a debt.

$$WACC = \frac{E}{E+D} r_e + \frac{D}{E+D} r_d \qquad (25)$$

When companies purchase funds from external lenders, the interest rate on these funds is called the cost debt. The cost of debt is found out by adding a default risk rate to the risk-free bond rate. This default risk rate is higher as the loan amount increases (since, ceteris paribus, the risk increases with the cost of borrowed capital). At the moment the risk-free bond rate for Russian Federation is equal 7.7%. There is no data concerning default risk rate, so it is assigned equal to 4%, because the $\frac{D}{E}$ ratio is close to 1 ($E = 568,4\ mill.rub.$ and $D = 511,9\ mill.rub.$), beside this, the company is big, the demand on their products is going to growth and according their annual report, the company is profitable, that leads to risk reducing.

$$r_d = \left(r_f + r_{default}\right) \cdot \left(1 - tax\right) = \left(7.7\% + 4\%\right) \cdot \left(1 - 20\%\right) = 9.36\% \qquad (26)$$

The cost of equity is derived by comparing investments with other investments of equivalent risk. Typically calculated using the Capital Asset Pricing Model (CAPM). Inputs for the calculation are risk free rate, market risk premium and beta. Important note is a range of CAPM appliance – the company has to trade om stock market. Public Joint Stock Company (PJSC) DALENERGOMASH is fulfil this requirement.

$$r_e = r_f + \beta_L \left(r_m - r_f\right) \qquad (27)$$

In order to estimate financial parameters for CAPM, the database of Aswath Damodoran is used. Aswath Damodaran is a Professor of Finance at the Stern School of Business at New York University, where he teaches corporate finance and equity valuation. He is best known and famous as author of several widely used academic and practitioner texts on Valuation, Corporate Finance and Investment Management. Damodaran is widely quoted on the subject of valuation, with "a great reputation as a teacher and authority". He has written several books on equity valuation, as well on corporate finance and investments. He estimates financial parameters for the continents and for some specific countries separately (Chine and India) [30]. Mr. Damodaran's data are reliable and may be used in the current thesis.

A stock beta is used to mathematically describe the relationship between the movements of an individual stock versus the entire market. Investors van then use a stock's beta for measuring the risk of a security. According his data, the unlevered beta coefficient for machinery industry is 1.02 for the whole world and 1.04 for the Europe [30]. For the project is accepted an average value between them - 1.03. The information about equity and debt values were taken from annual report [22] $E = 568,4\ mill.rub.$ and $D = 511,9\ mill.rub.$ The levered beta value is:

$$\beta_L = \beta_u\left(1+\frac{D}{E}(1-tax)\right) = 1.03\cdot\left(1+\frac{511.9}{568.4}\cdot(1-0.2)\right) = 1.772 \qquad (28)$$

Mr. Damodaran evaluates risk premiums for markets based upon the country ratings assigned by Moodys. Starting in June 2012, he is also reporting equity risk premiums based upon CDS spreads, where those are available. For Russia total equity risk premium is 9.43%. And according (27):

$$r_e = r_f + \beta_L\left(r_m - r_f\right) = 7.7\% + 1.772\cdot(9.43\% - 7.7\%) = 10.77\%$$

A company's assets are financed by either debt or equity, and the WACC is the average of the costs of these sources of financing, each of which is weighted by its respective use in particular case. By taking a weighted average, there is possible to observe how much interest the company has to pay for every euro it finances. Submitting all previous data in (25), the result is

$$WACC = \frac{568.4}{568.4+511.9}\cdot 10.77\% + \frac{511.9}{568.4+511.9}\cdot 9.36\% = 10.10\%$$

4.5. Bank loan

The assessment of the project profitability is a NPV value – positive or negative. Net Present Value (NPV) is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. Negative NPV value corresponds exceeding of expenditures over revenue, in such case the project is not investable. There are a few tools in order to improve NPV value. One of them is borrowing of money. The biggest weight have cash flows of the first years, because of the time value of money, so bank loan allows reduce the value of investments in the initial year and distributes it in time. In current project is borrowed a 70% of all investments that is equal 9.4 mill rub with 11.7% interest for 10 years, because bank's loan term for investment projects is 10 years for firms. Annuity payment factor for this loan is

$$\alpha_t = \frac{1}{PVAF} = \frac{1.117^{10}\cdot 0.117}{1.117^{10}-1} = 0.1748 \qquad (29)$$

So the equivalent annual annuity is $EAA = L\cdot\alpha_t = 9.4\cdot 0.1748 = 1.644\ mill.rub.$

Interests payments are included in the operating activities, but repayments of loan are in included in the financing activities, so it doesn't have an impact on tax base. That's why necessary to split EAA on two parts. For this purpose the redemption plan of debt should be prepared. Interest for the first year is:

$Interest = 9.403 \cdot 11.7\% = 1.1\,mill.rub;$

$Repayment = EAA - Interest = 1.644 - 1.1 = 0.544\,mil.rub.;$

$Residue = 9.403 - Repayment = 9.403 - 0.544 = 8.859\,mil.rub.$

For the second year:

$Interest = 8.859 \cdot 11.7\% = 1.037\,mill.rub;$

$Repayment = EAA - Interest = 1.644 - 1.037 = 0.607\,mil.rub.;$

$Residue = 8.859 - Repayment = 8.859 - 0.607 = 8.252\,mil.rub.$

For the next years data is presented in the Table 14.

Table 14. Redemption plan of debt

Year	Interest	Repayment	Residue
1	1,100,111	543,627	8,859,032
2	1,036,507	607,231	8,251,801
3	965,461	678,277	7,573,524
4	886,102	757,636	6,815,888
5	797,459	846,279	5,969,610
6	698,444	945,294	5,024,316
7	587,845	1,055,893	3,968,423
8	464,306	1,179,432	2,788,991
9	326,312	1,317,426	1,471,565
10	172,173	1,471,565	0

4.6. Revenue

In this financial model income is represented as opportunity costs of centralized network suppling for the first approach and revenue from selling electricity in the grid. Finally equation for income is:

$$I = \sum_{i=1}^{30} P_{gen}^{an} \cdot T \cdot \left(1+g\right)^{i-1} \cdot \left(0.97 - degr \cdot \left(i-1\right)\right)\ rub \qquad (30)$$

Where T – tariff, rub/kWh; g – escalation rate, %; $degr$ – degradation, %; P_{gen} – annual power from PV system, kWh.

Revenue in the 1st year is 1.6 mill. rub, 3 mill. rub in the 10th year, 5.7 mill. rub. in the 20th year and 11 mill. rub. in the 30th year. Accelerated growth of revenue is one of the reason of prolongation this project until 30 years.

4.7. NPV and IRR, PP and DPP, ROI

Net present value is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is calculated by the formula:

$$NPV = \sum_{i=0}^{30} \frac{CF_t}{(1+r)^t} \tag{31}$$

where CF_t - cash flow of appropriate year, r - discount rate, t - current year.

NPV is the most important financial evaluation tool, but doesn't the only one. The internal rate of return (IRR) is a metric used to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes NPV of all cash flows from a particular project equal to zero. The equation is:

$$\sum_{t=0}^{30} \frac{CF_t}{(1+r_{irr})^t} = 0 \tag{32}$$

The payback period refers to the amount of time it takes to recover the cost of an investment. Simply put, the payback period is the length of time an investment reaches a break-even point. The desirability of an investment is directly related to its payback period. Shorter paybacks mean more attractive investments. Investors and managers can use the payback period to make quick judgments on their investments.

$$\sum_{t=0}^{DPP} \frac{CF_t}{(1+r)^t} = 0 \tag{33}$$

$$\sum_{t=0}^{PP} CF_t = 0 \tag{34}$$

Return on Investment (ROI) is a performance measure used to evaluate the efficiency of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost.

$$ROI = \frac{\frac{\sum_{t=0}^{T} CF_t}{T}}{|CF_0|} \tag{35}$$

4.8. The first approach

Standalone photovoltaic system is applied for covering the demand of the industrial enterprise. And the firm is the owner of the project. Project allows to substitute power energy, purchased from centralized low voltage network, and initial investments should be returned during the project lifetime. The goal of the launching the project - reduce electricity bills for the industry, not saving money or their multiplication, that is why the main investments criteria will be NPV and IRR, because positive NPV leads to positive DPP and if the project is somehow profitable, it is acceptable.

Cash flow statement for the first approach is submitted in the Appendix E. Investments are paid in the 0 year, reinvestments are paid in the 10^{th} year (inverters are changed) and in the 20^{th} year (inverters and half of solar trackers). In order to cover 70% percent of investments in the 0 year was borrowed at 11.7% interest rate. Repayment loan includes in the financial part of the cash flow, because only interest includes in the tax base. All investments and reinvestments are depreciated according the Russian Tax Code. Electricity tariff is $T_{annual} = 1.861\frac{rub}{kWh}$, escalation is 3%.

For this approach NPV is equal to -7.85 mill. rub. The negative NPV is explained by low electricity price (PV is the most sensitive exactly to this parameter) and by significant reinvestments after 10 and 20 years of the project launch (-10 mill. rub. in nominal values). Beside this, Russian tax law doesn't influence as positive, as, for instance, Czech tax law. Assets were depreciated during 25 years instead of 10 years in Czech Republic, that approach would save around 1.5 mill. rub.

IRR for this project is equal -0.63% ($r_n = 10.10\%$). It means that even in the case of overestimation of the discount rate, the project is unprofitable.

PP and DPP exceed the lifetime of the project.

4.9. The second approach

As was mentioned, there are two approaches in the project. Now, let's evaluate economic effectiveness of selling generated power in the network. The installations with install capacity less than 25 MW are trading on the retail market. Assumed, that generated power will be sold for householders.

All previous assumptions and calculations are valid. The costs are the same, depreciation and taxation are included in this project too. The differences are in the tariff pricing and escalation rate.

The electricity tariff will be escalated by the rate, accepted for householders (7.5% per year) and the minimum electricity tariff will be $T_{hholders} = 4.53\frac{rub}{kWh}$ for the Khabarovskiy region. Appropriate cash flow statement is submitted in the Appendix D.

NPV of the project is positive and equal to 9.567 mill. rub. Significant difference in comparison with previous approach explained by different tariff price (two times higher). The tariff is the most sensitive parameter and even 10% changes may bring down net present value, because only it generates revenue for the project. Beside this, escalation rate's impact is significant in the long term (profit in the 11th year is 2.66 mill. rub., but in the 30th year is 9 mill. rub. in nominal values).

Internal rate of return is 18.27% ($r_n = 10.10\%$). Reserve of the project profitability at a discount rate is 8%.

Payback period because of reinvestments a little bit higher and equal to 11 years. Chart for payback period illustrates behaviour of cumulated cash flows during the project lifetime.

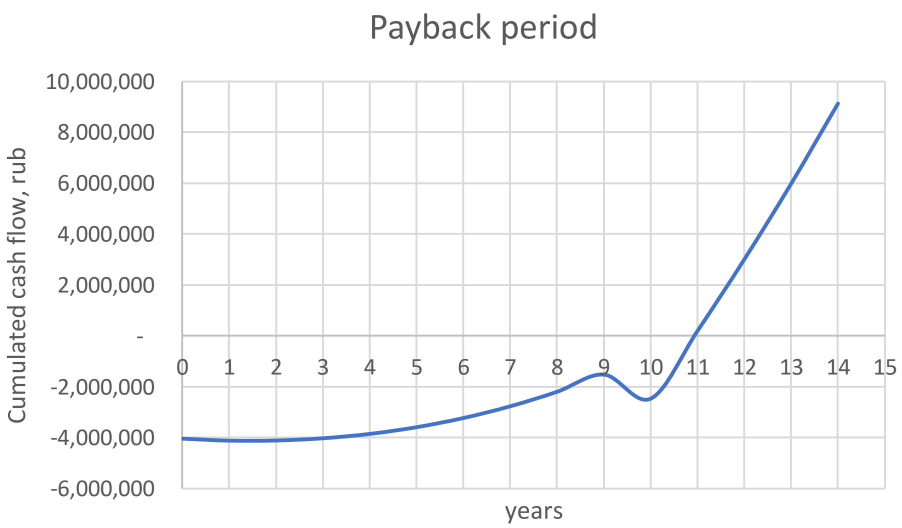

Figure 26. Payback period

Discounted payback period shows to the amount of time it takes to recover the cost of an investment in discounted values.

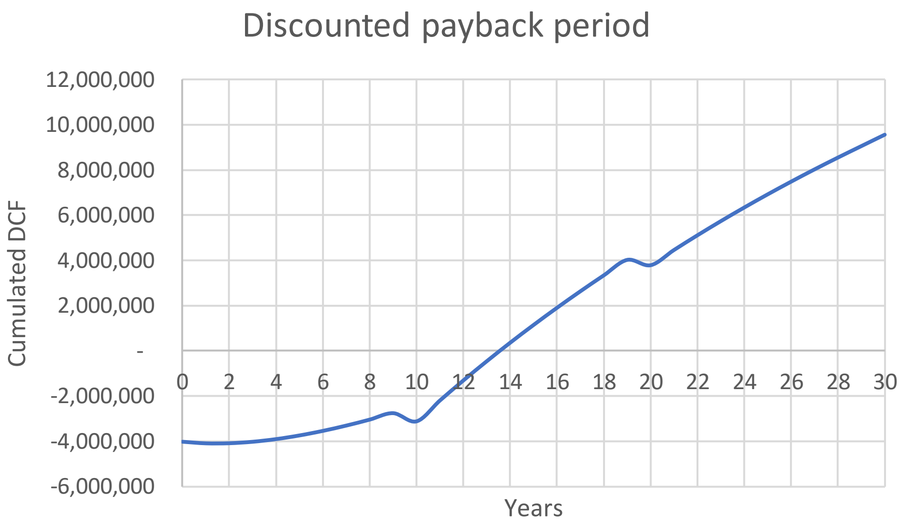

Figure 27. Chart of DPP

The last but not least parameter is ROI, that is calculated according the equation (33):

$$ROI = \frac{\frac{\sum CF}{30}}{|-4\,029\,711|} = 78\%$$

4.10. Sensitivity analysis

The second approach is much more attractive, that the first one, that's why sensitivity analysis will be provided only for the second. Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be divided and allocated to different sources of uncertainty in its inputs. Sensitivity analysis is one of the methods of effectiveness and stability estimation of projects, and it's purpose is definition of initial data impact on the result. The most important output parameters for analysing are NPV and IRR. Impact of ratio-loan to own funds, discount rate, electricity tariff and it's growth, amount of investments and inflation is going to be investigated.

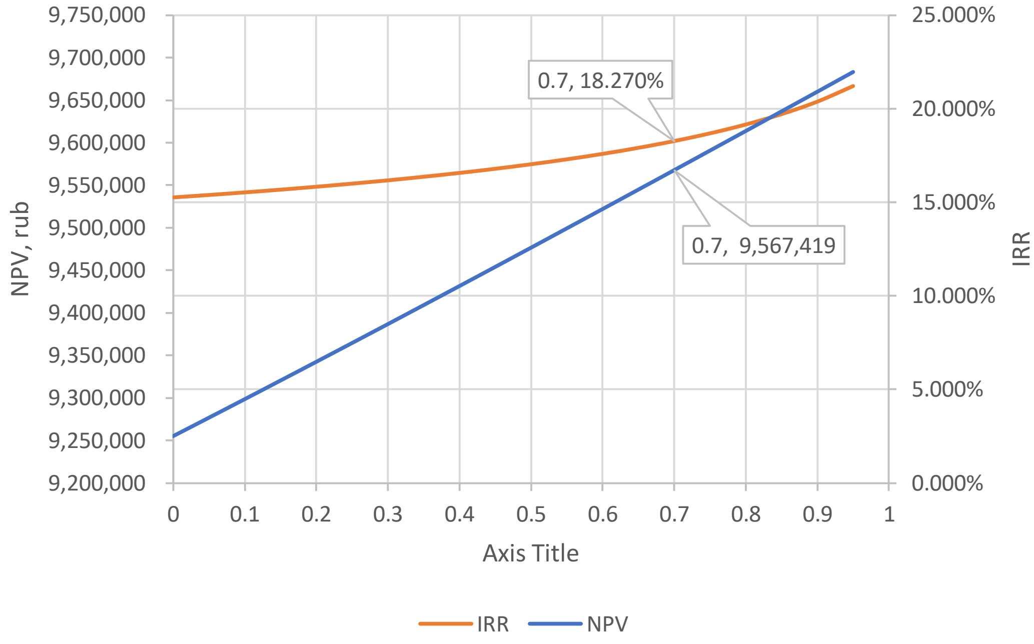

Figure 28. NPV and IRR as a function of ratio-loan to own funds

The first analyse refer to ratio-loan to own funds. As you can observe, the decision to borrow money was correct and has led to increasing of NPV on quarter of million and higher IRR on 3% (difference between IRR and discount rate is 4%). Remind, that it has happened because of the time value of money.

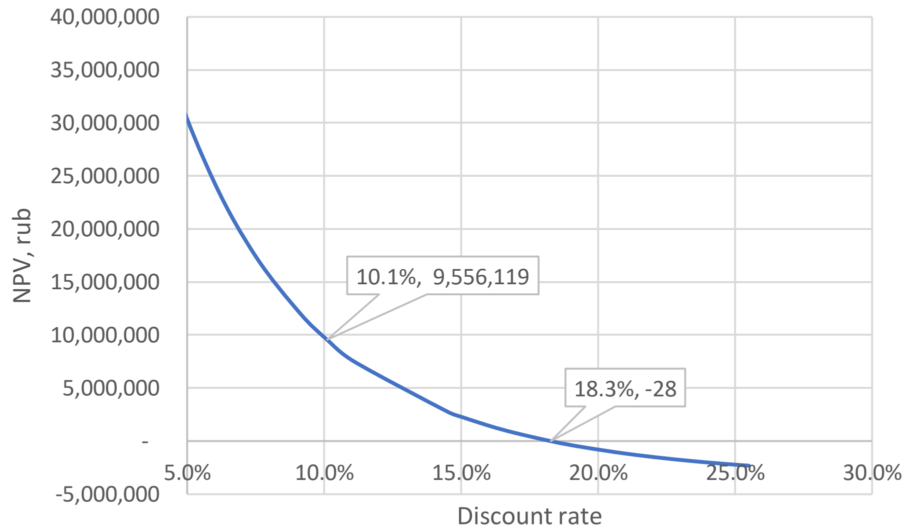

Figure 29. NPV as a function of discount rate

One of the most important input is discount rate. Reserve of 8.2% says about high stability of the project and a sizable sensitivity of NPV to this parameter change. An error in estimation of the project leads to the opposite result and photovoltaic plant won't be built.

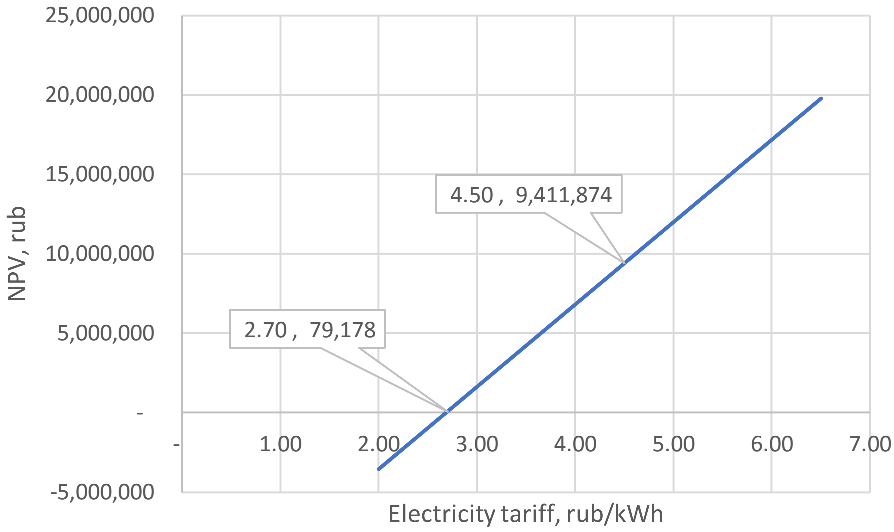

Figure 30. NPV as a function of electricity tariff

Electricity tariff for householders is a specific price under the government regulation. At the beginning of the 2019 was made an order, and tariffs were assigned, that is why there couldn't be any mistakes. That is possible to define the lowest tariff price for current project - 2.7 rub/kWh.

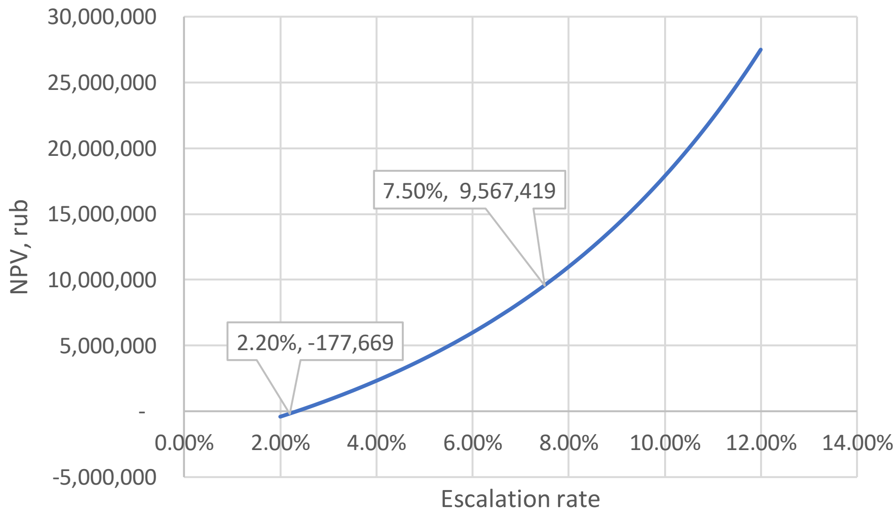

Figure 31. NPV as a function of the escalation of tariff

The parameter concerning income of the project is growth of the tariff. This value is under the government control and they promise not to exceed the value of 8% growth per year until 2036 [29]. Taking into account features of the country, annual growth couldn't be significantly lower, but higher – easily. NPV is sensitive to this parameter, because it has cumulated impact and it influence on the price significantly after a lot of years, taking into account 30 years lifetime of the project, growth of the tariff couldn't be neglected.

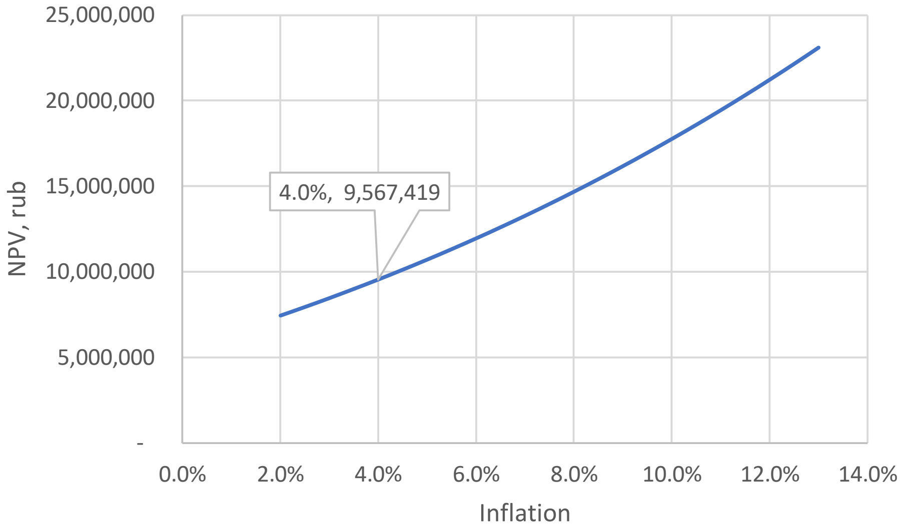

Figure 32. NPV as a function of inflation

According forecast of Central Bank of the Russian Federation [31] the predicted value of inflation is 4%. The behaviour of the curve is a little bit unexpected. This phenomenon is explained by the financial model particularities. Inflation has an impact on the escalation rate, each 1% of inflation increasing leads to 0.5% increasing of escalation rate. As was mentioned previously, escalation rate has a significant influence on the NPV value. Inflation has a negative impact too – amount of reinvestments in 10th and 20th years, because price of equipment every year increases. But impact of escalation rate if higher. It is an advantage of the photovoltaic systems – initial investments don't require operation costs and since the first year of operation it generates money.

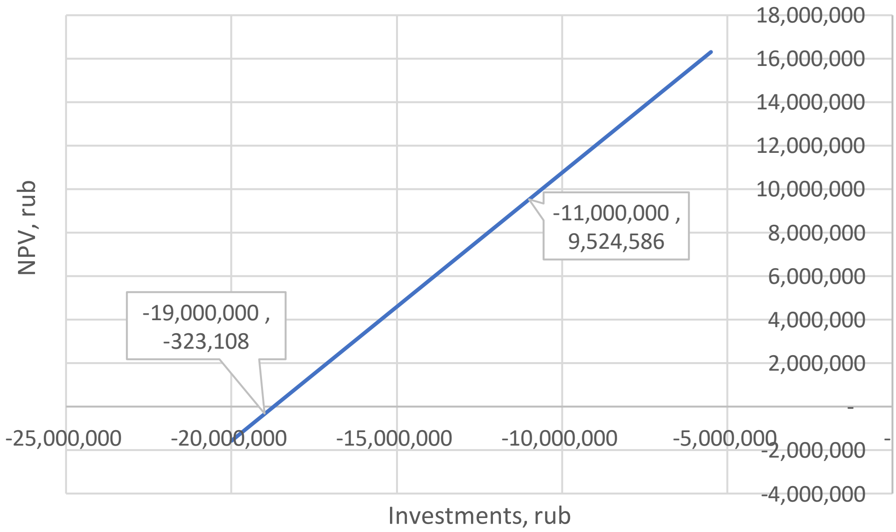

Figure 33. NPV as a function of investments

It may happens that the first assessment of investments would be exceeded and would require more investments for the project. In order to be profitable in the project the investments shouldn't exceed 19,000,000 rub. There is a mechanism inside the model, that allows to reduce negative impact of this parameter.

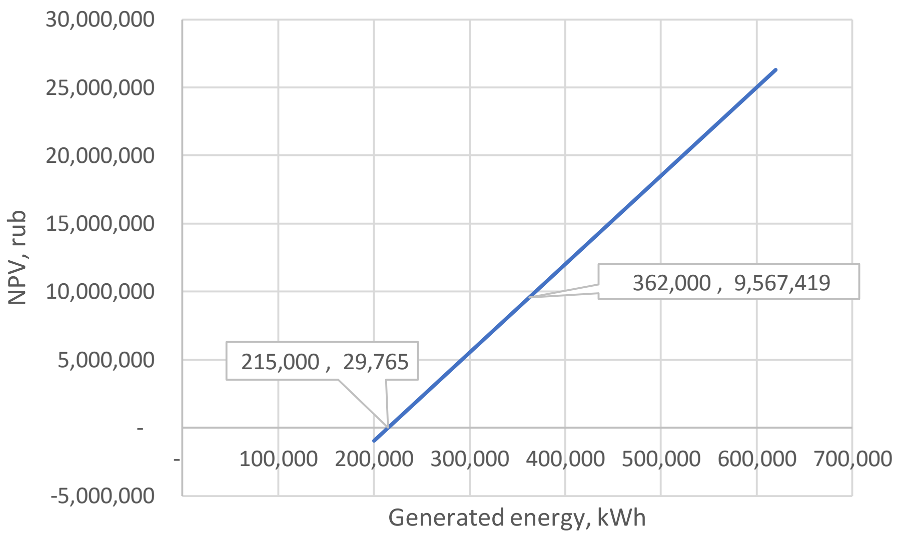

Figure 34. NPV as a function of Output power

As was mentioned in the Chapter 1, renewable energy is rapidly develop, so it is important to research NPV changed, when PV modules with higher efficiency would applied. Beside this, there are a lot of producers of PV modules all over the world, and they offer their products with different efficiency even nowadays, and chart 32 allows to observe this impact. Important to mention – more efficiency equipment costs more, that is why the initial investments would be higher.

Summarizing all data in the one table, for better understanding.

Table 15. Sensitivity analysis

Parameter	10% parameter change	New NPV, mill.rub	Found out NPV, mill.rub	NPV change in %	Sensitivity indicator	Rang
Discount rate	11.1%	7.48	9.57	-21.79%	-2.18	2
	9.1%	12.09		26.33%	2.63	
Tariff	4.983	11.92	9.57	24.55%	2.45	1
	4.077	7.22		-24.55%	-2.45	
Growth	8.25%	11.71	9.57	22.41%	2.24	3
	6.75%	7.66		-19.89%	-1.99	
Inflation	4.40%	10.02	9.57	4.76%	0.48	5
	3.60%	9.12		-4.64%	-0.46	
Investment	-12.06	8.22	9.57	-14.11%	-1.41	4
	-9.87	10.92		14.11%	1.41	

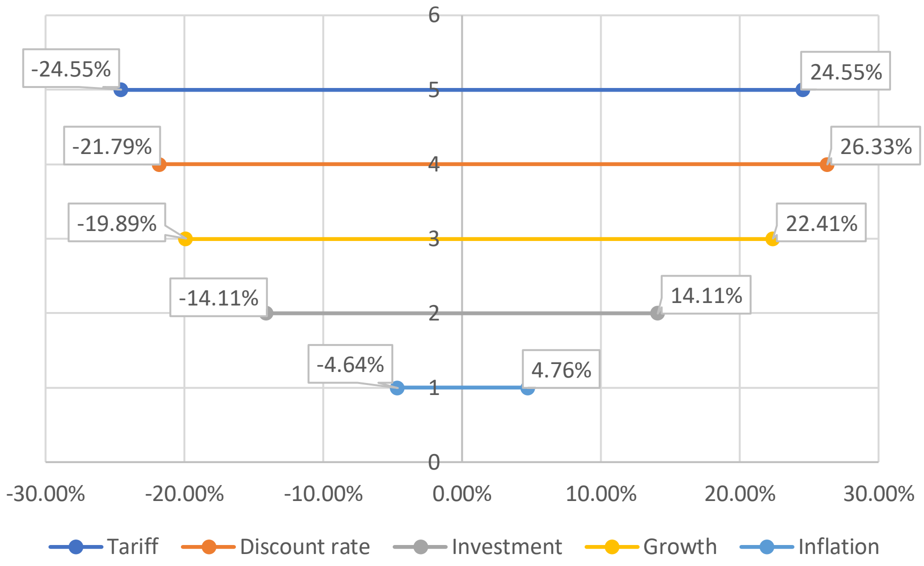

Figure 35. Tornado diagram

Tornado diagram shows changes of NPV, if the specific parameter is changes on 10%. This diagram graphically represents the stability of the project and considering the main result of the project.

Conclusion

The thesis was devoted to research of fields of standalone photovoltaic system's applicability. This objective was reached by following steps. First of all, was done a review of renewable energy systems development in the world. Without that would be impossible to understand the relevant of the project and adequacy of further steps. According the reports of international agencies and organizations, photovoltaic technology has a significant potential to partially substitute conventional sources of energy and reduce costs of power energy production. Nowadays there are two main approaches to implement photovoltaic – distributed generation and supply the demand of householders. And this approaches were implemented for the area and laws of the Russian Federation.

The first step to realize the project – design photovoltaic system. PV modules (360 units x 380W), inverters (48V/380V) and azimuth solar trackers (36 modules, 10 units). Assumed that storage battery is not effective and this standpoint was justified in the chapter three. All this components and stochastic external parameters were simulated in the MatLab Simulink. Model has shown adequate and relevant results, were submitted scopes in order to observe internal processes during the simulation day (86 400 sec) and recorded the cumulated solar irradiation and output power. The choice of location of a standalone PV system is a key to profitability of the project, that is why was chosen one of the most sunny region of the Russia – Khabarovskiy region. And this project was realized in the area of the industrial enterprise in the Khabarovsk – PJSC "Dal'energomash". Were collected and analysed data of the weather for this region. In the best month the installation covers 15% of consumption and annual generation is equal $P_{gen}^{an} \approx 362\ MWh.$ This power substitutes power from centralized network.

Evaluation of the economic effectiveness is the main issue of the thesis, which occupy almost the half of the whole thesis. Total investment costs including reinvestments in 10^{th} and 20^{th} years were found out equal to 25.5 mill. rub., the biggest part are solar trackers (34%), solar modules and inverters are 21% and 27% respectively. Investments were depreciated according the Russian Tax Codex. In order to improve NPV was decided to borrow 70% of investments in bank. Interest rate for the industry is 11.7%. A redemption plan was established and after 10 years the loan is covered. Discount rate was estimated according the annual report of the industry, applying CAPM method and WACC. Discount rate of the project is 10.10%. It is the common data.

There are a few personal input values for each approach. In the first approach generated power covers the demand of the industry. Revenue for this approach has been estimated as an opportunity costs of purchasing power from the centralized network. Tariff pricing for householders and industries distinguishes significantly. Tariff for industries low voltage on the retail market is equal $T_{ind} = 1.861 \frac{rub}{kWh}$ with escalation rate 3% per year according the plans of Russian Ministry of Development. NPV and IRR for this project are -7.85 mill. rub. and -0.63% respectively. This approach is absolutely not profitable, because of low electricity bills for industries.

In the second approach generated power sells in the network to supply householders. In this the revenue is defined as sail power. Tariff for householders in those region is assigned by governments and equal to $T_{hholders} = 4.53 \frac{rub}{kWh}$ with 7.5% escalation per year. NPV of this application variant is +9.567 mill.rub., IRR 18.27%, payback period 11 years, discounted payback period – 14 years. Return on investments is 78%. The profitability of the second approach is obvious, that is why the sensitivity analysis has been providing for the second case. According the analysis, the project if defined as high stability, because 10% change of each input parameter doesn't lead to more than 25% change of NPV.

Profitability of the PV system application depends on costs of electricity in the centralized network. This price becomes higher and higher because of allocation of conventional primary sources of energy, that leads to it's price increasing. Taking into account, that the price of kWh for householders higher relative to firms, projects of renewables implementation is more attractive exactly for householders, it was proved by all calculations and estimations in the thesis. But they face with the problem of requirement high initial investments, and their consumption doesn't allow to cover initial expenditures even after 20 years of operation. Summarize all results of the thesis, it is possible to make a conclusion, that distributed generation is the only one profitable option for supplying the householders in the Khabarovskiy region and such kind of projects have a high probability to be profitable for investors.

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Appendices

Appendix A. The design of photovoltaic system

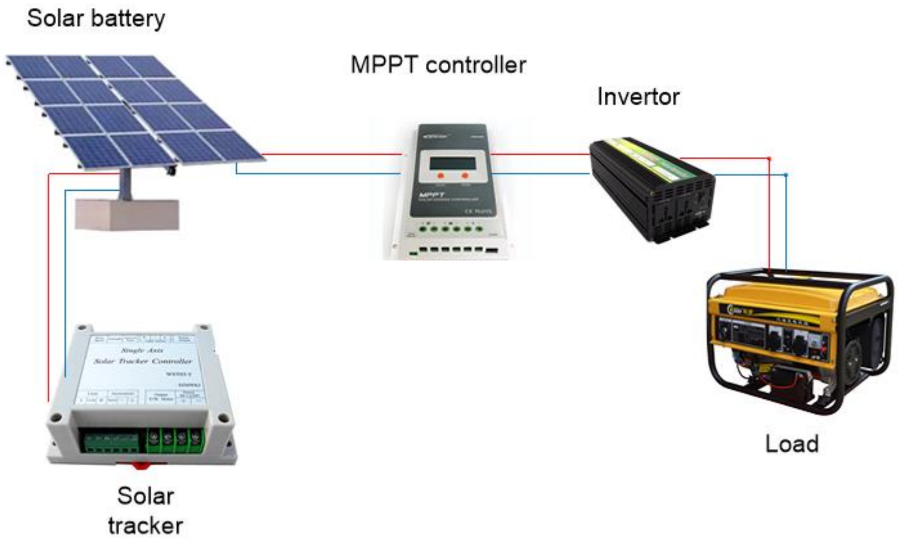

Figure A.1. PV system structure

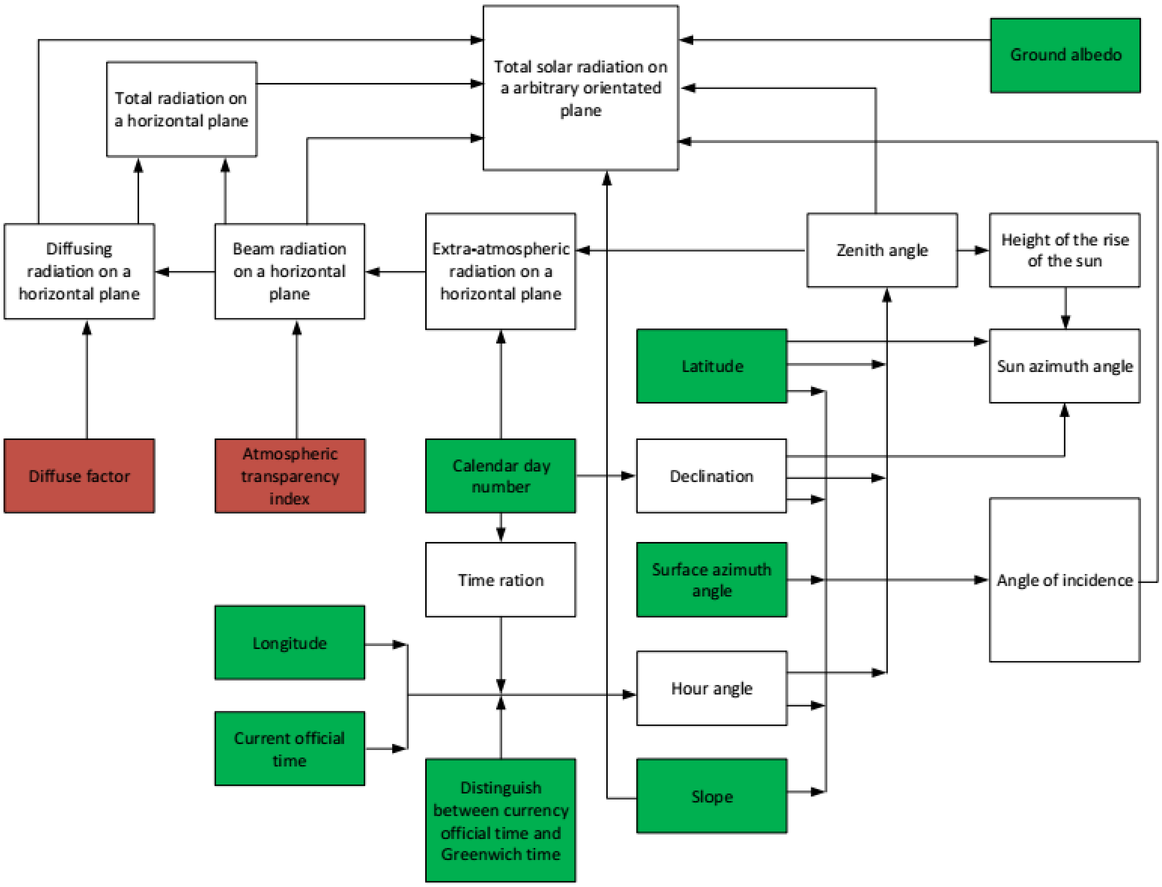

Figure A.2. Solar radiation

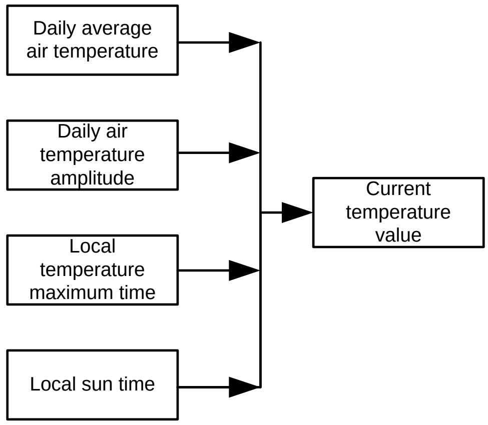

Figure A.3. Daily temperature calculations

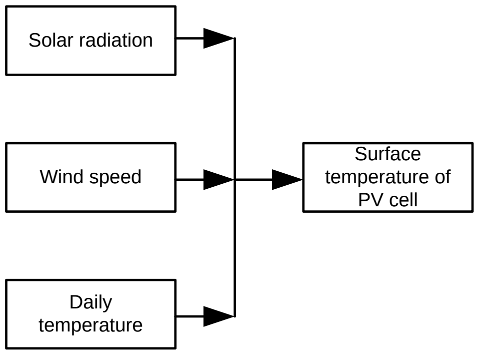

Figure A.4. Surface temperature calculations

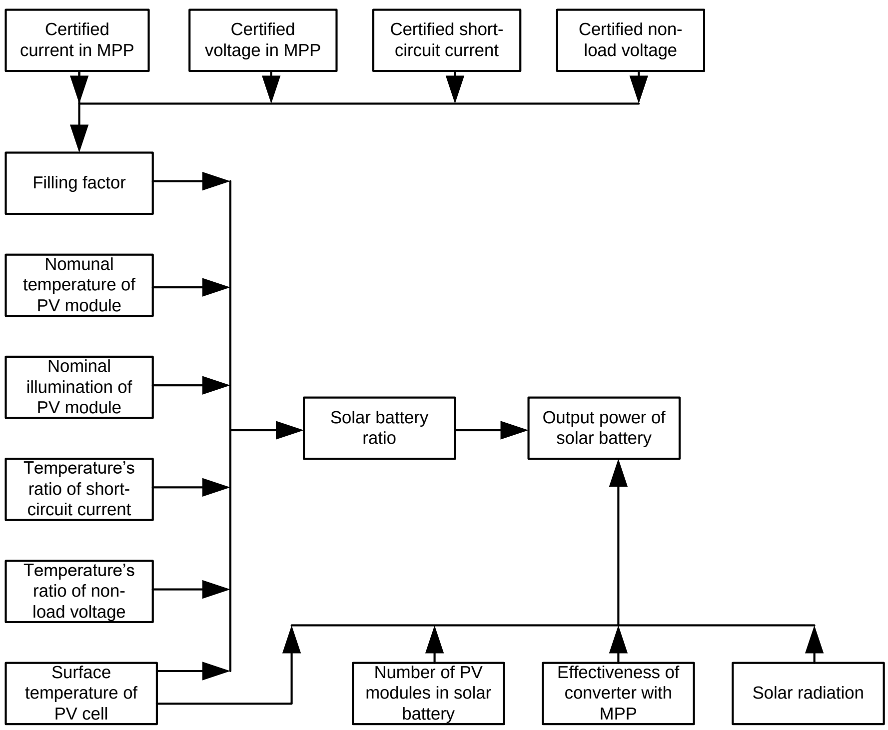

Figure A.5. PV solar battery calculations

Appendix B. Scopes

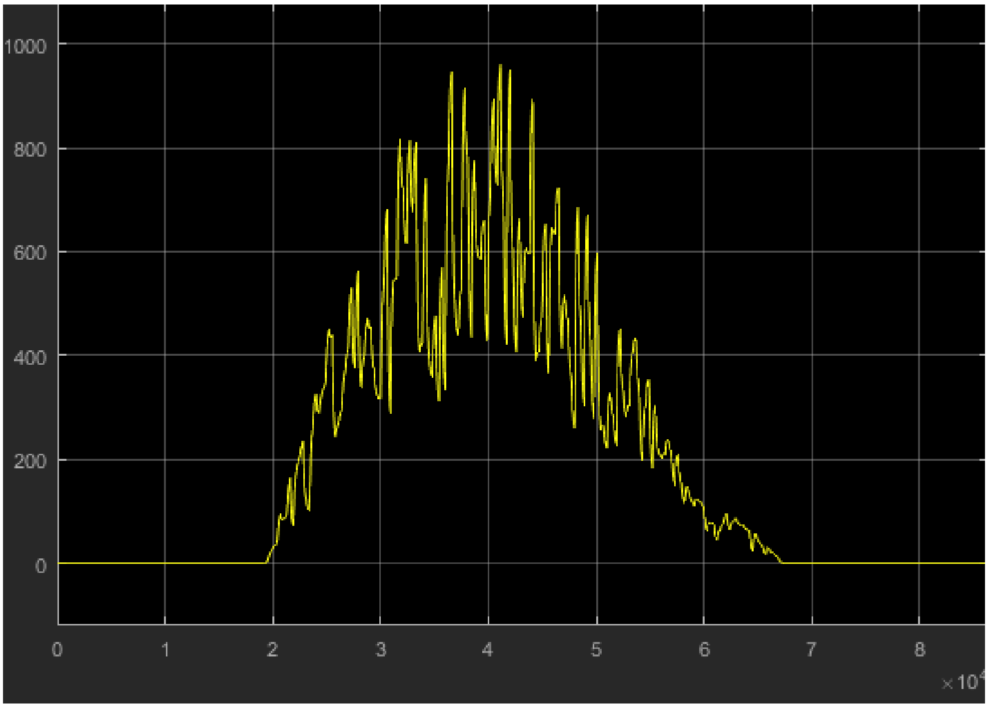

Figure B.1. The radiation without solar tracker

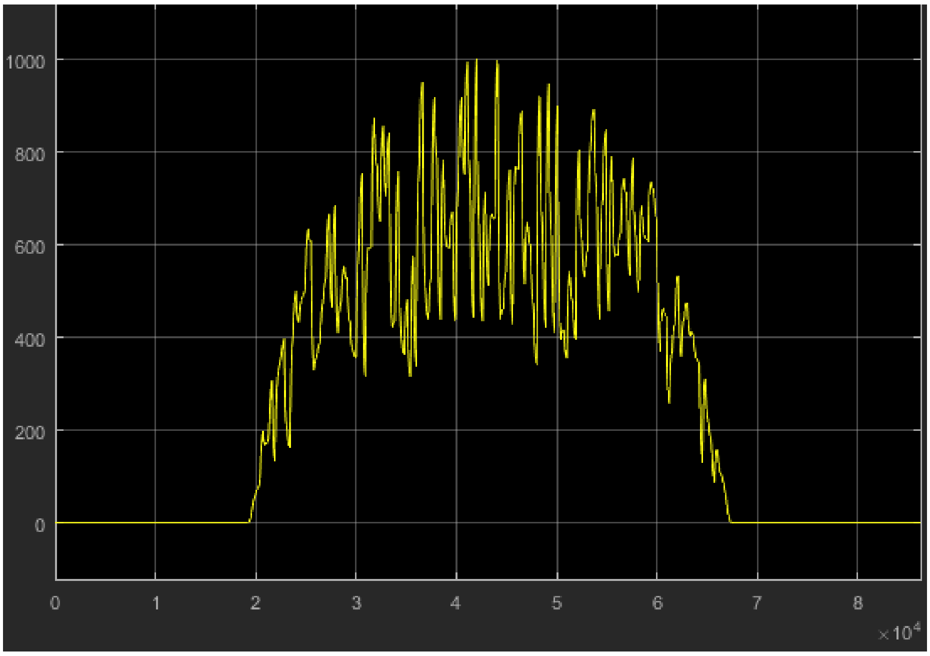

Figure B.2. The radiation with solar tracker

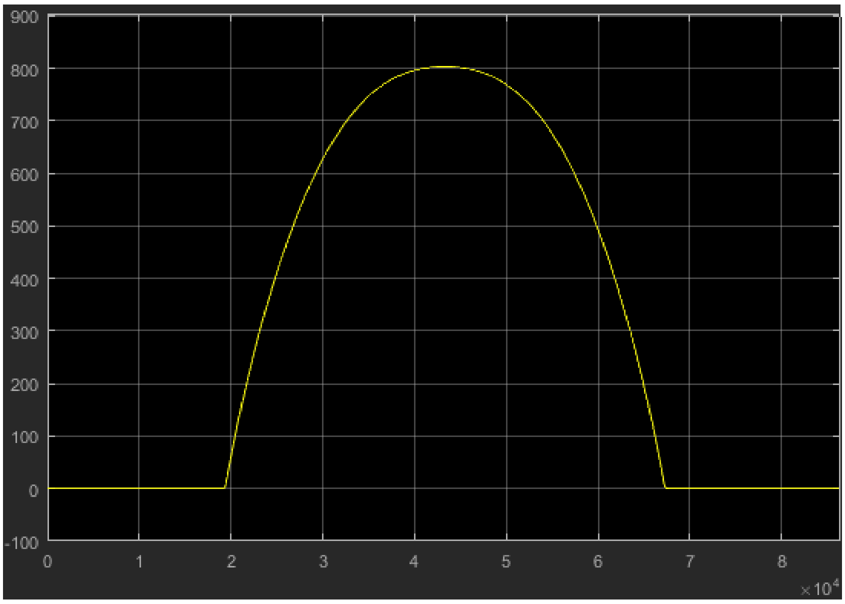

Figure B.3. Solar radiation without clouds.

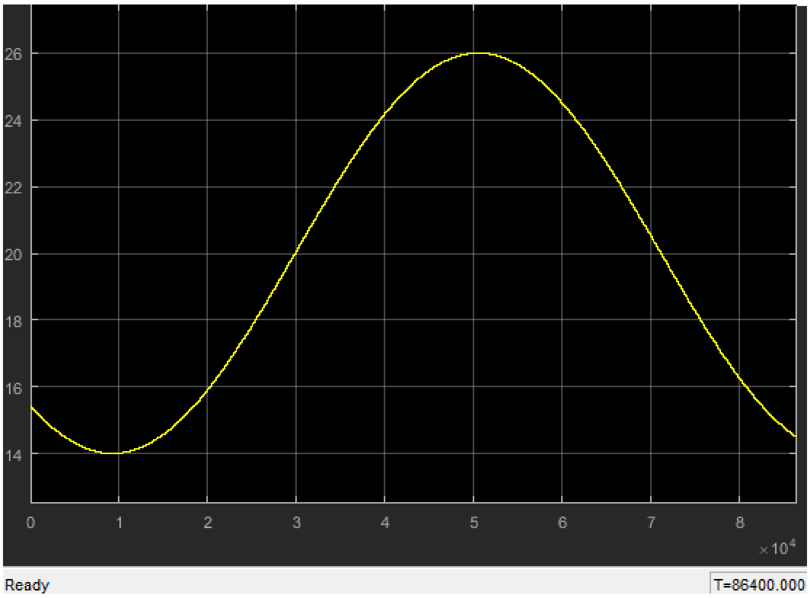

Figure B.4. The daily temperature curve

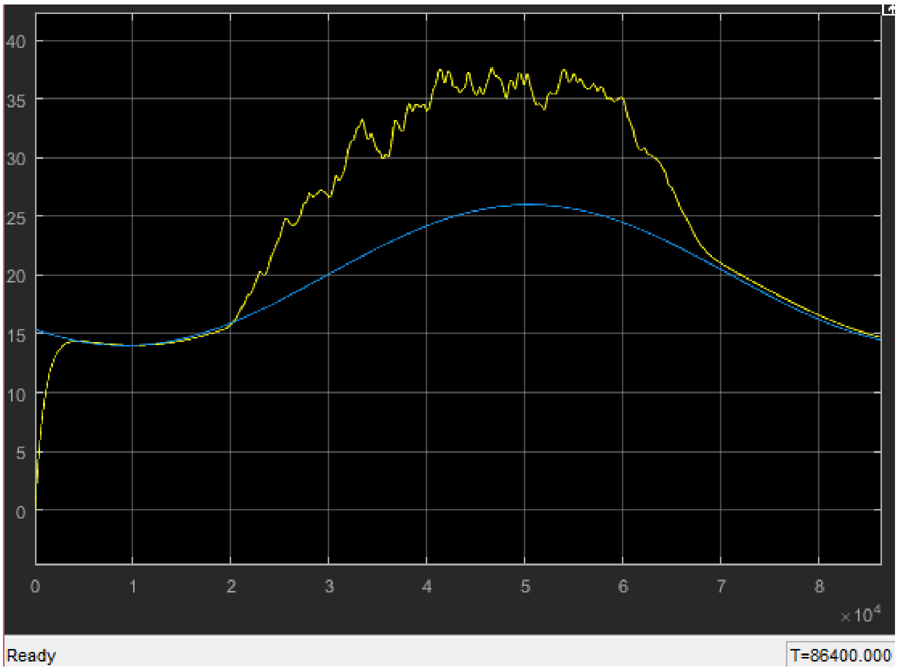

Figure B.5. Surface temperature scope

Blue curve corresponds daily air temperature's behaviour. Yellow curve corresponds surface temperature behaviour. The ripple appeared because of solar radiation impact.

Appendix C. Initial data in MatLab Simulink

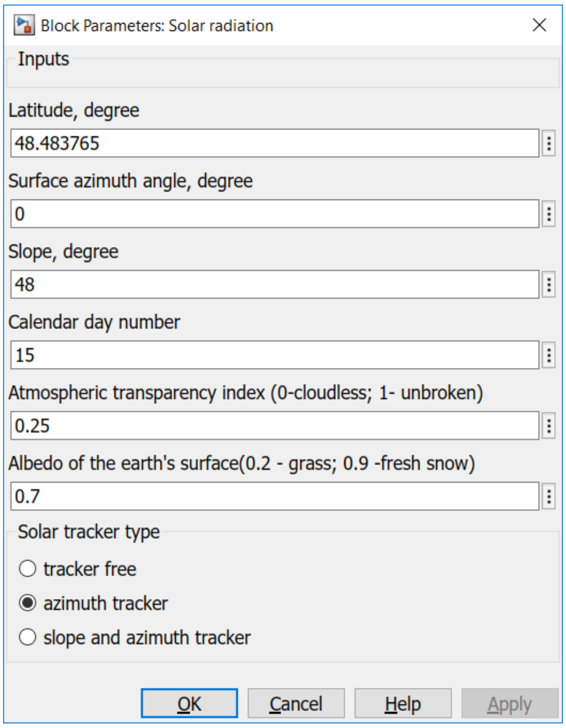

Figure C.1. Solar radiation

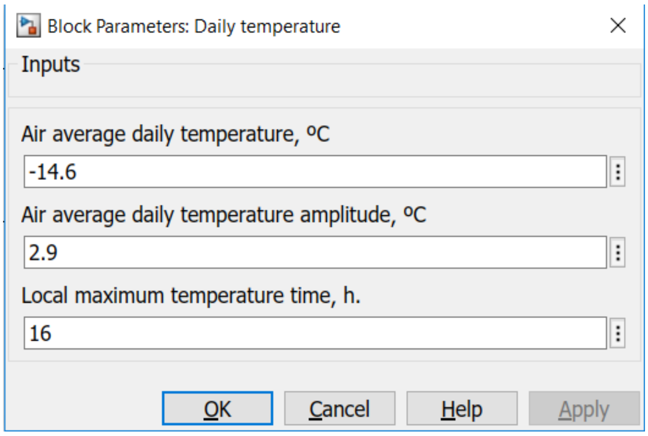

Figure C.2. Daily temperature

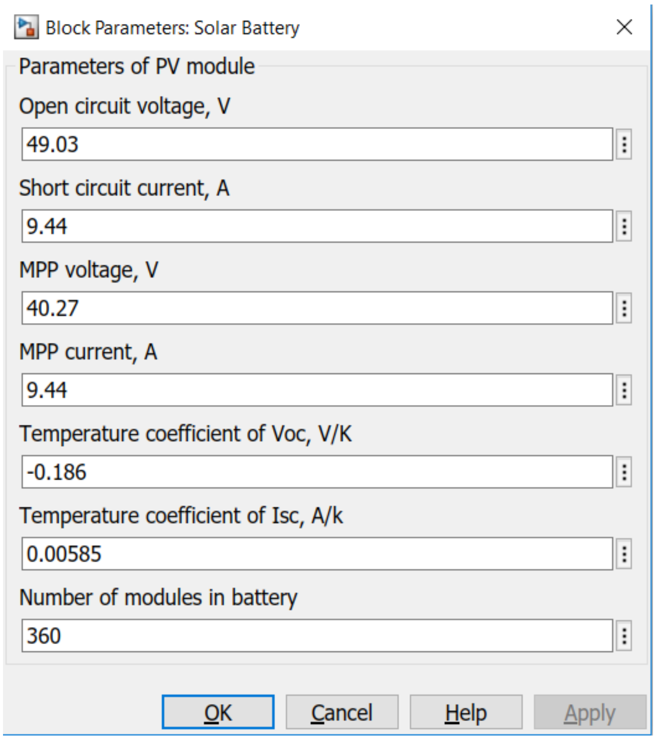

Figure C.3. Solar battery

Appendix D. Economic evaluation

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Investments	- 10,965,200										- 2,168,854			
Installation	- 1,918,910													
Shipping	- 548,260													
Maintenance		- 30,000	- 30,600	- 31,212	- 31,836	- 32,473	- 33,122	- 33,785	- 34,461	- 35,150	- 35,853	- 36,570	- 37,301	- 38,047
Bank loan	9,402,659													
Interest		- 1,100,111	- 1,036,507	- 965,461	- 886,102	- 797,459	- 698,444	- 587,845	- 464,306	- 326,312	- 172,173			
Depreciation		- 488,371	- 493,019	- 497,667	- 502,315	- 506,963	- 511,610	- 516,258	- 520,906	- 489,770	- 458,633	- 969,710	- 861,114	- 752,518
Revenue		653,364	672,965	689,454	706,326	723,590	741,254	759,326	777,816	796,732	816,082	835,877	856,125	876,835
EBT	- 4,029,711	- 965,117	- 887,160	- 804,886	- 713,927	- 613,305	- 501,924	- 378,562	- 241,856	- 54,500	- 2,019,430	- 170,402	- 42,290	86,270
TAX		- 193,023	- 177,432	- 160,977	- 142,785	- 122,661	- 100,385	- 75,712	- 48,371	- 10,900	- 403,886	- 34,080	- 8,458	17,254
EAT	- 4,029,711	- 772,094	- 709,728	- 643,909	- 571,142	- 490,644	- 401,539	- 302,850	- 193,485	- 43,600	- 1,615,544	- 136,322	- 33,832	69,016
CFo	- 4,029,711	- 283,723	- 216,709	- 146,242	- 68,827	16,319	110,072	213,409	327,421	446,170	- 1,156,911	833,388	827,282	821,534
CFf (repayment loan)		- 543,627	- 607,231	- 678,277	- 757,636	- 846,279	- 945,294	- 1,055,893	- 1,179,432	- 1,317,426	- 1,471,565			
CF	- 4,029,711	- 827,350	- 823,940	- 824,519	- 826,463	- 829,960	- 835,222	- 842,484	- 852,011	- 871,256	- 2,628,476	833,388	827,282	821,534

Figure D.1. CF statement for the first approach (first part)

2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048
14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
						- 7,702,236										
- 38,808	- 39,584	- 40,376	- 41,184	- 42,007	- 42,847	- 43,704	- 44,578	- 45,470	- 46,379	- 47,307	- 48,253	- 49,218	- 50,203	- 51,207	- 52,231	- 53,275
- 643,922	- 535,327	- 426,731	- 318,134.95	- 209,539	- 178,402	- 147,266	- 1,346,528	- 1,198,867	- 1,051,207	- 903,546	- 755,885	- 608,224	- 460,563	- 312,903	- 279,900	- 1,423,322
898,018	919,682	941,838	964,496	987,666	1,011,357	1,035,581	1,060,349	1,085,670	1,111,557	1,138,019	1,165,069	1,192,718	1,220,977	1,249,858	1,279,373	1,309,534
215,287	344,771	474,732	605,178	736,119	790,107	- 6,857,625	- 330,758	- 158,667	13,971	187,166	360,931	535,275	710,211	885,749	947,242	- 167,064
43,057	68,954	94,946	121,036	147,224	158,021	- 1,371,525	- 66,152	- 31,733	2,794	37,433	72,186	107,055	142,042	177,150	189,448	- 33,413
172,230	275,817	379,785	484,142	588,895	632,086	- 5,486,100	- 264,606	- 126,934	11,177	149,733	288,745	428,220	568,169	708,599	757,794	- 133,651
816,152	811,144	806,516	802,277	798,435	810,488	- 5,338,834	1,081,922	1,071,934	1,062,383	1,053,279	1,044,630	1,036,445	1,028,732	1,021,502	1,037,694	1,289,671
816,152	811,144	806,516	802,277	798,435	810,488	- 5,338,834	1,081,922	1,071,934	1,062,383	1,053,279	1,044,630	1,036,445	1,028,732	1,021,502	1,037,694	1,289,671

Figure D.2. CF statement for the first approach (second part)

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Investments	-10,965,200										-2,168,854			
Installation	-1,918,910													
Shipping	-548,260													
Maintenance		-30,000	-30,600	-31,212	-31,836	-32,473	-33,122	-33,785	-34,461	-35,150	-35,853	-36,570	-37,301	-38,047
Bank loan	9,402,659													
Interest		-1,100,111	-1,036,507	-965,461	-886,102	-797,459	-698,444	-587,845	-464,306	-326,312	-172,173			
Depreciation		-488,371	-493,019	-497,667	-502,315	-506,963	-511,610	-516,258	-520,906	-489,769.59	-458,633	-969,709.64	-861,114	-752,518
Revenue		1,590,664	1,709,964	1,828,398	1,954,978	2,090,260	2,234,838	2,389,345	2,554,456	2,730,895	2,919,431	3,120,885	3,336,136	3,566,120
EBT	-4,029,711	-27,818	149,839	334,058	534,724	753,365	991,661	1,251,456	1,534,784	1,879,664	83,918	2,114,606	2,437,721	2,775,555
TAX		-5,564	29,968	66,812	106,945	150,673	198,332	250,291	306,957	375,933	16,784	422,921	487,544	555,111
EAT	-4,029,711	-22,254	119,871	267,247	427,780	602,692	793,328	1,001,165	1,227,827	1,503,731	67,134	1,691,685	1,950,177	2,220,444
CFo	-4,029,711	466,117	612,890	764,913	930,094	1,109,655	1,304,939	1,517,423	1,748,734	1,993,501	525,767	2,661,394	2,811,291	2,972,962
CFf (repayment loan)		-543,627	-607,231	-678,277	-757,636	-846,279	-945,294	-1,055,893	-1,179,432	-1,317,426	-1,471,565			
CF	-4,029,711	-77,510	5,658	86,636	172,459	263,376	359,645	461,531	569,301	676,075	-945,798	2,661,394	2,811,291	2,972,962

Figure D.3. CF statement for the second approach (1st part)

2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048
14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
						-7,702,236										
-38,808	-39,584	-40,376	-41,184	-42,007	-42,847	-43,704	-44,578	-45,470	-46,379	-47,307	-48,253	-49,218	-50,203	-51,207	-52,231	-53,275
-643,922	-535,327	-426,731	-318,134.95	-209,539	-178,402	-147,266	-1,346,528	-1,198,867	-1,051,207	-903,546	-755,885	-608,224	-460,563	-312,903	-279,900	-1,423,322
3,811,836	4,074,349	4,354,798	4,654,396	4,974,438	5,316,305	5,681,471	6,071,508	6,488,092	6,933,011	7,408,173	7,915,611	8,457,494	9,036,134	9,653,996	10,313,709	11,018,076
3,129,105	3,499,438	3,887,691	4,295,077	4,722,891	5,095,055	-2,211,735	4,680,401	5,243,755	5,835,425	6,457,321	7,111,473	7,800,051	8,525,368	9,289,887	9,981,578	9,541,478
625,821	699,888	777,538	859,015	944,578	1,019,011	-442,347	936,080	1,048,751	1,167,085	1,291,464	1,422,295	1,560,010	1,705,074	1,857,977	1,996,316	1,908,296
2,503,284	2,799,550	3,110,153	3,436,062	3,778,313	4,076,044	-1,769,388	3,744,321	4,195,004	4,668,340	5,165,856	5,689,178	6,240,041	6,820,294	7,431,909	7,985,263	7,633,183
3,147,206	3,334,877	3,536,884	3,754,197	3,987,852	4,254,447	-1,622,122	5,090,849	5,393,871	5,719,547	6,069,402	6,445,064	6,848,265	7,280,858	7,744,812	8,265,163	9,056,505
3,147,206	3,334,877	3,536,884	3,754,197	3,987,852	4,254,447	-1,622,122	5,090,849	5,393,871	5,719,547	6,069,402	6,445,064	6,848,265	7,280,858	7,744,812	8,265,163	9,056,505

Figure D.4. CF statement for the second approach (2nd part)