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Optimization of Hybrid Power Supply Systems

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- algorithm for optimal design of hybrid power systems
- implementation of algorithm in the real case

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Deshmukha, M.K., Deshmukhb, S.S.: Modeling of hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 12 (2008)

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DECLARATION:

I hereby declare, that this thesis is a result of my own work, done under the supervision of scientific adviser Ing. Tomáš Králík. The work is done with respect of ethical principles of information usage. I declare, that all used sources are listed through the text.

I agree with the use of my Master thesis for the needs of Department.

May 2014 Oxana Demina

ABSTRACT

The diploma thesis focuses on the development of approaches to designing hybrid power systems for the needs of decentralized power supply. It develops an algorithm for determining an optimal structure of power supply system taking into account technical, economic, environmental and social aspects. The case study for the algorithm is the hybrid power supply system in laboratory of university in Tomsk town, which configuration will be compared to the one proposed in the thesis.

KEY WORDS

Renewable energy, hybrid power systems, decentralized power supply, optimal structure, decision making

CONTENTS

ABBREVIATIONS

AC – Alternative Current

CAPM – Capital Asset Pricing Model

DC – Direct Current

EU – European Union

IEA – International Energy Agency

GNG – Greenhouse Gases

LOLH – Loss of Load Hours

LOLP – Loss of Load Probability

LPSP – Loss of Power Supply Probability

MPPT – Maximum Power Point Tracking

NPV – Net Present Value

PWM – Pulse Width Modulation

PV - Photovoltaic

RES – Renewable Energy Sources

SAIFI – System Average Interruption Frequency Index

SPL – System Performance Level

TPU – Tomsk Polytechnic University

UPS - Uninterruptible Power Supply

WACC – Weighted Average Cost Of Capital

INTRODUCTION

The absence of access to central power grid is relevant problem for many developing countries, locations with bad geographical conditions and locations with low density of people. Such solutions of decentralized electrification as local generating units, based either on conventional energy sources or on renewables, are well-known for many years. The need in improving the performance of these systems generates an interest to hybrid power systems, which contain several types of power sources. These systems have good technical and economical characteristics, provides reliable power supply for different autonomous customers.

In this context an optimal design of hybrid power systems is quite reasonable and relevant question nowadays. This question is very broad: the tasks of optimal design take into account technical and economic performance of power systems, their environmental and social impacts. One of the primary tasks of optimal design is the decision on which power sources should be included into the system and what is their scale.

The *goal* of the thesis is the development of general recommendations for the design of hybrid power system and the algorithm for determining the optimal structure of hybrid power system for the needs of decentralized power sector.

To reach mentioned goal the following *tasks* are settled for the thesis:

- To underline the problem of decentralized electricity supplies and to analyze possible solutions;
- To make a literature review of the existing methods for power system's optimal design;
- To analyze aspects influencing the design of hybrid energy systems;
- To develop methodology of evaluation geographical conditions in the chosen area and choosing equipment for hybrid power systems;
- To develop the algorithm of determining optimal structure of hybrid power system for the need of decentralized sector;
- To apply the developed algorithm on the real case and to make relevant conclusions;
- To create economic model of power system and to analyze the influence of economic factors on the algorithm's results.

The thesis is the result of double-degree program between Tomsk Polytechnic University and Czech Technical University so that this work is based on the data of TPU and has its extension in form of diploma thesis on the similar topic for TPU.

The work consists of three main chapters. The first chapter deals with the problem of decentralized power supply and possible solutions; the second chapter is devoted to the development of algorithm for optimal design of decentralized power system and the last chapter describes the implementation of algorithm to the real customer - scientific laboratory of TPU.

1. OBJECT OF RESEARCH

1.1 THE PROBLEM OF ENERGY SUPPLY IN DECENTRALIZED ZONES

The World

The problem of electrification will always exist due to the constant growth of world's population and development of society in general. Nearly one fifth of the world's population – over 1.3 billion people – still has no access to electricity nowadays. Energy poverty mainly affects developing countries of Sub-Saharan Africa and Asia. Across developing countries, the average electrification rate is 76%, increasing to around 92% in urban areas but only around 64% in rural areas. However, there are gaps in the public electricity grid, not only in developing countries and emerging markets but also in industrialized countries, such as remote mountain regions, large forests or expanses of water.

Figure 1 shows the number of people living without the access to electricity by region according the statistics of International Energy Agency. While it is expected that the number of people without access to electricity will decline by 2030, the situation in sub-Saharan Africa is expected to worsen due to high population growth [1].

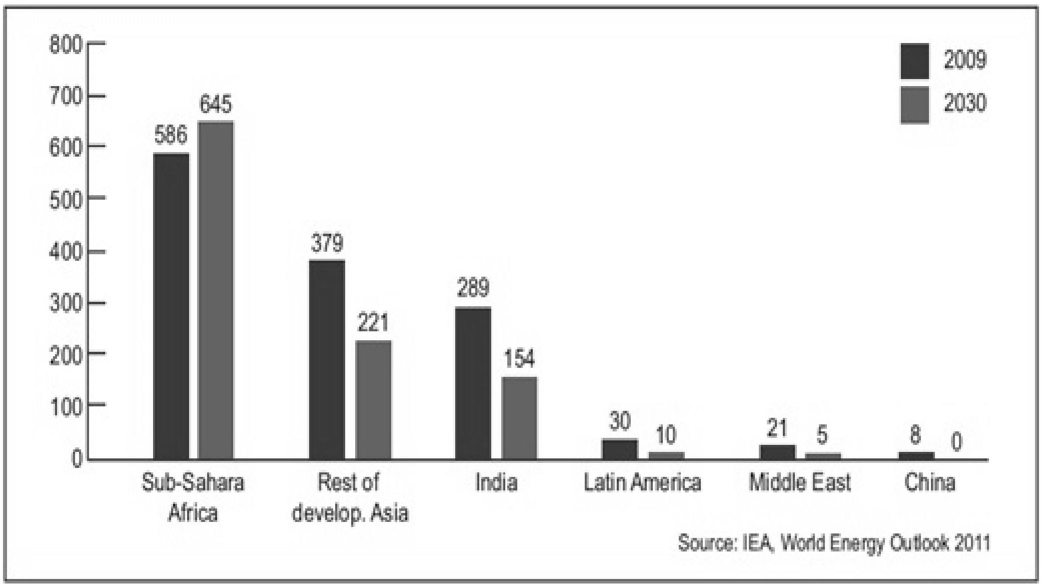

Figure 1 – Number of people without access to electricity by regions in millions (current and expected values) [1]

The problem of connection remote/rural areas to central grid can be caused by technical barriers such as unsuitable geographical conditions or by economic barriers such as economically not-approved installation. In many cases the problems are the ones of funding, management and implementation.

Electrification affects many areas of humanity. From economical point of view, the access to electricity is useful for region's technological progress, industrial development, urbanization, employment and in-migration. It also reduces fuels costs. From social point of view it influences people's everyday's life: living conditions, the quality of education, and the quality of health care.

Nowadays political institutions around the world are focusing on eliminating energy poverty. As an example, the key driver to achieve eight millennium target commitments by the 191 member states of the United Nations by 2015 is an access to modern energy services. A number of initiatives to increase access to electricity or lighting across various regions have been announced over the last year. These initiatives include:

- the Global Lighting and Energy Access Partnership, which is intended to catalyse markets for off-grid energy products and services;
- D.Light Design, which is committed to providing solar lamps to 30 million people in more than 40 countries by 2015;
- the Energising Development program, which aims to provide modern energy access to eleven million people by 2014;
- Lighting India, which plans to bring clean lighting services to two million people by the end of 2015 [2].

If there is no any feasible chance to be connected to central grid or it is not economically approved, alternative solution is needed to meet the energy requirements in these regions. *Decentralized (or off-grid) energy supply* is energy generated at or near the point of use. It could be defined as energy produced by generating plant of under 50MW, connected to a local distribution network system, rather than to a high voltage transmission system.

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

Off-grid systems have proven to be very cost-effective in many countries. Renewable and hybrid energy systems can replace or supplement existing traditional systems cost-effectively for areas not connected to the centralized electricity supply as done in Canada, the USA, Norway, Sweden and many other countries. The popularity of off-grid projects has grown so much that it is now a niche-industry in itself – with customer systems being engineered for specific functions.

Russia

Only one third of Russian territory is covered by central power network. The electrification of the rest of Russian territory – about 20 millions of people – is performed by local power stations with transported fuel or by local fuels (coal, peat, etc.). The figure 2 presents division of Russian territory by the level of electrification [3] and the population density in Russia.

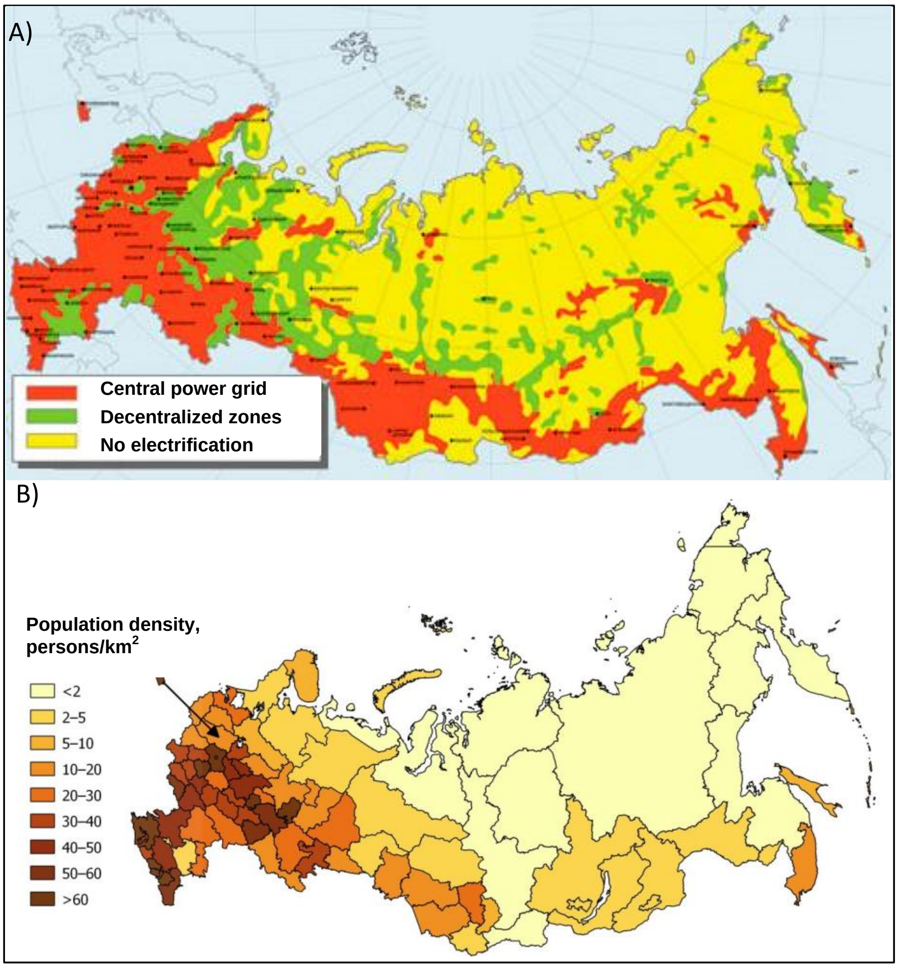

Figure 2 – Relative maps showing type of electrification (A) and population density (B) on the territory of Russian Federation [3]

According to these maps, the population in Russia is quite inhomogeneous: there is the big density on the West and on the South of Russia, and almost no population and no electrification in such regions as Far East and Northern Siberia. Obviously, that it is not economically proved to connect them to the central power grid. However, non-electrified regions of Russia face serious social problems: a high poverty rate and poor living conditions, unemployment, a potential demographic crisis, unfavorable migration patterns, etc. Both rural-to-urban and north-to-south migration patterns are evident in Russia nowadays [4]. The construction of efficient central or off-grid power systems would solve these problems and cause the development of rural not electrified areas.

Most of decentralized power supply in Russia is performed by means of diesel or gasoline power stations. This situation exists in is the North of Russia along an Arctic coast, many regions of Siberia, Yakutia, coast of Okhotsk sea and Kurile Islands.

The special feature of Russia is its huge size, which results in the problem of the fuel transportation. Most stand-alone systems are used in the far northern regions of Russia, in the Far East and in Siberia. Every year 6-8 million tons of liquid fuel (diesel, black oil) and 20-25 million tons of coal are sent to these territories. Remote northern and Far Eastern areas, not connected to oil and gas pipelines, get their fuel by rail or road and sometimes by helicopter. Such supplies are very unreliable and expensive. High transportation costs dramatically increase the total cost of fuel. Such territories as Kamchatka, Republic Tuva and Republic Altai spend more than half of their budgets on fuel.

Another problem is that some districts face frequent disruptions in fuel supplies due to bad weather transport conditions or due to suppliers' preferences for export markets. Also big amount of these diesel and gasoline systems are reported to be no longer operating because of fuel delivery problems or/and high fuel costs.

Altogether, low technical and economic indicators of diesel power systems, high fuel prices and high transportation costs lead to high net costs of electrical energy. Such conditions results in low electricity consumption by population. Aging of diesel/gasoline power systems equipment and the growth of fuel prices aggravate the situation, which could cause following decline of the total production, quality of power supply and massive non-payments.

Taking into account the geographical features of Russia and its low population concentration, the relevant decisions are off-grid projects with the use of renewable energy power supply. By the opinion of experts in Russian Academy of Science, the most prospective for Russia are such trends as nuclear power, hydropower, biomass energy, usage of biofuel and thermal power sources. For local purposes it is seen the big attention to the wind and solar autonomous power stations [3].

One of good examples of successful off-grid project, which solved the local problem of electrification, could be the project in Vologda region in 2000.

"The village of Shalotch in the Vologda region, 450 km north of Moscow, is not connected to a centralized grid. Because of the area's boggy terrain, construction of a transmission line would cost about $380,000. It would cost some $12,000 per year just to maintain it. Until 1993, the inhabitants of the village used kerosene lamps for lighting and kerosene or gas-fuelled appliances for cooking. Migration out of the village was such that in the early 1990s, only three families lived there. But in 1993-4, the Russian Institute for Electrification of Agriculture and the Centre "Elektrodomotechnika" installed three 160 W wind turbines and 14 PV modules with peak capacity of 65 and 130 W. The project was originally to be financed from the state budget, but the inhabitants of Shalotch paid 50% of the installation cost. The installed capacity in not sufficient to cover all of their electricity needs, yet it allows the use of energy-efficient electric lights, TV sets and water pumps. People have returned to the village and by the end of 2000 already 45 families lived there" [4].

1.2. AVAILABLE TECHNOLOGIES

The problem of electrification in decentralized regions makes engineers to design different methods for solving it. These methods vary by reliability, economic, ecological and other aspects. Three different methods of decentralized energy supply will be described in this subchapter.

1)Diesel and petrol stand-alone systems

Generator sets, using petrol or diesel remain the good choice for standby and emergency power systems, worldwide.

These generator sets can vary from small portable units to larger units. The larger units will often incorporate auxiliary control equipment to automatically start the generator on demand. Set sizes range from 8 to 30 kW for homes, small shops and offices and from 8 kW up to 2,000 kW (larger industrial generators), used for large office complexes and factories.

Diesel power systems usually contain a diesel generator itself and various ancillary devices (base, canopy, sound attenuation, control systems, circuit breakers, jacket water heaters and starting system).

Some generator sets produce DC electricity for charging batteries. But more commonly a generator produces AC electricity for running appliances and electrical equipment directly. Today, with the increased production of biofuels, it is possible to utilize traditional equipment with the usage of renewable fuels such as biodiesel and ethanol [5].

Diesel stand-along systems have such advantages as the guaranteed power output, easy installation and removal. Also, it is not tied by location, these systems can be installed everywhere.

The main drawbacks of these systems are their high operational costs, which are constantly increasing with the current growth in diesel's prices. Another drawback is the air pollution and GHG effect, which make this technology contrapositive to the current attempts of sustainable development of the world.

2)Renewable stand-alone systems

Renewable energies facilitate a universal use of regionally available energy sources, both off-grid and as a local supplement to unreliable grids. They are low-emission and low-risk with sustainable availability, they replace expensive imported fuels or save fuel being transported over long distances, they protect the environment and human health and contribute to peace-keeping. Low operational costs of RES and high prices for fossil fuels mean they are already competitive in many regions of the world in comparison to domestic electricity prices or power generation using diesel generators.

Renewable energy systems that have been carefully designed, installed and professionally operated can provide power and heat reliably. The independence of price trends for sources of fossil fuels means the operating and construction costs for renewable energies are easier to calculate.

Renewables provide energy for many applications independently of the public electricity supply. Energy in the form of electricity enables a lot of equipment to be operated in rural regions. Photovoltaics, solar thermal power plants, hydropower, wind energy, biodiesel and biogas can generate electricity locally, be used directly to operate electrical equipment or be stored if required. Thermal technologies for using renewable energies facilitate hot water, heating, cooling and drying. Depending on the technology used, renewable energies can also be used directly for cooking or for mobility purposes.

After the list of advantages it is necessary to mention about main drawback of renewable autonomous systems which is its inconstant power output. For example, a wind turbine installed in an area with a good wind resource can produce energy cost-effectively. However, the available wind resource typically varies from season to season, which creates a significant variation in the wind turbine output. Backup generation devices are usually required in order to meet any shortfall of energy during these times of low wind speeds.

Usually RES, installed in decentralized area, have additional source (traditional or renewable one) or battery.

3)Hybrid systems

Hybrid (or combined) power systems are systems which use two or more power sources for the production of electricity.

There are three basic elements in the system – the power sources, the battery and the power management center.

Energy sources (solar, wind, diesel, micro hydro power plant, biofuel, etc.) provide electricity to the common network of residential area. In this case renewables can be used as a primary, diesel – as a standby source or vice versa.

Every type of RES has its own drawback. Solar panels, for instance, are very expensive and have higher operational costs comparing to traditional methods of electricity production. They also do not operate at cloudy weather and at night. Similarly, wind mills do not operate with low and high wind velocities and biomass technology do not operate with a low temperature. Therefore, if to combine all of these technologies in common hybrid system, these drawbacks can be partially or fully excluded depending on control devices.

Below one can see the classification of hybrid energy systems:

1. By the number of sources

Hybrid system can consist of one or more RES. The most usual system is the one which contains one RES and diesel generator. One more solution is to combine solar panels, wind mill and diesel in one system. The rarest way is to combine two or more different sources with diesel generator.

*2.	By installed power*

Hybrid power systems can be divided into following groups:

- micro power systems (less 1 kW),
- low-power systems (1-100 kW),
- high-power systems (more than 100kW)

*3.	By construction method*

Elements can be connected either on direct or alternative current sides.

a) Connection between elements of power system on DC side

This is the most common and popular way of connection. The scheme in presented in Figure 3.

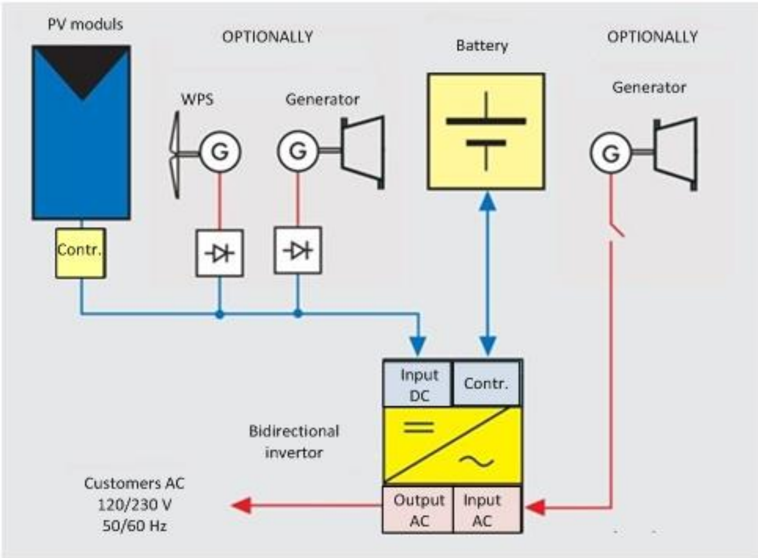

Figure 3 - Connection between elements of power system on DC side [6]

In this configuration PV panels charge batteries through the controller. At the same time batteries can be charged from the grid. Then DC from solar panels and batteries is converted in AC 220 V (or 380 V for 3-phase system) by invertor. The load is fed by this current.

The first drawback of this kind of systems is several stages of converting the energy from PV panels (controller-battery-invertor) on the low-voltage side. Another is that the organization of the system is quite complicated, if there is a need of priority for RES. In order to achieve it is necessary to include the UPS or similar device into the system, which can be switched off from the AC input if the voltage in battery is higher than setting value [6].

b) Connection between elements of power system on AC side

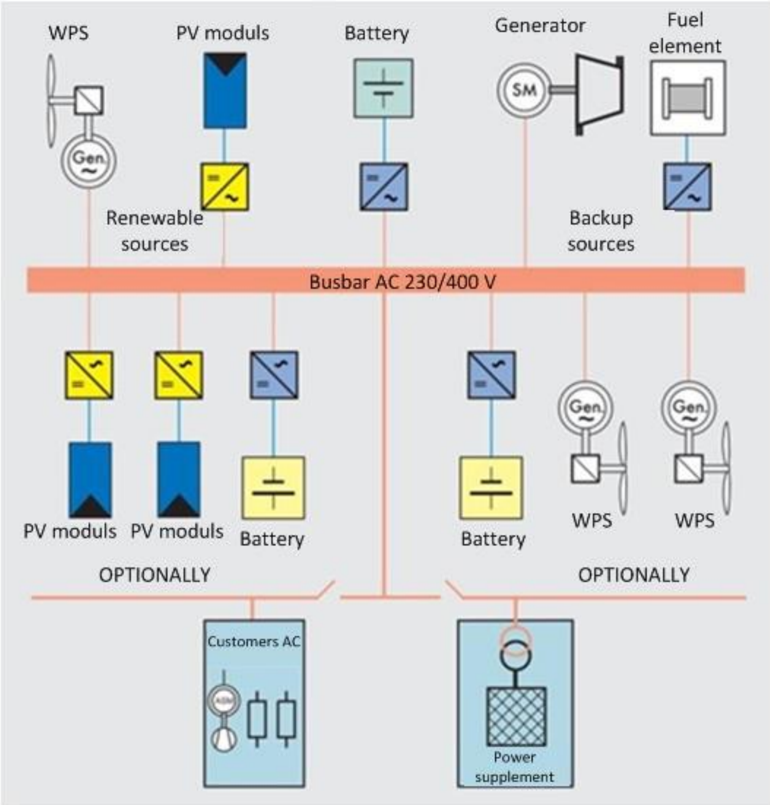

Figure 4 - Connection between elements of power system on DC side [6]

In this configuration all elements are connected to the AC side.

The biggest advantage of this kind of systems is the opportunity to connect different components of system by the grid AC 220 V. In DC 12/24/48 V it is necessary to have short and thick cables which is a big constraint, if the distance between PV panels, wind generator and battery is significant.

The first drawback of this configuration is the smaller efficiency if it is firstly necessary to save energy in batteries. The second is that the price of inventor for the grid is higher than for controller in DC system.

In practice the DC configuration is used in most cases. However, last time after the appearance of reliable and relatively cheap models of network invertors, AC configuration is used more frequently. It provides not only more flexibility, but also higher efficiency of using the energy of different power sources by decreasing losses in the system [6] .

In the end of discussion about hybrid-energy sources it is necessary to underline that these systems are economically justified alternatives for electrification of removed subjects to construction of electrical networks. These systems allow significantly reduce the amount of fuel consumption, maintenance and repair costs, improve the methods of power supply.

Among drawbacks of hybrid systems there are high investment costs, difficulties in design, construction and control.

To sum up the chapter it may be said that every available technology for off-grid power supply has its own pros and cons (Table 1).

Table 1 – Comparison of technologies used in decentralized power supply by different characteristics

Type of technology	*Investment costs*	*Operating costs*	*Power constancy*	*Environmental impact*
Diesel	Low	High	Constant	High
Renewable	High	Almost zero	Inconstant	Very small
Hybrid	High	Low	Constant	Small

However, the hybrid-energy-systems seem to be the most compromise decision of decentralized electrification, in terms of economic efficiency, reliability of supply, modern trends and policies, our further discussion will be dedicated to this kind of power systems.

2. DESIGN OF STAND-ALONE HYBRID ENERGY SYSTEMS

Based on the analysis performed in the chapter 1, hybrid stand-alone systems have comparably good economic and technical features and are well suited for the need of decentralized power supply.

The proper decisions in the questions of development the hybrid power system is quite a challenging task since it should take into account different aspects – technical, economic, environmental and social ones. In next subchapters we will consider different aspects influencing the decision on the choice of a proper hybrid power system structure and how can these aspects be evaluated by the person in charge.

2.1 CURRENT RESEARCHS

Currently there is a big amount of scientific works devoted to the optimal design of hybrid energy systems [7, 8, 9, 10].

Some researchs are focused on the optimization of hybrid energy systems initial design. In this case the main tasks are: combination of resources included onto the system, the choice of location, determination of suitable conditions, reduction of total costs, reliability and solving ecological problems for region. The main problem is faced while designing stand-alone hybrid systems is the uncertainty in amount of electricity, generated by RES. Thereby the choice of equipment is usually based on probabilistic theory or forecasts in solar and wind output, often with averaging and lots of simplifications.

Some researchs are focused on an optimization of modes in hybrid energy system. In this case the main tasks are: agreement of consumption and generation processes, determination of rational load modes, creation of automatic control systems. The uncertainty of RES requires an introduction of back-up sources or batteries into the system, user-friendly and reliable control system.

One of the primary tasks in designing the hybrid energy system is the determination of an optimal ratio between installed capacities of power sources included into the system (or optimum sizing/structure of system). This should be made by taking into account real climate and geographical conditions of region and features of the customer. The structure of power system significantly influences performance of designing power system and contains many primary tasks being considered in the beginning of power construction project, such as production costs, reliability, ecological and social impacts.

This question has been considered in many scientific works where the number of RES, included in system, is varying from one to five [11, 12, 13, 14, 7, 15].

There are several different ways of setting and solving the task of optimal ratio between installed capacities in hybrid energy system. For example, in [15] this task is solved by classical linear programming, in [14] – by tools of convex programing, in [12] – by simulation model of energy system.

Some works are solving the local energy problems, therefore their models contain the features of certain customer, weather and geographical conditions of specific region and chosen equipment [13,14]. Some works are aimed to develop the universal model [12].

Optimization criteria vary as well: total energy conversion efficiency [10], reliability of power supply [13], total costs [12,13,14,15], environmental impact [7], etc. In some of presented works the task was single-criterial [13,14], in some - multi-criterial [7,15,16].

The task of this work is to develop multi-criterial model, which help to make a decision on the installation this or another structure of stand-alone power system. The model will help to evaluate big amount of different solutions, taking into account a lot of influencing aspects. The model is universal so that it can be applied to any small-scale (up to 100 kW) power system.

In following chapters the algorithm for optimal design of hybrid power system will be developed.

2.2 EVALUATION OF FEASIBILITY OF THE PROJECT

The question of design of power system can be evaluated from different points of view. The role of decision makers can be assigned to:

- Private investors
- Government/municipality authorities
- Habitants

The determination of decision maker affects the preference to considered criteria. If we consider the private investor, such aspects as a system's performance, levelized costs, payback period, construction and business risk of the project should be taken into account. For government authorities – different policies such as laws and regulations, environmental issues related to the project, the increase of employment and of welfare in the region. For inhabitants the price on electricity, their tendency to the new "green" technologies, the number of possible interruptions, the simplicity of power supply and energy audit play the most significant role.

The determination of decision maker is usually obvious from the most beginning of project's design. In most cases this person is private investor or government authority and quite rarely – inhabitants due to the lack of competence in the questions of design.

After the determination of decision maker, the feasibility of a project should be evaluated. The feasibility of the project was divided into three main groups: *technical feasibility, funding feasibility* and *legislation*. Below there is a description of each of these components.

In this stage of decision making the person in charge consider all existing power sources used for the need of decentralized power supply – wind, solar, micro hydro, biomass, hydrogen, diesel, etc. – and different combinations of them.

1. Technical feasibility

In order to state that this or another project is feasible from the technical point of view the number of parameters should be considered.

First, it is important to consider the *geographical restrictions* related to the project. Primary data for this consideration is data of technical characteristics of power source, which shows if these characteristics are sufficient for installing generation unit or not. For micro hydro power plant the feasibility of the project is based on minimal speed of water steam in the place of construction and minimal flow rate. For wind power unit it is based on the minimum average annual speed of wind, which is enough to rotate the wind turbine. For solar plants the restriction can be caused by insufficient average daily insolation. For biomass technologies the feasibility of the project is based on the amount of possible produced biomass in the given region and on the distance of transportation. For geothermal energy it is based on the access to this source in region, which can usually be restricted by the geographical conditions and by the content of toxic metals and compounds. Besides, any equipment has its own operating temperature restriction.

As an example of evaluating the condition for feasibility of given generating units is presented below (on the example of diesel, wind, hydro and PV installations):

Table 2 – Evaluating technical feasibility of technologies

Technology	Condition
Wind	$V_{avar} \geq V_{turb\_min}$ $T_{env} \in [Tmin;Tmax]$
Solar	$I \geq I_{min}$ $T_{env} \in [T_{min};T_{max}]$
Hydro	$Q \geq Q_{min}$
Diesel	$T_{env} \in [T_{min};T_{max}]$

The second important issue is a technical competence of designer. The technical competence refers to the ability to construct the power system based on the given technology. The data for the evaluation of the technical competence can be taken by the evaluation of this kind of projects in the local scope. The review of existing projects could help to understand if there is enough skills and experience of engineers to be able to launch planned power system. In case if there is no local cases of designing the system based on the given technology, the ability to adopt some regional/international knowledge to the local case is evaluated.

2. Funding feasibility

Funding feasibility refers to the capability of funding the project by government/private sector or to the capability to receive the bank loan.

The capability of receiving the loan is quite crucial concern for projects based on RES. In some countries power project developers have difficulty in obtaining bank financing because of uncertainty as to whether utilities will continue to honor long-term power purchase agreements to buy the power. And in some cases banks even require the guarantee of stable output of RES power plants.

This capability can be insured by the tentative agreement with the potential investors or with the potential credit's approval by banking institution.

3. Legislation

Governmental restrictions (federal, regional and local) refer to such restrictions as law or enactments which forbid the installation of some particular generating units, make restrictions on the amount of installed capacity of the power source or restrictions related to the usage of the land plot, height of installed unit, its aesthetics, noise, safety and so on.

2.3 EVALUATION OF INFLUENCING FACTORS

The main factors of evaluation the efficiency of power systems and its environmental and social impacts can be combined into four main groups as the most influencing in the design of this kind of systems:

- Technical
- Economical
- Environmental
- Social

Task of optimal design of hybrid system is quite a challenging task because it includes power units with absolutely different features. For achieving the objectives of the work the method of multi-goal decision making will be used.

Four groups of criteria will be considered and evaluated. The quantitative and qualitative indicators will be used for this evaluation in this work. Quantitative indicators of the system will be obtained by statistical data or by calculations, qualitative indicators - through review scores given by decision makers and experts' opinions (score range 0-4).

2.3.1 TECHNICAL CRITERIA

Under the technical criteria it is meant everything related to the system's performance, all technical efficiency indicators and risks related to the system's operation.

From the technical point of view, the project can be evaluated by following criteria.

1. Power efficiency

One of the important aspects of any generating unit is its *power(or energy) efficiency*. Under the power efficiency it is understood the effective use of power sources for providing the desirable level of power consumption. Power efficiency of hybrid power systems is determined by many factors: wind mode, local solar radiation, load demand, ratio between installed capacities and the degree of sophistication of structure in power system and control principles. The energy efficiency of power system can be measured by the amount of max input by every source in the system.

$$\eta = \frac{Preal}{Pnom} \tag{2.1}$$

where

P_{real} - real power output

P_{nom} - nominal power output

Data for evaluation:

Real output (P_{real}) is measured average power output for the exact period, nominal power (P_{nom}) is the information from the manufacturer.

2.System's reliability

One more crucial factor for design of any power system is its *reliability.* This factor plays an important role in design, especially when we deal with such inconstant power sources as RES. Under the reliability of power system it is understood the system's ability to function in sufficient amount under the specific conditions.

The reliability of the system is usually divided into two parts – *modal reliability* (the evaluation is based on the number of possible deficit modes when generation cannot cover demand) and the *scheme reliability* (the evaluation is based on the possible deficits caused by the break-down of parts of a system).

The reliability of power system can be measured by such indices as LPSP (loss of power supply probability), LOLP (loss-of-load probability), LOLH (Loss of Load Hours), SPL (System Performance Level), SAIFI (System Average Interruption Frequency Index), the number or frequency of breakdowns, average recovery time and many others [13].

The example of LOLP model:

$$LOLP = P(S < D) \tag{2.2}$$

This equation shows the probability that demand will exceed supply

Data for evaluation:

The data of expected demand and supply can be used. The direct calculation methodology would derive the LOLP for all possible combinations of forced outages. For example, the formulas below calculate the probability that all generators are out of service (2.3), and all generators are available (2.4).

$$P(S = 0) = FOP1 \cdot FOP2 \cdot \ldots \cdot FOPn = \prod_{i=1}^{n} FOPi \tag{2.3}$$

$$P(S = \sum_{i=1}^{n} Ci) = \prod_{i=1}^{n} (1 - FOPi) \tag{2.4}$$

The calculation of these values is made by the exploring energy balances and the possible design of electrical scheme.

3. Construction risk

Construction risk refers to the risk that the technology will not perform properly under the given condition due to the wrong information from manufacture, risk of engineers' design errors and to the risk that environmental conditions will unpredictably change and cause the damage or lower the expected performance of equipment.

This criterion can be evaluated by the probability of damage/deterioration of performance or be set as qualitative criterion:

$$P = \{1,2,3\} \quad (2.5)$$

where

1- low probability

2- medium probability

3- high probability

<u>Data for evaluation:</u>

The data can be taken from experts or consulting companies and previous projects' statistics.

4. Probability of fuel undersupply

For some power systems, another important issue in the question of reliability is the on-time delivery of fuel. *The probability of fuel undersupply (or security of power supply)* can be set as one of criteria.

An energy source is defined as secure on this site if electricity generators can be sure of obtaining enough of the relevant fuel to maintain an adequate electricity supply. Countries that rely on fuel that must be constantly imported to power their electricity supply expose themselves to potential energy security issues, including fluctuating international market prices and disruptions to fuel supplies caused by geopolitical disturbances.

<u>Data for evaluation:</u>

This criteria can be evaluated quantitatively by the statistical calculation:

$$\mathrm{Pfuel} = \mathrm{P}(\mathrm{S} < \mathrm{D}) \quad (2.6)$$

Or qualitatively by means of consultation companies or experts:

$$P=\{1,2,3\} \quad (2.7)$$

1- low probability

2- medium probability

3- high probability

2.3.2 ECONOMICAL CRITERIA

Under the economic efficiency of power system it is understood effective ratio between economical effect (result) and costs influenced this result. The less costs and the higher value of result in production are, the higher economic efficiency is.

There are many factors which can be considered as indicators of economic efficiency. At times minimal investment or production costs has the biggest importance for designer and at other times - maximum revenues obtained from the electricity sale, low payback period or high payability and so on.

However, the most used economic indicators for the power project evaluation are levelized cost of energy or electricity price.

1. Levelized cost of energy/Electricity price

Levelized cost of energy(LCOE) is one of the utility industry's primary metrics for the cost of electricity produced by a generator. It is calculated by accounting for all of a system's expected lifetime costs (including construction, financing, fuel, maintenance, taxes, insurance and incentives), which are then divided by the system's lifetime expected power output (kWh). All cost and benefit estimates are adjusted for inflation and discounted to account for the time-value of money.

$$\mathrm{LCOE} = \frac{Costs}{W} \tag{2.8}$$

Data for evaluation:

Data is the basic economical parameters of equipment, escalation rates for the given region, average wages, fuel and rent prices, bank loans and so on.

Calculation of *minimum electricity price* takes into account also revenues obtained during the system's operation. The concept of electricity price will be used for the calculations in this work.

2.Business risk

Business risk refers to the risk of bankracy due to the taxes growth, subsidies cancel, equipment prices growth, guaranties not payed.

It can be measured by qualitative criterion:

$$P= \{1;2;3\} \tag{2.9}$$

where 1-low risk

2-medium risk

3-high risk

Data for evaluation:

Data is taken from the experts in power industry or consulting companies.

3. Complexity of administrative issues

This criterion refers to the administrative issues related to the implementation the investment projects.

Qualitative criterion can be used for this criterion:

$$P= \{1;2;3\} \tag{2.10}$$

where 1-low complexity

2-medium complexity

3-high complexity

Data for evaluation:

The data is taken from federal, regional and local rules and regulations. The example of federal case is the regulations from the Ministry of Energy.

4.Time to access the service

It refers to the time required for the completing sufficient repair in the case of breakdowns.

Quantitative method is to calculate the amount of hours required to be able to complete required repairs.

The qualitative method:

$$P= \{1;2;3;4\} \tag{2.11}$$

where 0-no time required

1-less than one hour

2-several hours

3-one day

3-several days

<u>Data for evaluation:</u>

The data is taken from manufacturer guarantee information, from the experience of local repair cases.

2.3.3 ENVIRONMENTAL CRITERIA

Power generation has many environmental impacts such as *greenhouse gases* in the atmosphere, *climate change*, *pollution*, *resource depletions*, *local eco systems damage* and others. All these impacts also significantly influence the decision making process, especially in these latter days. All environmental impacts can be evaluated and compared for different technologies beforehand.

1. GNG emissions

Greenhouse gases are gases which trap heat into the atmosphere. These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is reflected back towards space as infrared radiation (heat). Greenhouse gases absorb this infrared radiation and trap the heat in the atmosphere. Over time, the amount of energy sent from the sun to the Earth's surface should be about the same as the amount of energy radiated back into space, leaving the temperature of the Earth's surface roughly constant. Among these gases:

- *Carbon dioxide (CO_2)*: enters the atmosphere through burning fossil fuels (coal, natural gas and oil), solid waste, trees and wood products, and also as a result of certain chemical reactions (e.g., manufacture of cement).

- *Methane (CH_4):* is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills.
- *Nitrous oxide (N_2O):* is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.
- *Fluorinated gases*: Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes [17].

Only CO_2 is present during the burning of fossil fuels. PV and wind technologies do not have any GHG emissions during the operation.

The amount of CO_2 emissions is calculated by the multiplying the annual produced electricity(W,kWh) by the average annual emissions for the certain power system(q, kg/MWh).

$$Q(CO2) = qCO2 * W \tag{2.12}$$

<u>Data for evaluation:</u>

The evaluation is based on the standart values from the literature: 545 kg/kWh [18]. In order to evaluate the amount of GHG released during the electricity production the dependence the amount of GHG on the generator's load should be taken into account.

2. Other emissions

During the power system operation not only GHG are emitted, there are also some unnatural pollutants:

- *Sulfur dioxides:* Peak levels of SO2 in the air can cause temporary breathing difficulty for people with asthma who are active outdoors and children, the elderly, and people with heart or lung disease. Longer-term exposures to high levels of SO2 gas and particles cause respiratory illness and aggravate existing heart disease. SO2 contributes to the formation of acid rain, ground level ozone (smog), and particulate matter pollution.
- *Particulate Matter (PM) Long-term exposures*, such as those experienced by people living for many years in areas with high particle levels, have been associated with problems such as reduced lung function and the development of chronic bronchitis and even premature death. Small particles pose the greatest problems because they can travel deep in the lungs and may even get into the bloodstream. Exposure to such particles can affect both the lungs and the heart.
- *NOx*

The amount of emission can also be calculated by the multiplying the annual produced electricity(W,kWh) by the average annual emissions for the certain power system(q, kg/MWh).

$$Q(NOx) = q(NOx) * W \tag{2.13}$$

$$Q(SO2) = q(SO2) * W \quad (2.14)$$

$$Q(PM) = q(PM) * W \quad (2.15)$$

<u>Data for evaluation:</u>

The evaluation is based on the standart values from the literature: NOx:10,5 kg/MWh, SO2: 10,2 kg/MWh PM:0,35kg/MWh [18].

3. Influence on the local ecosystems

Influence on the local ecosystems refers to all other environmental influences besides GHG emissions and air pollution. In our work we considered the influence during the operation and construction of the system.

For example, for wind power this influence can be the loss of habitat for some species of birds and bats, noise, vibration, landscope change; for PV panels – the occupation of agriculture earth; for diesel – noise, smell and vibration.

The evaluation of criterion can be made by following qualitative method:

$$P = \{0;1;2;3\} \quad (2.16)$$

where

0 means no influence;

1-low influence;

2-medium influence;

3-high influence

<u>Data for evaluation:</u>

The data is usually public information.

4. Resources depletion

Resources depletion refers to the amount of resources used during the operation or during the life-cycle of a power generation. We will consider only the operation time. Among these resources can be biomass, gas, oil, coal, water.

The evaluation of criterion can be made by following qualitative method:

$$P = \{0;1;2;3\} \quad (2.17)$$

Where

0- not depleting;

1- low depletion

2- high depletion

<u>Data for evaluation:</u>

The data is usually public information.

2.3.4 SOCIAL CRITERIA

Social criteria refer to the influence on society of people which live in the place of power plant's installation. There is the big range of social aspects influencing the decision of power system design.

1. The increase on welfare/ The increase of employment rate

The influence on the improvement of inhabitants' life can be evaluated by increase in the general welfare of the region of by the improvement of employment situation.

Influence on employment in the region can be measured by the number of the new working places (*N).*

The social welfare can be evaluated by the reduction of money outflow, reduction of dependence on fuel prices, on local policies, future possible expenditures. The evaluation of welfare can be made by following qualitative method:

$$P= \{0;1;2;3\} \tag{2.18}$$

where

0 means no influence;

1 - low influence;

2- significant influence.

Data for evaluation:

Employment: typical amount of employees for the maintenance of the power system. For small decentralized projects up to 100 kW it is usually about 2 people.

Welfare: measured by the money saved on fuel, in case if some other inefficient power unit was installed in the region.

2. Consistence with the local policies

Nowadays governments apply different instruments for the need of RES development. Such measures as green certificates, emission allowances, quota system, carbon taxes and many others are used worldwide. These instruments have a large influence on the decision of power system design.

Technology's consistence with all emission allowances, construction and design standards are also taken into account.

The evaluation of criterion can be made by following qualitative method:

$$P= \{0;1;2\} \tag{2.19}$$

0-not consistent

1-partly consistent

2-consistent

Data for evaluation:

The date can be obtained from the local policies for a given region(for the projects based on RES) and the regional/national laws.

3. Acceptance of the technology by people

This criterion refers to the *society response*. It is always necessary to remember that people tend to be conservative and in rare cases would be willing to pay some additional money for green energy. However, the number of ecological promotions and consciousness about the sources depletion grows from year to year so that acceptance of such kind of projects strongly depends on the society.

Acceptance of technology can be measured by the percent of habitants accepting given technology.

Data for evaluation:

The data can be obtained by the survey of people, analysis of habitants acceptance of the similar projects.

As we can see there is quite a big set of criteria to be considered. These criteria can be combined in so-called "tree of criteria" (Fig.5).

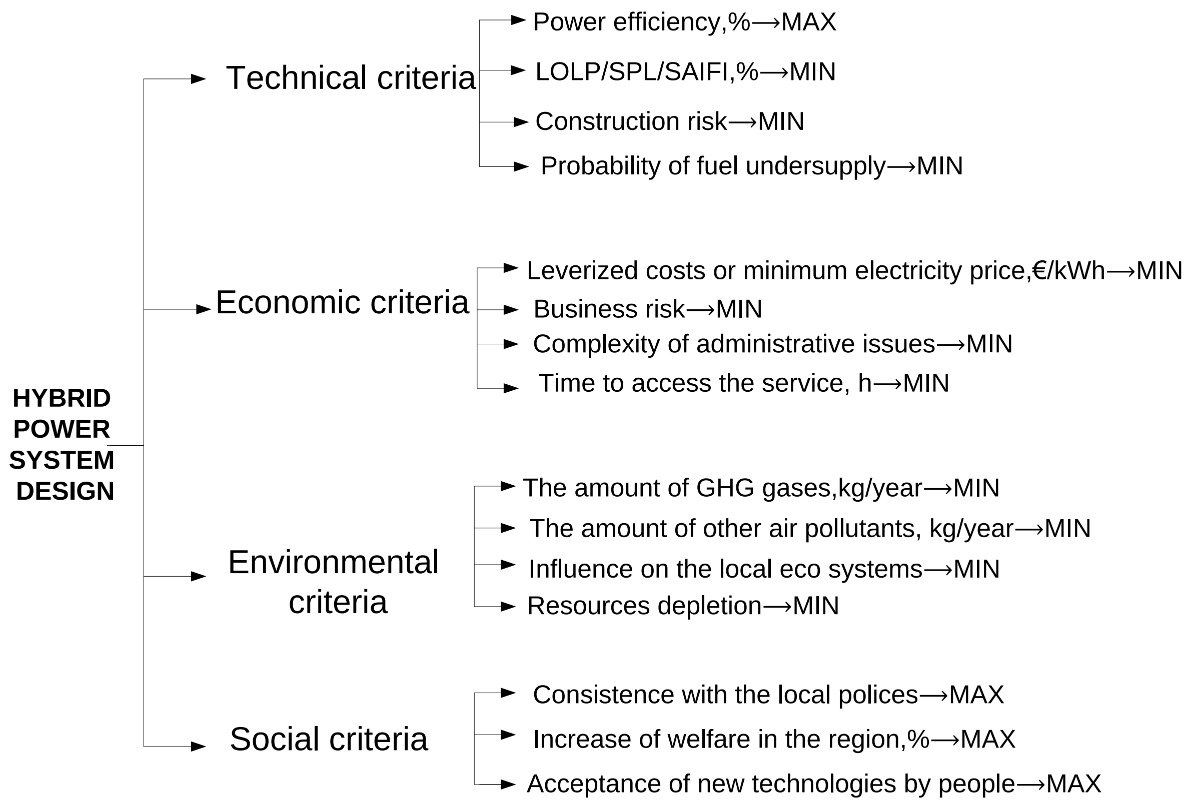

Figure 5 – The tree of criteria

Introduction of these parameters into the decision making model will be presented in the following subchapter. For the development of the system's model some of factors will be taken, some – neglected due to the mutually exclusiveness or irrelevance.

2.3.5 ANALISYS OF CRETERIA AND OBJECTIVE FUNCTION

After the broad discussion we determined 15 different criteria for the system to be taken into account. For different technologies different values of each criterion can be set (example in the Table 3).

As it was mentioned, the task will be decided by the methods of multi-tasking decision making. Among many other existing methods the method of global criterion has been chosen as one with the most suitable structure for the given task [19]. The optimal task in this case is decided in MS Excel software.

Maximum and minimum values for each criterion have been calculated and used for converting the absolute values to the relative ones. For the minimizing criteria it is made by dividing the value of criterion by some optimal value (in most cases this value is the minimum possible value of this criterion among all other alternatives), for the maximization criteria – conversely: the dividing the optimal value (maximum) by the value of considered criterion. The weights assigned to each criterion (from 0 to 100%) are set by the decision maker depending on the importance of the criterion.

The objective function in the method of global criterion is:

$$F = \sum_{N=1}^{15}\left(\frac{C_N}{C_{N\,MAX}}W_N + \frac{C_{N\,MIN}}{C_N}W_N\right) \longrightarrow MIN \qquad (2.11)$$

Where

$C_N -$ the value of criterion C_N

W_N, % - the weight for the criterion C_N

$C_{N\,max}$- maximum value for the criterion C_N (for minimizing criteria)

$C_{N\,min}$- minimum value for the criterion C_N (for maximizing criteria).

The structure of decision making process is presented in the Fig.6.

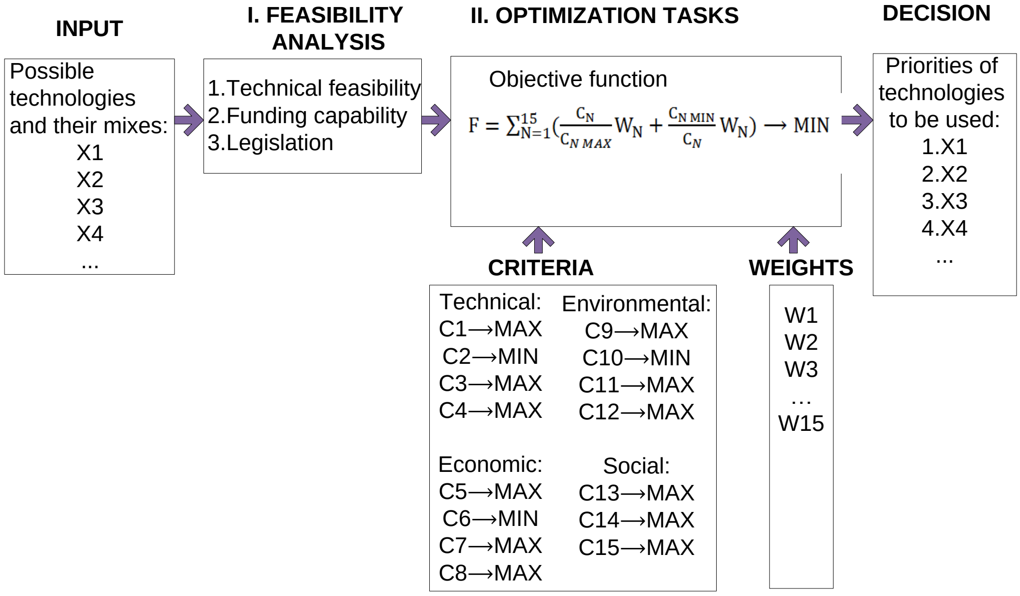

Figure 6 – Decision making task

The example of the weights assignment for random decision maker is presented in the Table 3.

Table 3 – The example of weighs assignment

№	Criterion	Goal	Weig ht,%	№	Criterion	Goal	Weight ,%
C1	Power efficiency, %	MAX	7	C9	Amount of GHG, kg/year	MIN	12
C2	Loss of load probability, %	MIN	10	C10	Amount of other emissions, kg/year	MIN	5
C3	Construction risk, %	MIN	5	C11	Influence on the local ecosystems	MIN	2
C4	Probability of fuel undersupply,%	MIN	5	C12	Resources depletion	MIN	3
C5	Levelized costs of electricity production, €/kWh	MIN	17	C13	Consistence with the local polices	MAX	4
C6	Business risk, %	MIN	5	C14	The number of the new working places/ Increase of welfare in the region	MAX	3
C7	Complexity of administrative issues	MIN	11	C15	Acceptance the technology by people	MAX	1
C8	Time to access the service, h	MIN	5				

3. CASE STUDY

3.1 GENERAL INFORMATION

The case study in this diploma work aims to implement developed optimization algorithm to the real customer. For this purpose the existing operating hybrid power system has been taken in order to ensure the proposed choice of equipment and system's control. Moreover, this allows to analyze current level of system's performance and to compare it with the performance, achieved by the implementation of the algorithm presented in the Chapter 2.

The customer is the scientific-research laboratory № 225 which is situated in the building № 8 of Tomsk Polytechnic University, Usova street 7, Tomsk city, Russia.

Unlike the off-grids projects, where the main aim of penetration the hybrid power system is the power supply of removed customers, the aim of creation this system is solely exploratory. The hybrid system allows to study characteristics of equipment, operation modes, make forecasts of electricity production and to collect statistics. Moreover, with the modernization of the system it is planned to supply the whole building №8 by means of installed capacities.

Currently the system operates in two modes: entirely autonomous (by wind generator and PV panels) and partly autonomous (partly supplied by means of central grid or diesel generator). Though the object of research is not a decentralized customer, this object can be a good case study for the designing this kind of hybrid power systems.

This particular customer has been taken as the case study in order to justify the choice of generating units, to propose alternative configuration of hybrid power system if it is necessary and to compare electrical characteristics of real and modulated power system for the extension of this work.

3.2 THE DESCRIPTION OF EXISTING HYBRID POWER SYSTEM

The structure of the system is presented on the Fig. 7, figures for the scheme were taken from [20, 21, 22, 23]:

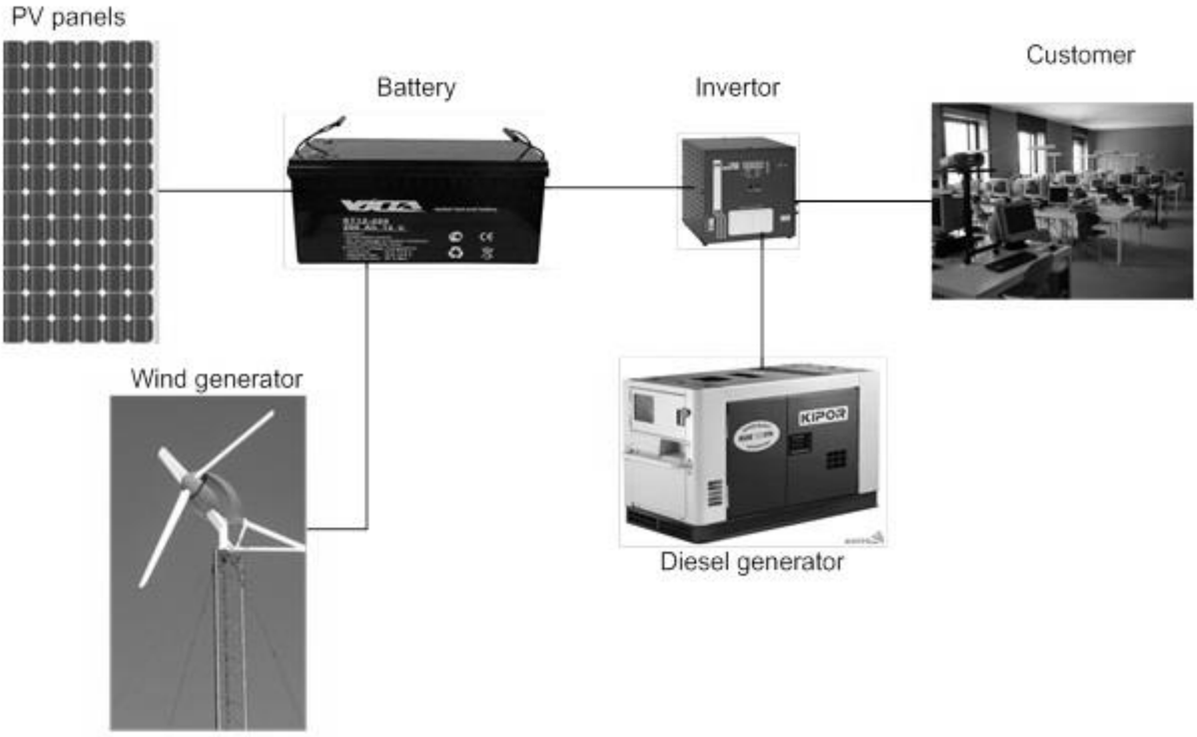

Figure 7 – The structural scheme of power system

The principal electrical scheme of the hybrid system with the presence of the number of phases, protection and measurement devices can be observed from the Figure 8.

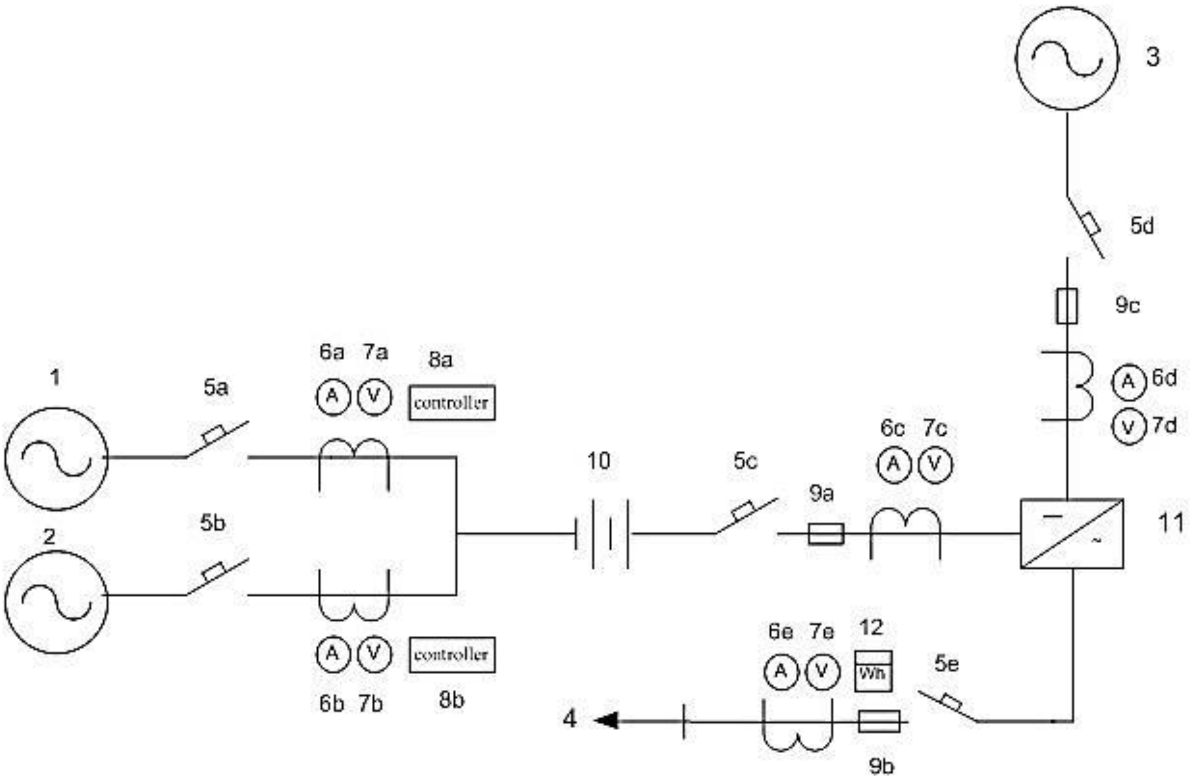

Figure 8 – The principal scheme of power system

1-Wind generator

2-PV panels

3-Diesel generator

4-Load 220V

5a, 5b, 5c, 5d, 5e - Circuit breakers

6a, 6b, 6c – Ampermeters

7a, 7b, 7c – Voltmeters

8a, 8b – Controllers

9a,9b – Fuses

10 – Battery

11 - Invertor

12 – Watthourmeter

In the following table one can see the list of equipment installed into the system and their location on the principal scheme.

Table 4 – Equipment data

Equipment	*Mark and basic parameters*	*The location on the principal scheme*
Wind generator	“Sapsan”(Russia), 1kW	1
PV panels	“Sunways”(Russia), FSM 180 (24), 12 units (6 in line and 2 in parallel)	2
Diesel generator	“Kipor”(China), KDE16STA3, 12 kW, 1 unit	3
Battery	“Volta”(China), ST12-200(12), 200 Ah, 1 unit	10
Controller	“MorningStar”, USA, MorningstarTriStar MPPT 60A	8
Invertor	“MicroArt” (Russia), MAP "Energia" SIN 9кВт, 12 B	11
Measurement devices	-Watthourmeter: “Incotex”(Russia), Merkuriy 230 ART-03 C (R)N -Voltmeters: no data -Amperometers: no data	12 7 6
Protection devices	Circuit breakers: no data Fuses: no data	5 9

The main technical characteristics of equipment installed in the laboratory are represented in the Appendix 1.

3.3 THE OPTIMAL DECISION TASK

3.3.1 CUSTOMER

The main electric loads in the laboratory are lighting units, computers and training simulators, maximum power of which is 2 kW (Table 5).

All loads operate on the alternative current, which requires the installation of invertor in the system.

The working hours of laboratory are from 8:00 to 18:00, all other time only emergency equipment is under the operation. The daily load diagram for a typical winter day of a laboratory is presented on the Fig.9. During the spring, autumn and summer seasons the load changes depending on the shortage of a day (Fig.10).

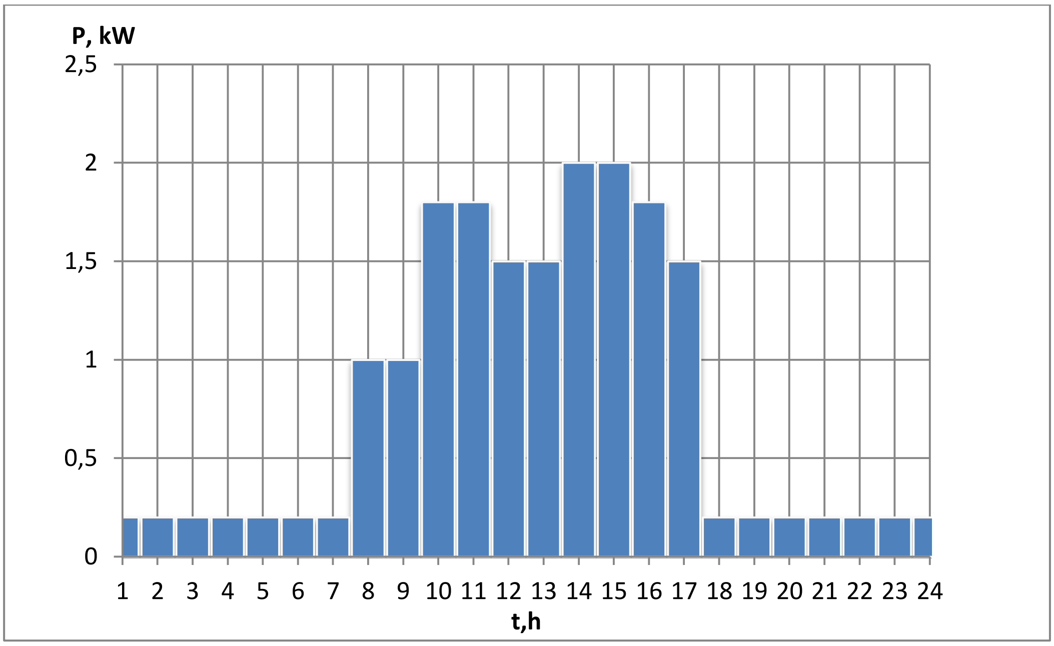

Figure 9 – Winter load diagram of laboratory

Daily load diagrams for all four seasons:

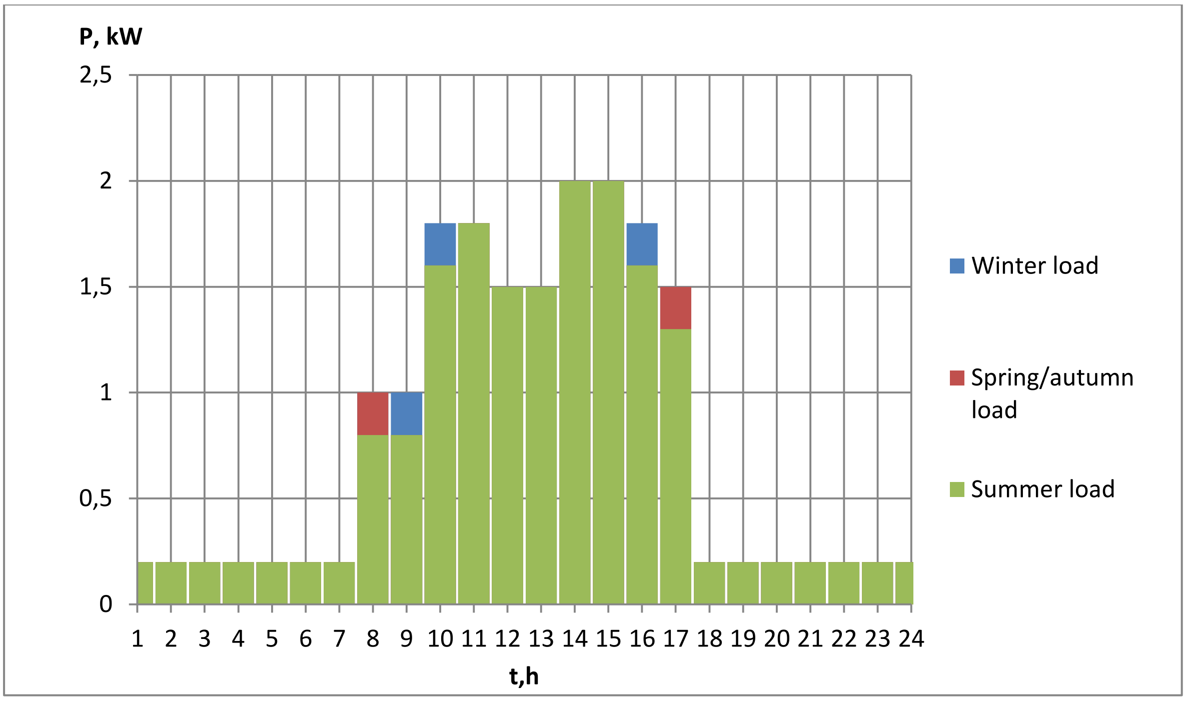

Figure 10 – Load diagram of laboratory for all seasons

Based on these diagrams we will calculate monthly amount of electricity by multiplying daily figures with the number of working days in Russia in this month:

$$W_{CONS} = N_{WORK} \cdot \sum_{i=1}^{24} \mathrm{P}_{CONSi} \cdot t_i \tag{3.1}$$

Where N_{WORK} – number of working days in month

P_{CONSi}- power for i interval

t_i – duration of i interval

Calculation of the total electricity demanded (Table 5):

$$W_{CONS\_TOTAL} = \sum_{i=1}^{12} W_{CONS\_MONTH} \quad (3.2)$$

Table 5 – Total electricity demanded

	Winter	Autumn/ Spring	Summer
T,h	P,kW	P,kW	P,kW
0	0,2	0,2	0,2
1	0,2	0,2	0,2
2	0,2	0,2	0,2
3	0,2	0,2	0,2
4	0,2	0,2	0,2
5	0,2	0,2	0,2
6	0,2	0,2	0,2
7	1,0	1,0	0,8
8	1,0	0,8	0,8
9	1,8	1,6	1,6
10	1,8	1,8	1,8
11	1,5	1,5	1,5
12	1,5	1,5	1,5
13	2,0	2,0	2,0
14	2,0	2,0	2,0
15	1,8	1,6	1,6
16	1,5	1,5	1,3
17	0,2	0,2	0,2
18	0,2	0,2	0,2
19	0,2	0,2	0,2
20	0,2	0,2	0,2
21	0,2	0,2	0,2
22	0,2	0,2	0,2
23	0,2	0,2	0,2
Total daily electricity, kWh	18,7	18,1	17,7
Days in season	91	183	92
Total annual electricity, kWh			**6642,4**

Total electricity demanded per year is 6642,4 kWh

3.3.2 EVALUATION OF PROJECT FEASIBILITY

Based on the algorithm, developed in Chapter 2, we will examine different generating options for the need of our customer for the technical feasibility, funding feasibility and legislation.

For this purpose we evaluated 6 the most popular power sources, which are used for the need of off-grid small-scale customers nowadays:

- Wind
- Solar
- Micro hydro

- Biomass
- Hydrogen
- Diesel

We will evaluate each of these sources for our study case.

Wind power

Wind potential is usually evaluated by comparing the average wind speed in the region with the minimal (starting) speed for wind generator set by manufacturer. In the small 1-5 kW range this minimum speed is usually 2,5 – 3 m/s. So, one can see that the average wind speed in Tomsk town exceeds the starting speed:

$$Vwind > Vmin:\ 4{,}04\ m/s > 3\ m/s \quad (3.4)$$

However, the low wind potential and general high fluctuation of wind source do not allow using this technology as an independent source, so it is recommended to add battery to the system or to use wind generator as a part of any hybrid power system.

There are no legislation restrictions which can forbid the installation of wind generator on the roof of building and university funds are willing to fund this technology.

The decision: can be used as stand-alone system with battery or as a part of any hybrid power system

Micro hydro

We will not consider the micro hydropower system due to the technical restriction: long distance between the closest available river and customer, which requires construction of power lines and make the project too complex and does not allow using the system for research purposes “on site”.

The decision: cannot be used due to the absence of close available water source

Geothermal

The case of geothermal energy is similar to the micro hydropower system. The long distance between the customer and the closest available geothermal water is too high for using this technology for our customer

The decision: cannot be used due to the absence of close available geothermal source

Hydrogen

The hydrogen power source has no big geographical, weather or legislation limitation. The only restriction can be the absent of hydrogen in the market. This technology is already used in TPU: the small-scale hydrogen energy units are installed and used for research in university’s buildings. So, university is able to fund this technology for research purposes, however it is not ready to fund it in purpose of laboratory’s power supply due to the high prices on hydrogen and constant dependence on the delivery of this source.

The decision: cannot be used due to the absence of funding

Biomass

The case of biomass is similar to the micro hydropower system. The installation of this system requires special infrastructure which will process the biofuel. Moreover, the constant delivery of a biofuel is required. The university is not ready to fund this kind of technologies.

The decision: cannot be used due to the absence of funding

Solar energy

Solar potential is usually evaluated by the minimum value of solar radiation in region which should be higher than 0,2 kWh/m^2 [11]. The average solar radiation in Tomsk town exceeds this value for all four seasons (see chapter 3.3).

However, general high fluctuation of solar radiation during the day does not allow using this technology as an independent source, so it is recommended to add battery to the system or to use PV panels as a part of any hybrid power system.

There is no legislation restrictions which can forbid the installation of PV panels on the roof of building and university funds are willing to fund this technology.

The decision: PV panel can be used as stand-alone system with battery or as a part of hybrid power system

Diesel

Diesel generators are commonly used power source for the university's needs. There is no any technical, funding or legislation restrictions related to the installation of diesel generator.

Decision: can be used as an independent power source or as a part of hybrid power system

The results for feasibility evaluation of possible technologies are presented in Table 6

Table 6 – Feasibility evaluation

Parameters	*Technical feasibility*		*Funding capability*	*Legislation*	*Decision*
	Geographical restrictions	Technical competence			
Wind	$V_{avar}>V_{min}$ minimum wind speed restriction is satisfied	Several local project's experience	University funds	No restriction to the small-scale systems	Can be used as stand-alone system with battery or as a part of hybrid power system
Micro hydro	Absence of available water source	Several local project's experience	No	Hard to say	Cannot be used
Geothermal	Absence of available geothermal water source	Several local project's experience	No	Hard to say	Cannot be used

Hydrogen	The restriction on delivery of hydrogen is satisfied	Several local project's experience	No	No restriction to the small-scale systems	Cannot be used
Biomass	No restrictions	Several local project's experience	No	Hard to say	Cannot be used
Solar	$I_{avar}>I_{min}$ minimum solar radiation restriction is satisfied	Several local project's experience	University funds	No restriction to the small-scale systems	Can be used as stand-alone system with battery or as a part of hybrid power system
Diesel	No restrictions	Big local experience in this technology	University funds	No restriction to the small-scale systems	Can be used as an independent power source or as a part of hybrid power system

As one can see, the technologies which are possible to use for the given customer are: wind, solar and diesel energy sources. Further we will consider these power sources as independent technologies, technologies with the battery backup or as combination of these sources into the common hybrid power system. In next subchapter will evaluate more preciously the data required for the system's design.

3.3.3 GEOGRAPHICAL INITIAL DATA

Basic geographical information about the considered region – Tomsk town – is presented in the Table 7 [24].

Table 7 – Geographical information about the region [24]

Latitude: +56.5 (56°30'00"N) Longitude: +84.97 (84°58'12"E) Time zone: UTC+6 hours Local time: 15:44:19 Country: Russia Continent: Europe Sub-region: Eastern Europe Distance: ~4500 km (from your IP) Altitude: ~120 m Tomsk, nearby locations

Meteorological data on the average values of wind velocities for Tomsk town are presented in the Table 8[25]:

Table 8 – Average wind velocities in Tomsk [25]

January	February	March	April	May	June	July	August	September	October	November	December
4,42	4,14	3,98	4,13	4,15	3,72	3,52	3,68	3,89	4,18	4,33	4,37

Meteorological data on the average solar insolation for Tomsk town are presented in the Table 9 [24].

Table 9 – Average solar insolation in Tomsk[4]

Variable	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Insolation, kWh/m²/day	0.61	1.42	2.73	4.16	5.35	5.74	5.69	4.46	2.78	1.60	0.81	0.42
Clearness, 0 - 1	0.41	0.48	0.51	0.52	0.52	0.51	0.52	0.50	0.44	0.42	0.42	0.37
Temperature, °C	-14.60	-12.82	-7.73	-0.55	10.60	16.50	19.87	16.71	9.28	1.91	-8.21	-13.51

The hourly wind speed values have been derived based on the average monthly wind speed by the usage of Weibull distribution function. This simulation has been done by using the Homer software [26]. The parameters for Weibull distribution were inserted into program in following way, taking into account information about the region:

- average monthly wind speed, 12 values;
- m=120 m (altitude, the elevation above mean sea level);
- z_{anem}=25 m(anemometer height, the height above ground at which the wind speed data are measured);
- k=2 (Weibull factor, reflects the breadth of a distribution of wind speeds);
- r_1 =0,85 (autocorrelation factor, reflects how strongly the wind speed in one time step depends on the wind speeds in previous time steps);
- d=0,25 (diurnal pattern strength, reflects how strongly the wind speed tends to depend on the time of day);
- ϕ=15 (hour of peak windspeed, the hour of the day that tends to be the windiest, on average).

For simplification of calculation we assumed that hourly wind speed distribution function is the same for each day of month. The wind speed profile is presented in Appendix 2. For the calculation of balances we took hourly wind speed for three days in year from different seasons: 1st December,1st of April and 1st of June (Fig. 11-13).

For the evaluation of the solar insolation we need to consider the global horizontal radiation - the total amount of solar radiation striking the horizontal surface on the earth. But the power output of the PV array depends on the amount of radiation striking the surface of the PV array, which in general is not horizontal. We can describe the orientation of the PV array using two parameters, a slope and an azimuth. The slope is the angle formed between the surface of the panel and the horizontal, so a slope of zero indicates a horizontal orientation, whereas a 90°

slope indicates a vertical orientation. The azimuth is the direction towards which the surface faces, so an azimuth of -45° corresponds to a southeast-facing orientation, and an azimuth of 90° corresponds to a west-facing orientation. The other factors relevant to the geometry of the situation are the latitude, the time of year, and the time of day. The time of year affects the solar declination, which is the latitude at which the sun's rays are perpendicular to the earth's surface at solar noon[26].

The hourly solar radiation values have been derived based on the average monthly values of solar radiation and the latitude. In order to get the synthetic solar data the Graham algorithm has been used in the Homer software. This algorithm is based on the realistic day-to-day and hour-to-hour patterns. For example, if one hour is cloudy, there is a relatively high probability that the next hour will also be cloudy. Similarly, one cloudy day is likely to be followed by another cloudy day [26]. The parameters were inserted into program in following way, taking into account information about the region:

- Average monthly values of solar radiation, 12 values;
- Latitude: +56.5 (56°30'00"N);

For simplification of calculation we assumed that hourly solar radiation distribution function is the same for each day of month. The solar radiation profile is presented in Appendix 3. For the calculation of balances we took hourly solar radiation distribution for three days in year from different seasons: 1st December, 1st of April and 1st of June (Fig. 11-13).

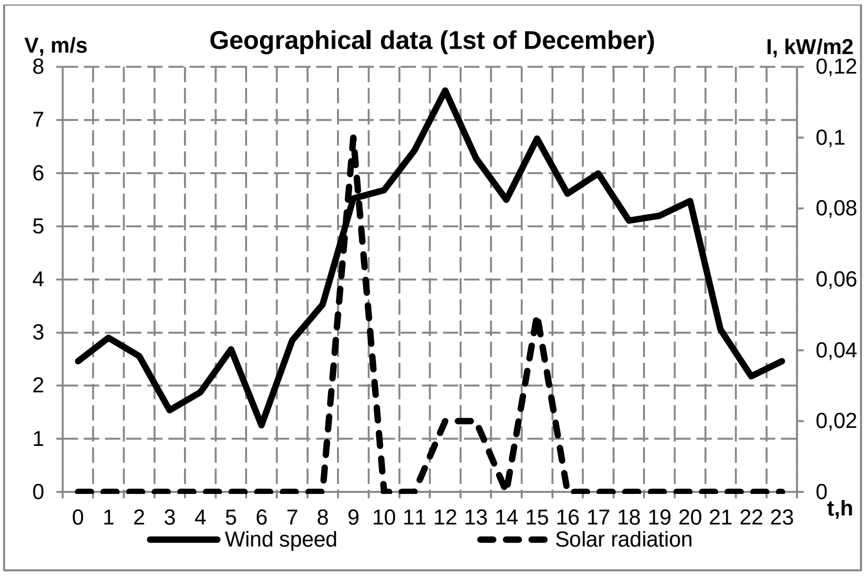

Figure 11 – Wind and solar data for 1st of December

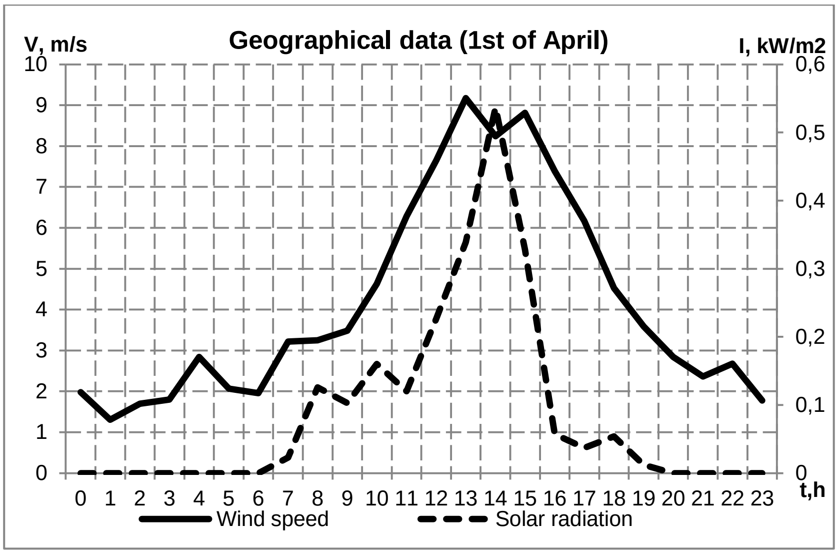

Figure 12 – Wind and solar data for 1st of April

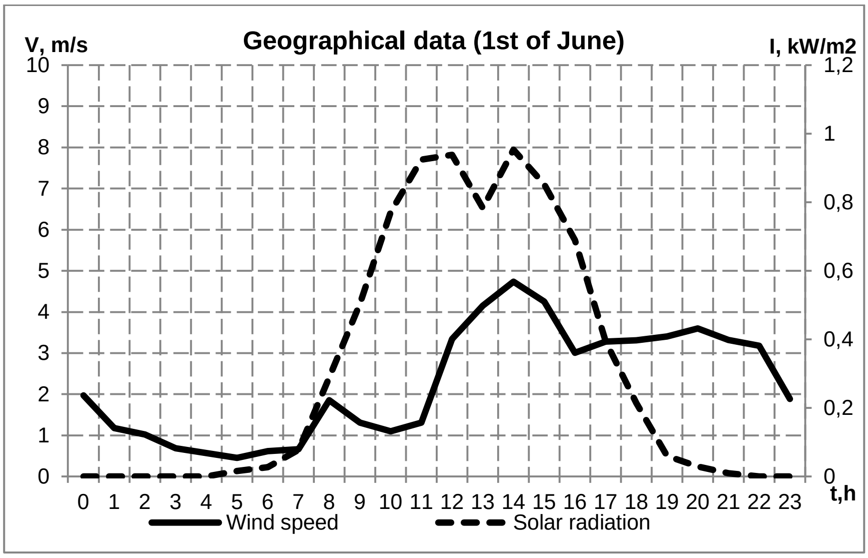

Figure 13 – Wind and solar data for 1st of June

One can notice the general tendency in these three graphs. The highest wind speed is seen in the winter. However, the solar radiation equals almost to zero. Vice versa: in summer the wind speed is the smallest, however the solar radiation is quite stable during the daylight.

3.3.4 THE MAIN COMPONENTS OF POWER SYSTEM

1) Battery

The goal of having the battery in the system refers to the improving reliability of power system by means of creating additional energy reserve. One of the goals of batteries is the agreement of consumption and generating schedules by smoothing variable generating output.

The choice of the battery depends on the wind and solar profile, conditions of usage the wind generator, customer's power and the way of consumption.

The capacity of the battery installed in the power system depends on the characteristics of customer and time for which electricity can be supplied by battery.

In this work we will consider different scales of installed batteries – from 200 Ah to 2000 Ah. The choice of the capacity will be based on the amount of installed RES in the system and time required for the storage.

The most efficient way of using the battery is when discharge current does not exceed the value 0,2-0,3C (where C is the nominal capacity of battery) and charging current does not exceed 0,15-0,2C. In case of using the battery this way, the lifetime of battery will be close to nominal value of 10-12 yeas [6].

We will consider two options of using the capacity of battery – 5-hours discharge ($I_{dcharge}$=36,3A~0,2C) and 10-hours discharge ($I_{dcharge}$=20A~0,1C) – the example of the battery 200Ah with 12 V [22].

The 1-hour electricity given to the system from the battery:

I=36,3A:

$$\mathrm{W1} = \frac{1 \cdot 36{,}3 \cdot 12}{1000} = 0{,}44\ \mathrm{kWh} \tag{3.3}$$

$$\mathrm{Wtotal} = 0{,}4356 \cdot 5 = 2{,}18\ \mathrm{kWh} \tag{3.4}$$

I=20A:

$$\mathrm{W1} = \frac{1 \cdot 20 \cdot 12}{1000} = 0{,}24\ \mathrm{kWh} \tag{3.5}$$

$$\mathrm{Wtotal} = 0{,}24 \cdot 10 = 2{,}4\ \mathrm{kWh} \tag{3.6}$$

As we can see, for I=0,1C the battery generated the amount of energy equal to the nominal capacity rate ($\mathrm{Wnom} = 200\mathrm{Ah} \cdot 12\mathrm{V} = 2400\mathrm{Wh}$).But for I=0,2C the battery was not able to generate the same amount of energy. With the higher discharging current efficiency would drop even more.

2) Wind generator

Wind is an inconstant power source. That is why power characteristics of wind are usually representing by probability functions of stochastic changing in wind potential. Another possibility is the usage of average figures of wind potential. In this case it is necessary to determine the average wind speed for every month for the given region. It can be calculated by statistical data - daily wind speed for the last 5 years or taken from local cadasters [25].

The power output of wind generator depends on the speed in location in the third dimension: P ~V^3.One of the ways to express this dependence is the usage of following model [41]:

$$P_{WIND}(V) = \begin{cases} 0\,, & V < V_{MIN} \\ aV^3 - bP_{NOM}, & V_{MIN} < V < V_{NOM} \\ P_{NOM}, & V_{NOM} < V < V_{MAX} \\ 0, & V > V_{MAX} \end{cases} \tag{3.7}$$

where a, b – coefficients of the system:

$$a = \frac{P_{NOM}}{(V_{NOM}^3 - V_{MIN}^3)},\ b = \frac{V_{MIN}^3}{(V_{NOM}^3 - V_{MIN}^3)} \tag{3.8}$$

V- real wind speed

V_{MIN} –minimum wind speed (start-up speed)

V_{NOM}-nominal wind speed

V_{MAX} – maximum speed of wind (security speed)

P_{WIND} – real power of wind generation

P_{NOM} – nominal power of wind generator

The typical graph of dependence power output of generator on the wind speed P(V) is shown in Fig.14.

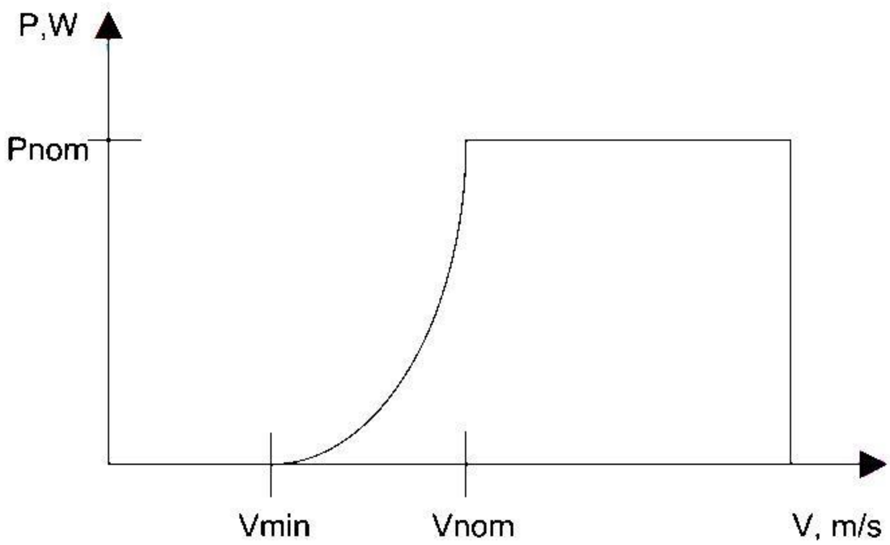

Figure 14 – P(V) - power characteristic of wind generator [41]

The amount of electricity produced by wind generator:

$$W_{WIND} = (8760 - t) \cdot P_{WIND}, \text{ kWh} \tag{3.9}$$

where t, h – the time of no-wind conditions.

3) PV panels

We will calculate the amount of electricity produced by PV panels for every day by the usage of the program HOMER. The formula used for the calculation of power output of a series of PV panels is [26]:

$$P_{\text{REAL PV}} = P_{\text{PV}} \cdot f_{\text{PV}} \frac{G_T}{G_{TSTC}}, \text{kW} \quad (3.10)$$

where

P_{PV}, kW-summ of nominal values of PV panels installed;

f_{PV},%-is the PV derating factor, we took it equal to 80%;

G_T,kW/m2 - is the solar radiation incident on the PV array in the current time step;

G_{TSTC}, kW/m2- is the incident radiation at standard test conditions;

The amount of electricity produced by PV panels:

$$W_{PV} = P_{\text{PV REAL}} \cdot t, \text{ kWh} \quad (3.11)$$

where t, h – the duration of considered period.

4) Diesel generator

The role of diesel generator in the system is to cover load demand which cannot be covered by RES (except of the case when we use only diesel generator).

We choose generator based on the maximum power of a load.

$$P_{DIES} = 2 \text{ kW} \quad (3.12)$$

The electricity produced by diesel generator can be derived as:

$$W_{DIES} = P_{DIES} \cdot t, \text{ kWh} \quad (3.13)$$

where t – the duration of considered period.

Diesel generator performs well under the stable conditions of load, where diesel generator works in about 70-90% of nominal power. If generator will operate for more than 80% it will reduce its lifetime, if it works for less than 80% the fuel consumption (kg/kWh) will increase proportionally. This fact should be taken into account while calculating economic performance of a system.

3.3.5 ENERGY BALANCE AND POWER EFFICIENCY

Amount of produced energy should equal to demand one:

$$\sum W_i = W_{DIES} + W_{SOL} + W_{WIND} + W_{BAT} = W_{CONS} \quad (3.14)$$

The primary goal of an optimal design is to cover yearly demand in electricity by combination of 3 given sources.

This equation will be evaluated for the daily loads for 3 different cases – winter, spring/autumn and summer day. For this purpose we will consider the 1st of December, the 1st of April and the 1st of June which have the wind and solar profile presented before.

Power efficiency in system will be calculated as the average sum of efficiencies for each source:

$$\eta = \sum_{n=1}^{3} \frac{Preal(N)}{Pnom(N)} \quad (3.15)$$

3.3.6 ECONOMIC MODEL OF SYSTEM

For the economic evaluation of the project we will use the net present value (NPV) model. For the comparison of projects we will use values of minimum prices on electricity produced by each technology or by the mix of technologies. This methodic is good because we can compare the prices on electricity with the existing in the region.

The main components of economic model of the project are described below.

1) Investment costs

Since for the aim of this thesis is to evaluate different options for power generation options, it could be quite time-consuming to select equipment for every new option. That is why it was decided to calculate investment costs by using specific prices of equipment (€/kW). The methodology for this calculation was taken from [43]. The specific price of equipment is derived through the statistical data - current prices for RES equipment on the Russian market for the year 2014 (Appendix 4). It was evaluated for the purposes of small-scale units (up to 100 kW). The fluctuations of specific prices are quite high - the basic tendency is that the specific prices are decreasing with the increase of installed capacity. Since the customer is in low range (2kW) we expect the generating units to be close to this value, so we take the maximum values of specific prices and use for our future calculations without referring to specific model and producer [20,21,22,27]:

- Wind generator: 1700 €/kW
- PV panels: 2200 €/kW
- Diesel generator: 600 €/kW
- Battery: 1,4 €/Ah

The prices for equipment needed for RES were taken from the manufacturers web-sites: controller is priced as 270 € and invertor is priced as 1450 € [21,28]. All other equipment (protection devices, measurement devices, cables) was priced as 250 € in total [28]. The construction of the power system is not complicated by the geographical conditions, large transportation issues or works at the big heights – all equipment installed inside the laboratory and on the roof of building. That is why total design and construction costs are accepted equal to the 1% of investment costs.

The type of project's investment can be done by the own funds or by the bank loan. The most influencing factor in the choice of the type of investment is the value of *discount rate*.

Discount rate refers to the interest rate used to determine the present value of future cash flows. It takes into account the time value of money and the risk or uncertainty of future cash flows.

In case of funding the project by own equity the CAPM model can be used. CAPM (Capital Asset Pricing Model) describes the relationship between risk and expected return. In the formula the time value of money is represented by the risk-free rate and compensates the investors for placing money in any investment over a period of time. The second part of formula represents risk and calculates the compensation on the additional risk for the investor [29].

$$r_{CAPM} = r_f + \beta \cdot (r_m - r_f) = 3{,}803 + 1{,}07 \cdot 7{,}3 = 11{,}614\% \quad (3.16)$$

where

r_f is the risk free rate which is defined from the profitability of Russian governmental bond "Russia-2020-EUR" ($r_f = 3{,}803\%$) [30];

$r_m - r_f$ is the market risk premium, it is taken from the survey of business institute ($r_m = 7{,}3\%$) [31];

β is beta coefficient, it is taken from the book of Asvat Damodaran for power companies ($\beta = 1{,}07\%$) [32].

In case of the bank loan WACC (Weighted Average Cost Of Capital) model can be used. WACC is the average of the costs of these sources of financing, each of which is weighted by its respective use in the given situation. By taking a weighted average, we can see how much interest the company has to pay for every dollar it finances [29].

Since the project is fully funded by its own capital (university's funds), the share of debt is zero and only the CAPM model will be used for economic calculations.

2) Depreciation

There are several methods of depreciation in Russia. According to Tax Code of the Russian Federation the company can choose by itself the method of depreciation from linear and non-linear. For given project the linear method of depreciation was chosen. The equipment in the system refers to the 8th group for 20 years lifetime [33]. Calculation of depreciation payments are:

$$\text{Depreciation} = \frac{\text{Investment costs}}{20} \quad (3.17)$$

3) Operational costs

All costs and revenue have been calculated as a sum for n years of project's lifetime

Fuel costs are calculated by using the value of average fuel consumption, current diesel price in the region and taking into account predicted fuel price growth in nominal values. The costs related to the transportation of diesel were ignored due to the small distance between supplier and customer.

The total fuel costs throughout the whole project's lifetime are:

$$\text{Fuel costs} = \mathrm{P_{dies}} \cdot \mathrm{Q_{dies}} \cdot \sum_{n=1}^{T} (1 + \mathrm{r_{fuel}})^{\mathrm{n}}, € \quad (3.18)$$

where $\mathrm{P_{dies}} = 0{,}7€/\mathrm{l}$ – the current price on diesel for given region[34];

Q=0,3 liter/kWh – the fuel consumption, derived from statistical data (Appendix 4);

$\mathrm{r_{fuel}}$=6,5% - annual fuel prices growth, higher than the value of inflation rate [35].

Wages are calculated by using average value of wages for given industry and taking into account the change of wage according to the region and predicted wages growth in nominal values.

The total wages costs throughout the whole project's lifetime are:

$$\text{Wages costs} = \mathrm{N} \cdot \mathrm{C_{nom}} \cdot \mathrm{k_{reg}} \cdot \sum_{n=1}^{T} (1 + \mathrm{r_{wages}})^{\mathrm{n}}, € \quad (3.19)$$

where $\mathrm{N} = 2$ – the number of employees, typical for these systems;

$\mathrm{C_{nom}} = 591{,}4$ € - the current nominal wage for given sector in Russian Federation[36];

$\mathrm{k_{reg}}$– the regional wage coefficient, which depends on the location of power plant, equal to 1,3 for Tomsk region[37];

$\mathrm{r_{wages}} = 7{,}8\%$ - the yearly growth of wages, equaled to the value of 7,8% as it is expected by the forecasts of consulting companies [38].

Maintenance and repairs costs are assumed equal to the 2% of total investments:

$$\text{M\&R costs} = 2\% \cdot \text{Capital costs} \cdot \sum_{n=1}^{T} (1 + \mathrm{r_i})^{\mathrm{n}}, \quad (3.20)$$

where $\mathrm{r_i}$=5,5% - escalation rate equal to inflation[36].

Then the total operating costs for the whole lifetime of a project including depreciation, are:

$$\text{Total oper costs} = \text{Fuel costs} + \text{Wages} + \text{M\&R} + \text{Depr}, € \quad (3.21)$$

4) Revenues

Though the project is done as non-commercial project and the consumer and producer are both university, the calculation of revenue only shows the potential price for selling the electricity or the price on saved electricity, which can be compared to the existing market price.

Revenues are calculated for the minimum project's price and its predicted growth.

The revenue of a project is:

$$\text{Rev} = \mathrm{C}_{min} \cdot \mathrm{W} \cdot \sum_{n=1}^{T} (1 + \mathrm{r_i})^{\mathrm{n}}, € \quad (3.22)$$

where C_{min} – price of electricity;

W, kWh - generated electricity

r_i - inflation rate

5) NPV and minimum electricity price

Since there are no loans included into the project then the payment of interests is absent. We can move to the calculation of earnings before and after taxes and:

$$\text{EBT} = \text{Revenues} - \text{Total costs}, € \quad (3.23)$$

$$\text{Taxes} = \text{d} \cdot \text{EBT}, € \quad (3.24)$$

$$\text{EAT} = \text{EBT} - \text{Taxes}, \quad (3.25)$$

where d=20% - the income tax for organizations in Russia according to the Tax Code of the Russian Federation [39].

Total cash flow:

$$CF = EAT - Depr - Inv, € \quad (3.26)$$

NPV of the project set to be equal zero:

$$\text{NPV} = \sum_{\text{n}=1}^{\text{T}} \text{CF} \cdot (1+\text{r})^{-\text{n}} = 0 \quad (3.27)$$

Where r is the discount rate.

The lifetime of project is taken equal to 20 years, since this is the average lifetime of the main equipment in system (diesel generator, PV panels, wind generator and invertor). Because the typical lifetime of used batteries is about 12 years and the lifetime of controller is about 10 years, we change both battery and controller once during the project (on the 10th year of operation).

After derivation, the minimum price set for project is:

$$\text{C}_{min} = \frac{\sum_{n=1}^{T}\left[(1-d)(P_d \cdot Q_d(1+r_{fuel})^n + NC_{nom}k_{reg}(1+r_{wages})^n + 0{,}2 \cdot Inv \cdot (1+r_i)^n) + \text{Inv} - \text{Depr}\right] \cdot (1+\text{r})^n}{W(1-d)\sum_{n=1}^{T}(1+r_i)^n(1+r)^{-n}}, €/\text{kWh}$$

(3.28)

We will use the same economic model for calculation of each design option, by changing only capital input data of these calculations: deleting some unnecessary auxiliary equipment, changing the installed capacity of each source and capacity of the battery.

3.3.7 CO_2 EMISSIONS

The amount of average annual harmful emissions per MWh of produced electricity for the diesel generator is presented in the Table 10 [18]. This dependence is made for the most optimal way of diesel operation (70-80% of load). In this work only CO_2 emissions will be calculated. Since we consider only emissions during the system's operation, it is assumed that that technologies based on PV and wind do not have any emissions.

Table 10 – Average annual harmful emissions for diesel generator [18]

Emissions type	CO2	NOx	SO2	PM
Average annual emissions for the certain power system (kg/MWh)	545	10,5	10,2	0,35

3.3.8 DECISION MAKING TASK

After the excluding some generation options, the following options will be compared between each other:

1. Wind generator + battery
2. PV panels + battery
3. Wind generator+ PV panels + battery
4. Diesel generator
5. Wind generator + diesel generator
6. PV panel+ diesel generator
7. Wind power generator + PV panels + diesel generator + battery (№1: existing system)
8. Wind power generator + PV panels + diesel generator + battery (№2:big share of RES)
9. Wind power generator + PV panels + diesel generator + battery (№3: big share of diesel generator capacity)

We use simplified algorithm, taking into consideration only 3 criteria – *average power efficiency, minimum electricity price* and *amount of CO_2 emissions* per year. Below one can see the description of each option and the results obtained

1. Wind power generator + battery

In the case of variant with power supply only by means of only wind energy we tried to use different installed capacities of wind generator and different capacities of the battery. Due to the low wind potential in Tomsk town and the big fluctuation of wind speed from season to season the big capacity of wind generator and of battery is required in order to cover daily demands: 40kW of wind generator and 3000 Ah of battery. The total system energy profile for this option is represented in the Appendix 5.

We can see that the power efficiency of this option is extremely low: wind generator gives the power close to nominal value only in summer season, for other seasons the real output hardly covers the demand curve, for some days system has to use batteries throughout the whole day. Although we tried to cover demand even with some backup reserve, the big possibility of demand exceeding supply still exists.

Due to the big investments costs the minimum electricity price for this option is extremely high, exceeding the electricity price even for decentralized power systems in Tomsk region [11].

The advantage of this option is in producing zero CO_2 emissions.

2. PV panels + battery

This option is similar to the first option. Due to the big fluctuation of solar radiation from season to season the big total capacity of PV panels and of battery is required in order to cover daily demands: 70kW of PV panels (for example 350 panels with 200 W of each) and 3000 Ah of battery. The total system energy profile for this option is represented in the Appendix 6.

We can see that the power efficiency of this option is also extremely low and the minimum electricity price is even higher than for the first option.

This option also produces no CO_2 emissions.

3. Wind+PV+battery

The usage of wind generator and PV panels in one system allows smoothing the inconstant power output of one technology by means of another. The mix of wind and solar generating units befits well to this particular region where wind speed and solar radiation output are in the antiphase to each other. The capacity of chosen wind generator is 5 kW, PV panels – 7,5 kW (for example 25 panels per 300W for each) and the capacity of battery is 200 Ah, The total system energy profile for this option is represented in the Appendix 7.

Though the power efficiency of this system is also not much higher than for two previous options, the minimum electricity price is much lower and can be compared to the electricity price even for decentralized power systems in Tomsk region. This option also produces no CO_2 emissions.

4. Diesel generator

In case of power supply of customer only by means of diesel fuel the generation profile is very clear – the output of diesel generator of 2 kW is regulated depending on the load with a small backup power. The power efficiency has the maximum for this kind of technology. The total system energy profile for this option is represented in the Appendix 8.

This variant has low investment costs due to the fact that the price of diesel generator is very low and there is no invertor, converter and batteries included into investment, The electricity price is formed mainly by the fuel costs, For our case the diesel technology is the second cheapest technology, however in case of higher fuel prices it can be less attractive solution.

The main disadvantage of this option is that it produces the highest amount of CO2 emissions.

5. Wind generator + diesel generator + battery

For the purpose of power supply by means of combination of wind and diesel power sources it was decided to install the wind generator with 2 kW of nominal power, battery with 200 Ah capacity and diesel generator with nominal power of 2 kW.

For this combination the wind generator produces big amount of electricity during the winter, spring and autumn seasons, the battery works for saving extra energy of wind generator and operation during the night time. However, the diesel generator produces the most energy for covering the demand. The total system energy profile for this option is represented in the Appendix 9.

This option has high power efficiency value and the lowest minimum electricity price thanks to the significant saving of fuel by wind generator. This option still produces significant amount of CO_2 emissions.

6. PV panels + diesel generator + battery

This option is similar to previous one. For the purpose of power supply by means of combination of solar and diesel power sources it was decided to install the PV panels with 2 kW of total nominal power(for example 10 panels for 200 kW each] , battery with 200 Ah capacity and diesel generator with nominal power of 2 kW.

The total system energy profile for this option is represented in the Appendix 10.

This option also has high power efficiency value and quite low value of the minimum electricity price thanks to the significant saving of fuel by PV panels, but still produces significant amount of CO_2 emissions.

7. Wind power generator + PV panels + diesel generator + battery (№1: existing system)

In this case we explored the configuration of already existed power system: 1 kW of wind generator, 2,16 kW of PV panels (12 panels by 180W each), battery 200 Ah and 12 kW of diesel generator. The total system energy profile for this option is represented in the Appendix 11.

The system has low power efficiency level due to the under-utilization of diesel's installed capacity, comparably low electricity price and big amount of CO_2 emissions.

8. Wind power generator + PV panels + diesel generator + battery (№2:big share of RES)

For this option we tried to build the system with the big share of both wind and solar RES, having battery and diesel generator as backup sources. The configuration of system is: 3 kW of wind generator, 4 kW (for example 20 panels of 200W for each) and battery with 200 Ah of capacity. The total system energy profile for this option is represented in the Appendix 12. As it is seen from the profile RES are the main sources for covering daily load demand for most seasons.

This option has the good compromise of all aspects: power efficiency, minimum electricity price and the amount of CO_2 emissions.

9. Wind power generator + PV panels + diesel generator + battery (№3: big share of diesel generator capacity)

For this option we tried to build the system with the big share of diesel generator capacity, having wind and solar sources and battery as adittional. The configuration of system is: 3 kW of wind generator, 4 kW (for example 20 panels of 200W for each) and battery with 200 Ah of capacity. The total system energy profile for this option is represented in the Appendix 13. As it is seen from the profile diesel is the main sources for covering daily load demand for most seasons, RES and battery generate power for small amount of time

This option has high power efficiency and minimum electricity price. However, it produces big amount of CO_2 emissions.

After the calculation the values of criteria for each option the weights to each criterion was assigned.

We assigned weights based on the point of view of the average investor which plan to construct the new power system for the need of removed customer. For this investor the electricity price will play the most significant role since he will try to make it higher than the alternative possible price for the option of building new power line. Also this investor will care about the power efficiency in order not to install unjustified high power capacities. Taking into account last concerns in the world about the environmental impact of power production the investor will also care about the amount of CO_2 emissions in order to avoid additional legislation restrictions or penalties. So, the weights were assigned in the following way: power efficiency – 30%, electricity price – 50%, CO_2 emissions – 20%.

Then the optimal function was calculated. The minimum value of optimal function was obtained for the 8th option (Tab.11).

Table 11 – Table of results

Options		*P1*	*P2*	*P3*	*Battery*	*Power efficiency*	*Minimum electricity price*	*CO2 emissions*	*Objective function*	*Priority*
№	*Name*	*kW*	*kW*	*kW*	*Ah*	*%*	*euro/kWh*	*kg/year*		
1	Wind	40	0	0	3000	2,7	1,407	0	0,443	8
2	PV	0	70	0	3000	1,8	2,842	0	0,800	9
3	Wind+PV	5	7,5	0	2000	7,0	0,656	0	0,191	2
4	Diesel	0	0	2	0	43,1	0,438	4129	0,289	7
5	Wind+ Diesel	2	0	2	200	15,7	0,392	2314,6	0,215	3
6	PV+Diesel	0	2	2	200	22,1	0,448	2964,2	0,246	5
7	W+PV+D, existing	1	2,16	12	200	8,2	0,556	2534,4	0,284	6
8	W+PV+D, 2 (more RES)	3	4	1	200	13,5	0,472	884,9	0,165	1
9	W+PV+D, 3 (more D)	1	1,2	2	200	22,1	0,457	2448,7	0,223	4
Weights of criteria						0,3	0,5	0,2		
Max value						43,1	2,842	4129		
Min value						1,8	0,392	0		

Example of calculations for the optimal case of power system’s structure (№8):

Calculation of minimum electricity price was made by the formula derived in 3.3.6 chapter.

$$C_{min} = \frac{\sum_{n=1}^{T}\left[(1-d)(P_d \cdot Q_d\left(1+r_{fuel}\right)^n + NC_{nom}k_{reg}\left(1+r_{wages}\right)^n + 0{,}2 \cdot Inv \cdot (1+r_i)^n) + \text{Inv} - \text{Depr}\right] \cdot (1+\text{r})^n}{W(1-d)\sum_{n=1}^{T}(1+r_i)^n(1+r)^{-n}}, =$$

$$0{,}472\ €/kWh \qquad (3.29)$$

The calculation of revenues, cash flows and NPV for this price is shown in Appendix 15.

The obtained price significantly exceeds the current electricity price in Tomsk town which equal to 0,054 $€/kWh$ [40]. However, since the project is made for academic purposes, it will be accepted even with this price.

If to consider the construction of similar power system in some districts of Tomsk region one can notice that the obtained price can be even more attractive than the existing price which people pay by usage the imported diesel and gasoline fuel for the price reaching the value of 2 $€/kWh$ for some cases [11]. If to consider the option of building the new power line for connecting the customer to the central grid then the larger distance and geographical restrictions are, the higher electricity price is. This fact also makes the obtained price more attractive for the customer in the majority of cases.

Power efficiency calculation:

$$\eta = \frac{Preal}{Pnom} = \frac{P_{real\_wind}+P_{real\_PV}+P_{real\_diesel}}{P_{nom\_wind}+P_{nom\_PV}+P_{nom\_diesel}} = \frac{0{,}2967+0{,}5865+0{,}1931}{3+4+1} = 13{,}5\% \quad (3.30)$$

The values of real power output of each power source mean the average 1-hour power considering the whole year. This value is very small for wind generator and PV panels because of not excellent conditions in Tomsk city. This value is also small for diesel generator in this particular case when diesel generator is only backup source to RES, so that it does not perform under its nominal value.

CO2 emissions calculation:

We will multiply the amout of electricity produced by diesel generator by the specific CO2 extraction per kWh:

$$Q_{CO2} = 545\frac{kg}{Wh} \cdot 1623{,}7kWh \cdot 0{,}001 = 884{,}9kg \qquad (3.31)$$

The calculation of an optimal function for the example of option №8:

$$\text{F} = \sum_{\text{N}=1}^{17}\left(\frac{\text{C}_\text{N}}{\text{C}_{Nmax}}\text{W}_\text{N} + \frac{\text{C}_\text{NMIN}}{\text{C}_N}\text{W}_\text{N}\right) = \frac{1{,}8}{13{,}45} \cdot 0{,}3 + \frac{0{,}472}{2{,}842} \cdot 0{,}5 + \frac{884{,}9}{4129} \cdot 0{,}2 = \ 0{,}165 \qquad (3.32)$$

As it is mentioned in the table, the structure of the system is 3 kW of wind power, 4 kW is the cumulative power of PV panels (for example, 20 for 200 W) and 1kW is for diesel generator. The battery is chosen in such a way that its capacity is enough to work during the night and it would have enough time during the day to be charged from the extra electricity of RES. The battery with capacity 200 Ah is quite ok for this purpose. The battery will be used in 2 the most economic ways: with 5-hours discharge (36,7 A) and 10-hours discharge (20A).

The demand of customer is fully covered by the installed generating units as it is seen from the system profile for 3 typical days of the year (Fig 15-17, tables in Appendix 12).

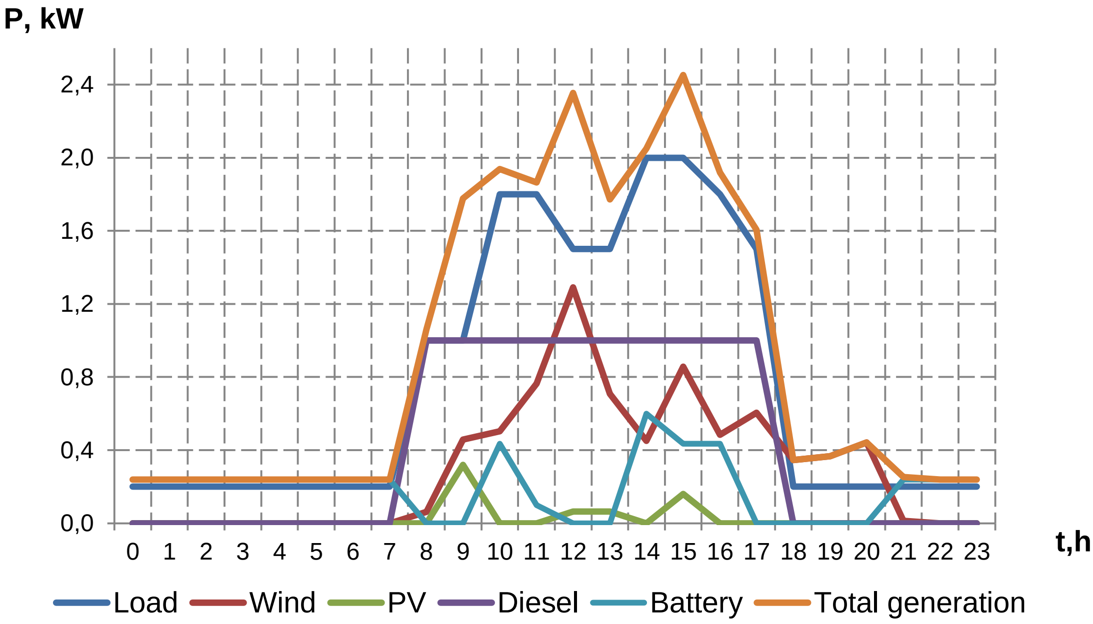

Figure 15 – Hybrid system profile, 1st of December

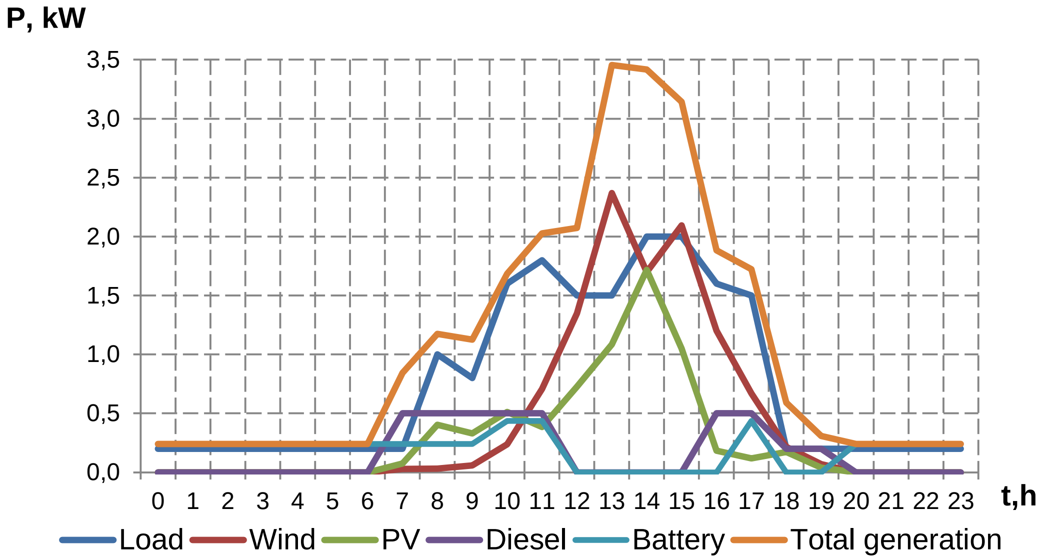

Figure 16 – Hybrid system profile, 1st of April

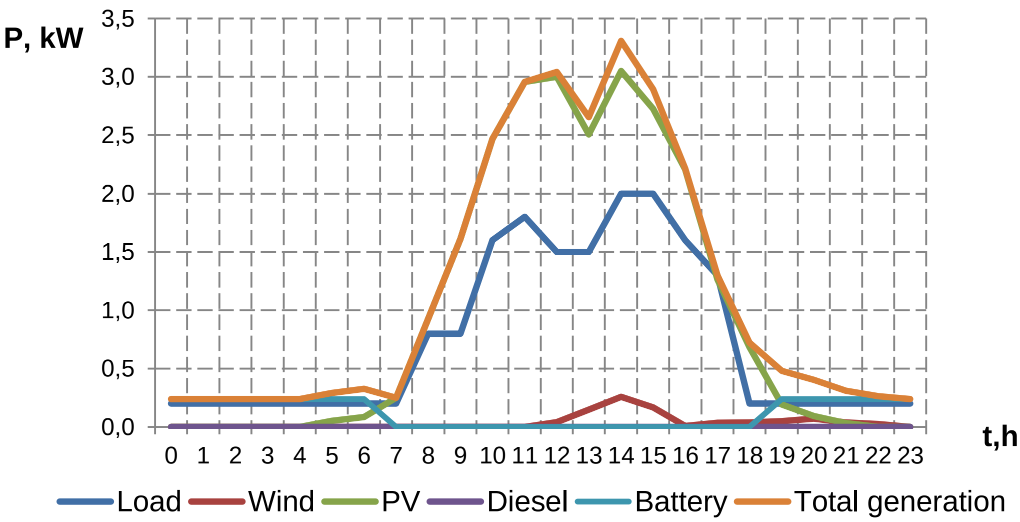

Figure 17 – Hybrid system profile, 1st of June

As one can see from the graph the diesel does not work at June's day at all. It also happens in many others summer days, which allows to save diesel fuel very significantly.

3.3.8 EXPERIMENTAL DATA OF A SYSTEM

In order to evaluate the performance of designed system it is also useful to compare it with the real data of already existed power system. For this purpose we took the readings of instruments installed in the laboratory. The data was collected by the measurement instruments (watthourmeter ,ampermeters, wattmeters, voltmeters,) and software Trace Mode which is used to display and process results.

The data was taken on the 03.09.2013. In appendix 14 one can see the graphs of battery $I_{АБ}$(t), voltage level on solar panel $U_{СМ}$(t), current of solar panel $I_{СМ}$(t), voltage level of wind generator $I_{ВГ}$(t) for three different operating modes: the full autonomy of customer, the full autonomy of customer with reduced load and the connection to the central grid.

We will show an example for full autonomous mode.

Since the mode is autonomous, the reading of watthourmeter Merkuriy does not show any results in the section of central grid.

The voltage of solar unit which consists of 12 PV panels is 52,25V which is almost the same as a nominal value:

$$U_{PV} = U1 + U2 = 24 + 24 = 48V \qquad (3.33)$$

Instantaneous value of power of PV panels according to the reading of wattmeter is:

$$P_{PV} = U \cdot I = 52{,}25 \cdot 0{,}37 = 19{,}3\text{W} \qquad (3.34)$$

The wind generator gave zero output due to insufficient wind speed this particular time of a day.

Amplitude value of discharging current of battery is about 110 A.

The instantaneous value of power of battery, which has the voltage level of 12 V, is:

$$P_{BAT} = U \cdot I = 12 \cdot 75 = 900W \qquad \textit{(3.35)}$$

The total power of generation units:

$$P_{TOTAL} = P_{PV} + P_{BAT} = 900 + 19 = 919W \qquad \textit{(3.36)}$$

This calculated value is closed to the value showed by the watthourmeter Merkuriy in the output of invertor - 811W (Appendix 1).This power is enough to cover the current need of customer.

The data measured for the one day of a year does not show the total statistic of generating ability of a system. The total data throughout the year is not collected yet due to the short time of power system operation. The further research based on the serias of measurement will allow to evaluate the performance of existing system. This can be an extend of this work, which will be aimed to compare the real generation profile with the profile, obtained by the probability theory and by calculations. Another extend is to research of electrical characteristics as an essential part of power quality management and their modelling in MathLab Simulink software.

3.4 SCENARIO AND SENSITIVITY ANALYSIS OF A PROJECT

In the following two subchapters the influence of such factors as weights' combinations and key economic characteristics of project on the decision making process will be evaluated.

3.4.1 SCENARIO ANALYSIS ON THE WEIGHTS ASSIGNED

In economic theory scenario analysis describes the impact of several input variables within several scenarios on the final result. In our case we will consider the influence of decision maker's set of preferences on the choice of the optimal system's configuration.

For this purpose we set different combinations of weights trying to assign some the most very typical combination such as setting each of criteria as the only influencing factor (2-4 scenarios), setting equal distribution of criteria (1), choosing two of them as the most influencing (5-7) or ranging criteria from the most to the least influencing (8-13).

For each scenario the decision making algorithm described in the Chapter 2 was applied. The scenarios showing the different weights assigned, the optimal function obtained and the decision made are presented in the Table 12. The base scenario, presented before, is marked by the grey color.

Table 12 – Sensitivity analysis on the weights of decision task

Scenario	w1,%	w2,%	w3,%	Value of objective function	Decision	
	Power efficiency	Minimum electricity price	Emissions		№	Description
1	33,3	33,3	33,3	0,159	3	Wind+PV+Battery
2	100	0	0	0,041	4	Diesel
3	0	100	0	0,140	5	Wind+Diesel+Battery
4	0	0	100	0,000	1,2,3	Wind+Battery PV+Battery Wind+PV+Battery
5	50	50	0	0,099	4	Diesel
6	0	50	50	0,116	3	Wind+PV+Battery
7	50	0	50	0,126	3	Wind+PV+Battery
8	50	30	20	0,158	8	Wind+PV+Diesel+Battery (big share of RES)
9	50	20	30	0,163	8	Wind+PV+Diesel+Battery (big share of RES)
10	30	50	20	0,166	8	Wind+PV+Diesel+Battery (big share of RES)
11	20	50	30	0,166	3	Wind+PV+Battery
12	30	20	50	0,122	3	Wind+PV+Battery
13	20	30	50	0,120	3	Wind+PV+Battery

As it is seen from the table, the option № 3 and option № 8 are accepted more often than other seven options. Both of them are examples of hybrid method of power supply. It was already mentioned that the hybrid power systems are compromised solutions as from the technical, economic and environmental point of view.

The option №3 (wind-PV-battery system) is accepted in case when the most significant factors are electricity price and environmental impact. It can be more massive because it requires higher nominal power than for conventional power sources and have some problems with regulations of power output. For designer or investor which wants to save operational costs and have no harmful environmental impacts this configuration is the best one.

The option №8 (wind-PV-diesel-battery system with big share of RES) is accepted in case when the most significant factors are electricity price and power efficiency. In this case the fluctuations of unstable power sources are smoothed by the battery and diesel generator. Moreover, the systems where RES are the main power source and diesel is the backup allow to save fuel and reduce the number of emissions. It was already discussed before that the hybrid power systems are the most compromised solutions from the technical, economic and environmental point of view.

Simply speaking, both of these configurations are almost equal good in case when all three considered criteria are important at the same time with the slight fluctuations in weights.

The option №4 (diesel system) is the best when the high power efficiency and reliability are required. Unlike all other options, this kind of systems has no dependence on the weather conditions and its output does not have to be secured by battery or other power source. In our particular case, where the fuel costs are not so high, the diesel power systems are also good compromise between price and power efficiency, but the worst option when the ecological impact is important.

Option№5 (wind+diesel+battery system) turned out to be the cheapest option. In case when decision maker concerns only about economical side of the project, this configuration is the best one.

Option№1 and №2 (fully renewable PV-battery and wind-battery systems) are accepted when the only environmental impact is important. However, this happens very seldom. From the other hand, these technologies are quite bad due to the low power efficiency, reliability and high electricity price.

3.4.2 SENSITIVITY ANALYSIS ON THE KEY ECONOMIC FACTORS

Unlike scenario analysis, where several combinations of inputs are considered, sensitivity analysis refers to the process of taking one key input and seeing how sensitive the model is to the change in that input.

In our case we will make the series of analyses on how the decision of optimal system's configuration is sensitive to some crucial economic factors such as RES equipment prices, fuel price, discount rate and lifetime of a project.

The economic evaluation of the project was made by the calculation of minimum price on electricity produced by the system:

$$C_{min} = \frac{\sum_{n=1}^{T}\left[(1-d)(P_d \cdot Q_d(1+r_{fuel})^n + NC_{nom}k_{reg}(1+r_{wages})^n + 0{,}2 \cdot Inv \cdot (1+r_i)^n) + \mathrm{Inv} - \mathrm{Depr}\right] \cdot (1+\mathrm{r})^n}{W(1-d)\sum_{n=1}^{T}(1+r_i)^n(1+r)^{-n}}, \text{€/kWh} \quad (3.37)$$

For simplification of analysis the investor, which considers the only economic aspect of the project, will be considered (scenario№3) so that his decision depends only on the value of minimum electricity price.

For evaluation the sensitivity of his decision the influence of the key economic factors on minimum electricity price was for all 9 possible configurations of power system.

1) ***Influence of the wind generator specific price change on the minimum electricity price***

The market prices on diesel generators tend to be quite stable. However, the market prices on wind generators and PV panels tend to decrease during the last years quite significantly [43] due to the technical development.

Below one can observe the changes of minimum electricity price by the change of the specific price on the wind generator for all 9 options (Tab.13 and Fig.18).

Table 13 – Dependence of the minimum electricity price on the wind generator specific price change

Percent of current specific price	Specific price of wind generator, €/kW	Minimum electricity price, €/kWh								
		1	2	3	4	5	6	7	8	9
20%	340	0,500	2,842	0,542	0,438	0,347	0,448	0,534	0,404	0,435
40%	680	0,727	2,842	0,571	0,438	0,358	0,448	0,539	0,421	0,440
60%	1020	0,954	2,842	0,599	0,438	0,370	0,448	0,545	0,438	0,446
80%	1360	1,181	2,842	0,627	0,438	0,381	0,448	0,551	0,455	0,452
100%	1700	1,407	2,842	0,656	0,438	0,392	0,448	0,556	0,472	0,457
120%	2040	1,634	2,842	0,684	0,438	0,404	0,448	0,562	0,489	0,463
140%	2380	1,861	2,842	0,713	0,438	0,415	0,448	0,568	0,506	0,469
160%	2720	2,088	2,842	0,741	0,438	0,426	0,448	0,573	0,523	0,474
180%	3060	2,315	2,842	0,769	0,438	0,438	0,448	0,579	0,540	0,480
200%	3400	2,541	2,842	0,798	0,438	0,449	0,448	0,585	0,557	0,486
220%	3740	2,768	2,842	0,826	0,438	0,460	0,448	0,590	0,574	0,491

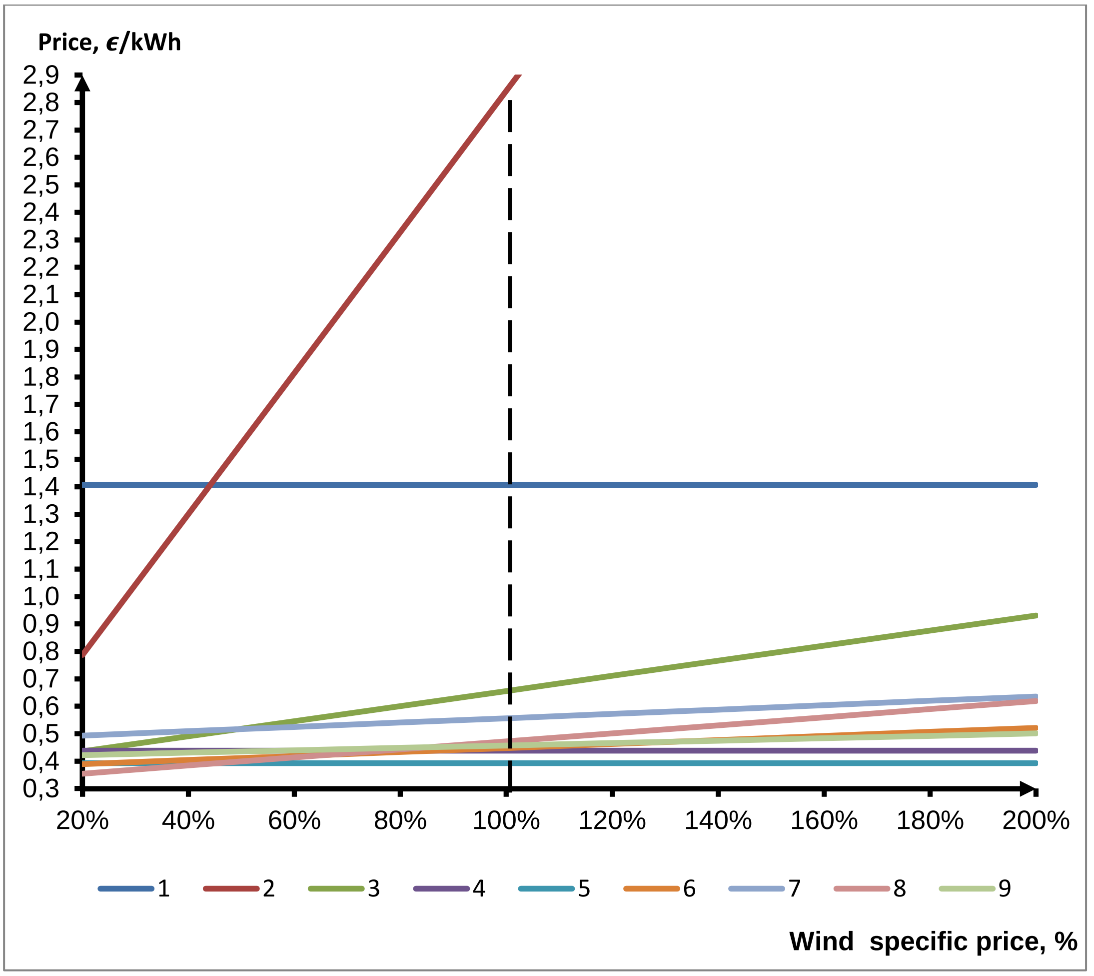

Figure 18 - Dependence of the minimum electricity price on the wind generator specific price change

As we can see from the graph, the change in wind specific price influence significantly the electricity minimum price on technologies with the high share of installed capacity of wind generator (1,3,8), slight influence for systems with low share (5,7,9) and remain the same for system configurations without wind generator(2,4,6).

However, the decision is not so sensitive to the change of wind specific price for considered fluctuation interval: the best option for the investor, the option №5 (wind+diesel) remains the best due to the lowest minimum electricity price value. Conversely, the option № 2 (PV+battery) remains the worst due to the highest value of minimum electricity price.

2) *Influence of the PV panels specific price change on the minimum electricity price*

The same analysis was done to observe the changes of minimum electricity price by the change of the specific price on PV panels for all 9 options (Tab.14 and Fig.19).

Table 14 – Dependence of the minimum electricity price on the PV panels specific price

Percent of current specific price	Specific price of PV panels, €/kW	Minimum electricity price, €/kWh								
		1	2	3	4	5	6	7	8	9
20%	440	1,407	0,787	0,436	0,438	0,392	0,389	0,493	0,355	0,422
40%	880	1,407	1,301	0,491	0,438	0,392	0,404	0,509	0,384	0,431
60%	1320	1,407	1,814	0,546	0,438	0,392	0,419	0,525	0,413	0,440
80%	1760	1,407	2,328	0,601	0,438	0,392	0,433	0,541	0,443	0,448
100%	2200	1,407	2,842	0,656	0,438	0,392	0,448	0,556	0,472	0,457
120%	2640	1,407	3,355	0,711	0,438	0,392	0,463	0,572	0,501	0,466
140%	3080	1,407	3,869	0,766	0,438	0,392	0,477	0,588	0,531	0,475
160%	3520	1,407	4,382	0,821	0,438	0,392	0,492	0,604	0,560	0,484
180%	3960	1,407	4,896	0,876	0,438	0,392	0,507	0,620	0,590	0,492
200%	4400	1,407	5,410	0,931	0,438	0,392	0,521	0,636	0,619	0,501

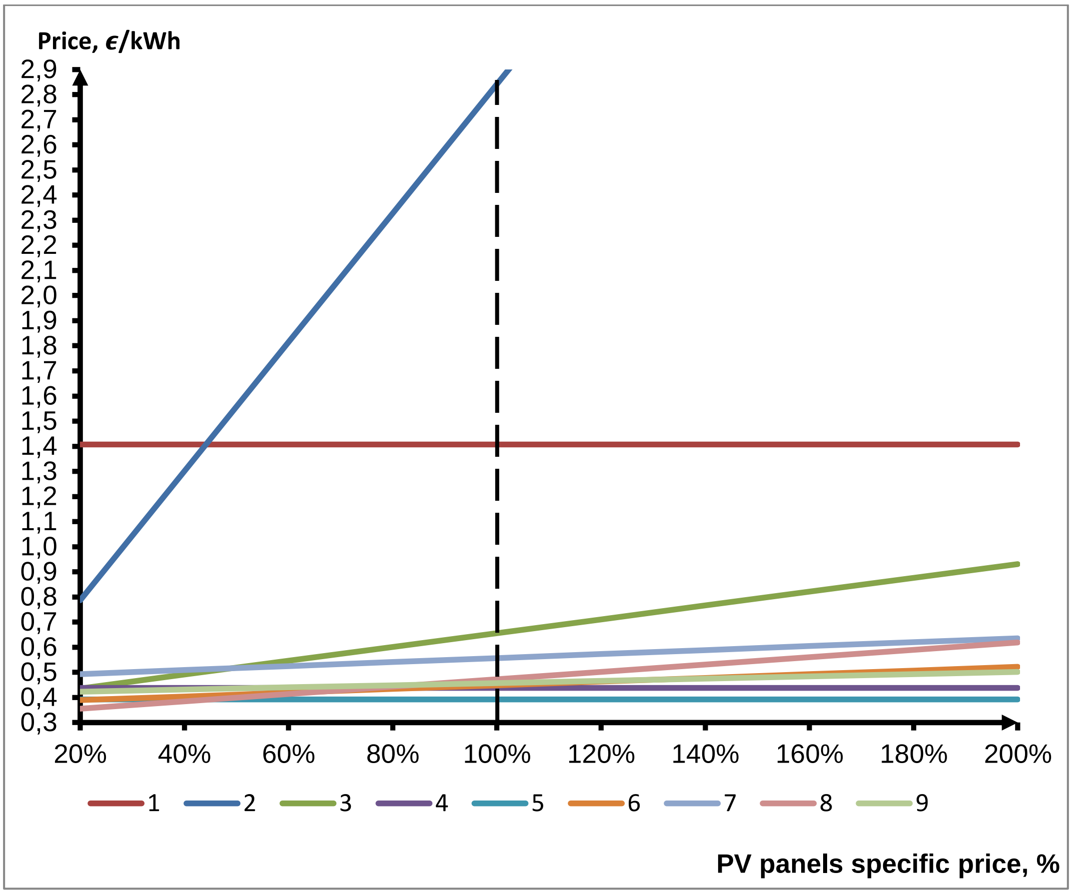

Figure 19 - Dependence of the minimum electricity price on the PV panels' specific price

The same as for the wind power, the change in PV specific price influence significantly the electricity minimum price on technologies with the high share of installed capacity of PV panels (2,3,5,7,8), slight influence the technologies with the high share (9) and remain the same for system configurations without wind generator(1,4).

However, the decision is not so sensitive to the change of PV specific price for considered fluctuation interval: the option №5 (wind+diesel) remains the best due to the lowest minimum electricity price value. Conversely, the option №2 (PV+battery) remains the worst due to the highest value of minimum electricity price. But for the drop of price to the value less than 55% make the most expensive the option №2 (PV+battery cheaper than the option№1 (wind+battery).

3) Influence of the fuel prices changes on the minimum electricity price

Another significant factor influencing the power system based on the conventional energy sources is fuel prices. For our case study we have quite small fuel market prices compared to EU countries.

In the Tab. 15 and Fig.20 one can see how the change of diesel could change the minimum electricity price.

Table 15 – Dependence of fuel prices change on the minimum electricity price

Percent of current fuel price	Fuel price, €/l	Minimum electricity price, €/kWh								
		1	2	3	4	5	6	7	8	9
20%	0,14	1,407	2,842	0,656	0,239	0,281	0,306	0,435	0,423	0,307
40%	0,28	1,407	2,842	0,656	0,289	0,309	0,341	0,465	0,434	0,344
60%	0,42	1,407	2,842	0,656	0,338	0,337	0,377	0,496	0,445	0,382
80%	0,56	1,407	2,842	0,656	0,388	0,365	0,412	0,526	0,455	0,420
100%	0,7	1,407	2,842	0,656	0,438	0,392	0,448	0,556	0,466	0,457
120%	0,84	1,407	2,842	0,656	0,487	0,420	0,484	0,587	0,477	0,495
140%	0,98	1,407	2,842	0,656	0,537	0,448	0,519	0,617	0,487	0,532
160%	1,12	1,407	2,842	0,656	0,586	0,476	0,555	0,648	0,498	0,570
180%	1,26	1,407	2,842	0,656	0,636	0,503	0,590	0,678	0,508	0,608
200%	1,4	1,407	2,842	0,656	0,685	0,531	0,626	0,708	0,519	0,645
220%	1,54	1,407	2,842	0,656	0,735	0,559	0,661	0,739	0,530	0,683
240%	1,68	1,407	2,842	0,656	0,784	0,587	0,697	0,769	0,540	0,721
260%	1,82	1,407	2,842	0,656	0,834	0,614	0,732	0,800	0,551	0,758
280%	1,96	1,407	2,842	0,656	0,883	0,642	0,768	0,830	0,562	0,796
300%	2,1	1,407	2,842	0,656	0,933	0,670	0,804	0,860	0,572	0,833
320%	2,24	1,407	2,842	0,656	0,982	0,698	0,839	0,891	0,583	0,871

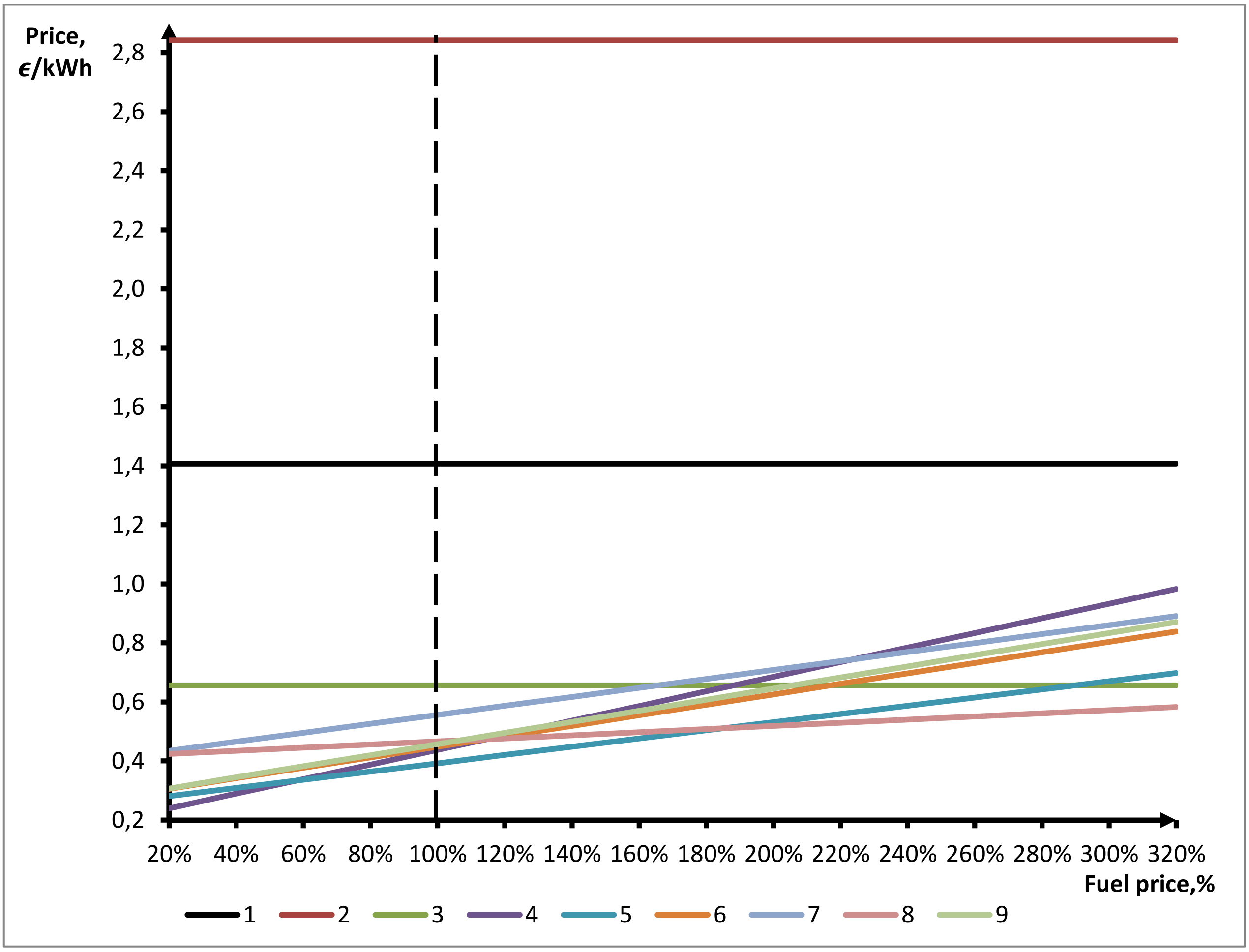

Figure 20 - Dependence of the minimum electricity price on fuel price

As we can see from the graph the change in the local fuel price has big influence on the price for options with the high share of usage the diesel generator (4,5,6,7,9), for others – this is just the constant line or the line the slight slope (1,2,3,8).

It means that decision strongly depends on the fuel price. In case of low fuel price (up to 20% of current price) the diesel and wind-diesel systems remain the best options the same as for situation – for diesel price in 0,7 euro/liter. However, with the increase of price (up to 320%) other technologies become more economically efficient, such as wind-PV system or wind-PV-diesel system with the small share of diesel generator capacity.

For this particular case study the transportation costs were ignored. If we will consider the decentralized customer where diesel fuel price can be twice or three times higher due to the transportation costs, the influence of fuel price on the decision can be even more significant.

4) Influence of the discount rate increase on the electricity price:

In the Tab. 16 and Fig.21 one can see how the change of discount rate could change the minimum electricity price.

Table 16 – Dependence of minimum electricity price on the discount rate

Discount rate	Minimum electricity price, €/kWh								
	1	2	3	4	5	6	7	8	9
0%	0,713	1,341	0,379	0,418	0,336	0,383	0,416	0,317	0,393
2%	0,784	1,496	0,408	0,420	0,342	0,390	0,430	0,332	0,399
4%	0,885	1,714	0,448	0,422	0,350	0,399	0,450	0,353	0,408
6%	0,999	1,959	0,493	0,425	0,359	0,409	0,473	0,377	0,419
8%	1,125	2,231	0,543	0,429	0,369	0,421	0,499	0,404	0,430
10%	1,261	2,526	0,598	0,433	0,380	0,434	0,526	0,434	0,443
12%	1,407	2,842	0,656	0,438	0,392	0,448	0,556	0,466	0,457
14%	1,561	3,174	0,717	0,443	0,405	0,463	0,588	0,500	0,472
16%	1,721	3,520	0,781	0,448	0,419	0,479	0,621	0,536	0,488
18%	1,886	3,876	0,847	0,454	0,433	0,495	0,656	0,573	0,504
20%	2,053	4,238	0,914	0,460	0,448	0,512	0,691	0,610	0,520
22%	2,223	4,603	0,981	0,466	0,463	0,529	0,726	0,648	0,537
24%	2,392	4,970	1,049	0,472	0,478	0,546	0,762	0,687	0,554
26%	2,562	5,336	1,117	0,479	0,493	0,563	0,798	0,725	0,571
28%	2,730	5,698	1,185	0,485	0,508	0,580	0,833	0,763	0,588
30%	2,896	6,057	1,251	0,492	0,522	0,597	0,868	0,800	0,605
32%	3,060	6,410	1,317	0,498	0,537	0,614	0,903	0,837	0,622

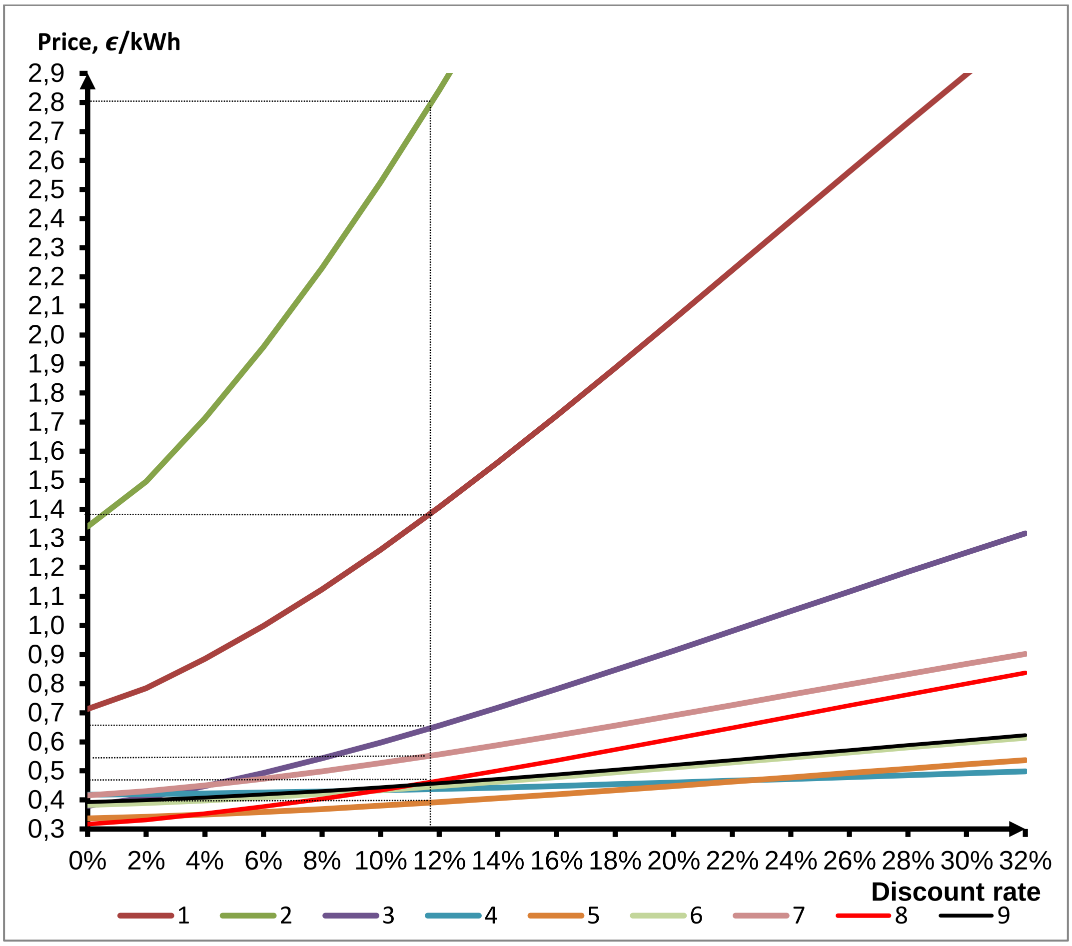

Figure 21 - Dependence of the minimum electricity price on the discount rate

As we can see from the graphs the change of discount rate influence the minimum electricity price for all considered configurations: the higher discount rate, the lower NPV of the project and the higher minimum electricity price.

For our calculation due to the luck of data about municipality and university investments we considered the discount rate for the private investor in Russia. We expect that the real discount rate will be 3-4% lower, which will not influence decision significantly, but will increase the minimum electricity price to the value of 0,4 – 0,43 €/kWh for the 8th configuration.

However, the change of discount rate does not significantly influence the decision. For the increase of discount rate the graphs for minimum electricity prices of almost all possible options are in parallel, so that the investor does not change decision as much for the change of fuel price.

The lowest price remains to be the minimum for the option№5 (diesel-wind systems), despite the case when DR becomes less than 4% - the option№8 becomes the best and when DR exceeds 23% and option№4 becomes the best, and the highest price remains to be the highest for the option№2 (PV-battery) for the whole range of considered discount rate.

5) Influence of lifetime of the project on the electricity price:

For the calculation of the price for different lifetimes the revenues and operational costs were prolonged or reduced and the depreciation costs were changed according to the new lifetime. In the Tab. 17 and Fig.22 one can see how the change of lifetime could change the minimum electricity price for all 9 options.

Table 17 – Dependence of the minimum electricity price on lifetime of project

Lifetime, years	Minimum electricity price, €/kWh								
	1	2	3	4	5	6	7	8	9
8	2,179	4,53	0,957	0,445	0,4521	0,518	0,713	0,6387	0,526
12	1,756	3,56	0,795	0,439	0,4178	0,478	0,624	0,545	0,487
16	1,535	3,118	0,706	0,438	0,4007	0,458	0,581	0,498	0,467
20	1,407	2,842	0,656	0,437	0,3923	0,448	0,556	0,472	0,457
24	1,321	2,659	0,620	0,437	0,3873	0,442	0,541	0,457	0,451
28	1,267	2,5404	0,600	0,439	0,3855	0,44	0,533	0,447	0,449

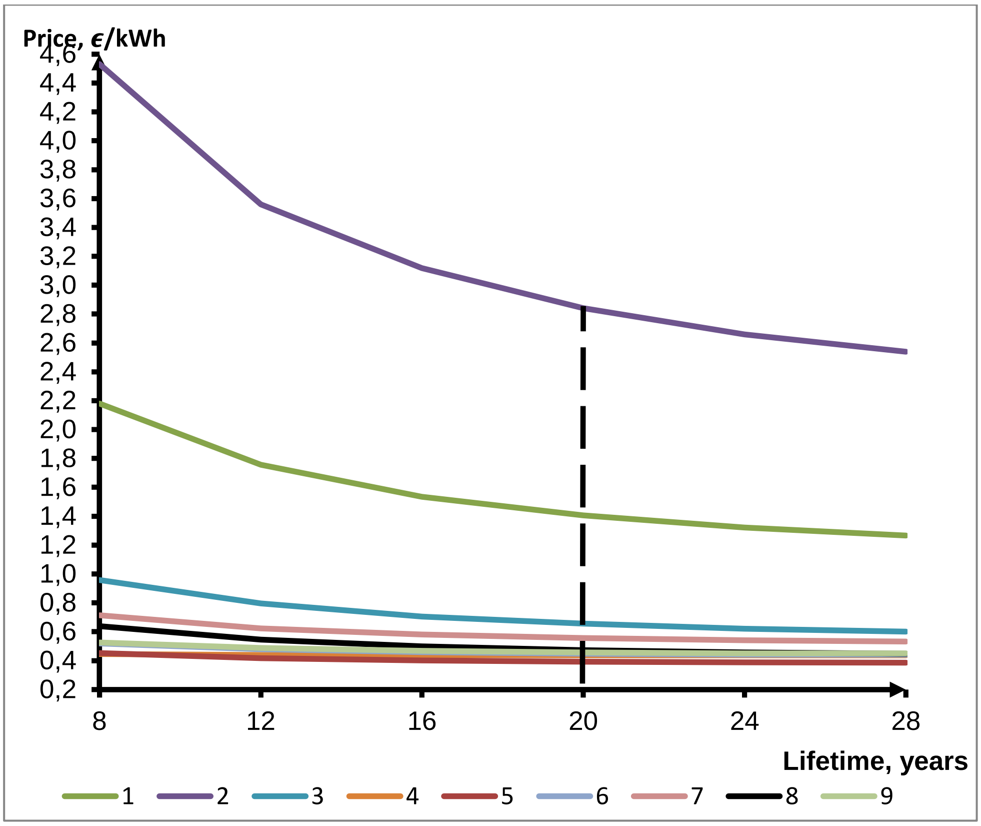

Figure 22 - Dependence of the minimum electricity price on the lifetime of project

This graph shows that the increase of time of operation in any possible configuration leads to the increase of the NPV of project and hence to the decrease of the minimum electricity price.

However, all graphs are located in parallel, so there is no influence on the investor's decision.

CONCLUSION

The problem of decentralized power supply was discussed in the beginning of this work. There is no ideal solution of this problem: either it is made by means of renewables, by diesel/gasoline generator or by the combination of both.

Existing methods for optimal design of the hybrid power systems are very complex, because they have a lot of variables and face many aspects to evaluate. Usually these methods deal with the technical and economic performance, environmental and social impacts or with the mix of them.

The main output of this work is the developed algorithm for the optimal design of decentralized power system. Created model takes into account very wide range of factors, trying to evaluate the main possible risks and concerns related to the problem of power system's construction. The application of the algorithm is quite a tough task because it should consider too much data, starting from the basic information such as wind speed or diesel fuel prices and finishing with such uncertain information as the increase of welfare rate or the level of business risk. However, this complexity is close to the real situations where the designer faces not only the technical obstacles while building new generating unit.

For the application of developed algorithm the subject with existing hybrid power system has been chosen. The evaluation of power system's feasibility showed that the only technologies which could be presented in system are wind, solar and diesel power sources. The further evaluation was based on the considering three crucial criteria. The evaluation of 9 possible system's configurations from the point of view of potential investor has shown that the most optimal is the one with the 3 kW installed of wind generator, 4 kW (20x200W) of PV panels, 200 Ah of battery and 1kW of diesel generator. It has the total power efficiency of 13,45%, the minimum price of 47 eurocents/kWh and 885 kg of CO_2 emissions per year. The existing configuration of system is not the best one due to the too high installed capacity of diesel generator.

The minimum electricity price, obtained for the project, is much higher than the one existing in Tomsk town; however the similar system can be constructed for many decentralized customers in Tomsk region where the electricity price, obtained for the alternative project of connecting to the central power grid, can be much higher.

Scenario and sensitivity analysis has shown the influence of weights assigned and the economic characteristic on the decision. This analysis showed high dependence of investor's decision on the weights assigned to criteria and on diesel fuel costs and low dependence on such factors as discount rate, wind/PV investment costs and project's lifetime.

The total generation profiles showed the coverage of daily demands for all four seasons in the year. These total power outputs were compared to the real instruments data of existing power system. However, it is hard to make conclusion about the matching of real and modeled characteristics because of the lack of collected data yet.

The proposed algorithm is quite universal. It can be applied for any decentralized object by considering the huge amount of decisions available and by setting high priorities (weights) to the aspects which play more important roles and low priorities to the ones which play less important roles.

The possible extension of the work is the developing detailed analysis of the system's performance by creating more precise technical model, gathering whole year data of meteorological and electrical characteristics by laboratory's instruments. Another extension is the improving of algorithm by specification of sources for criteria data collection and specification of criteria evaluation. Moreover, it is possible to apply the proposed algorithm in its full version, thereby making valuable analysis of some future power system.

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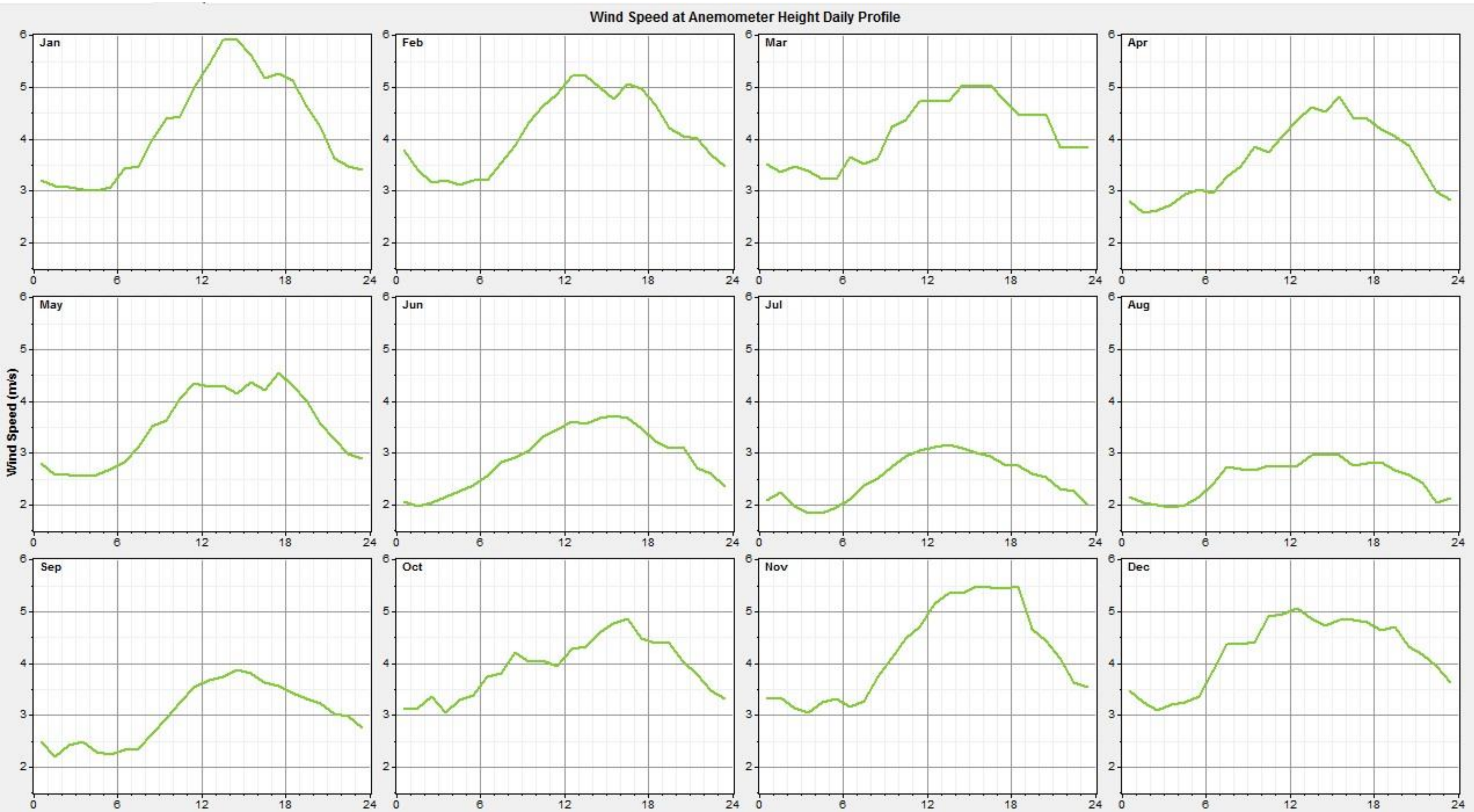
APPENDIXES

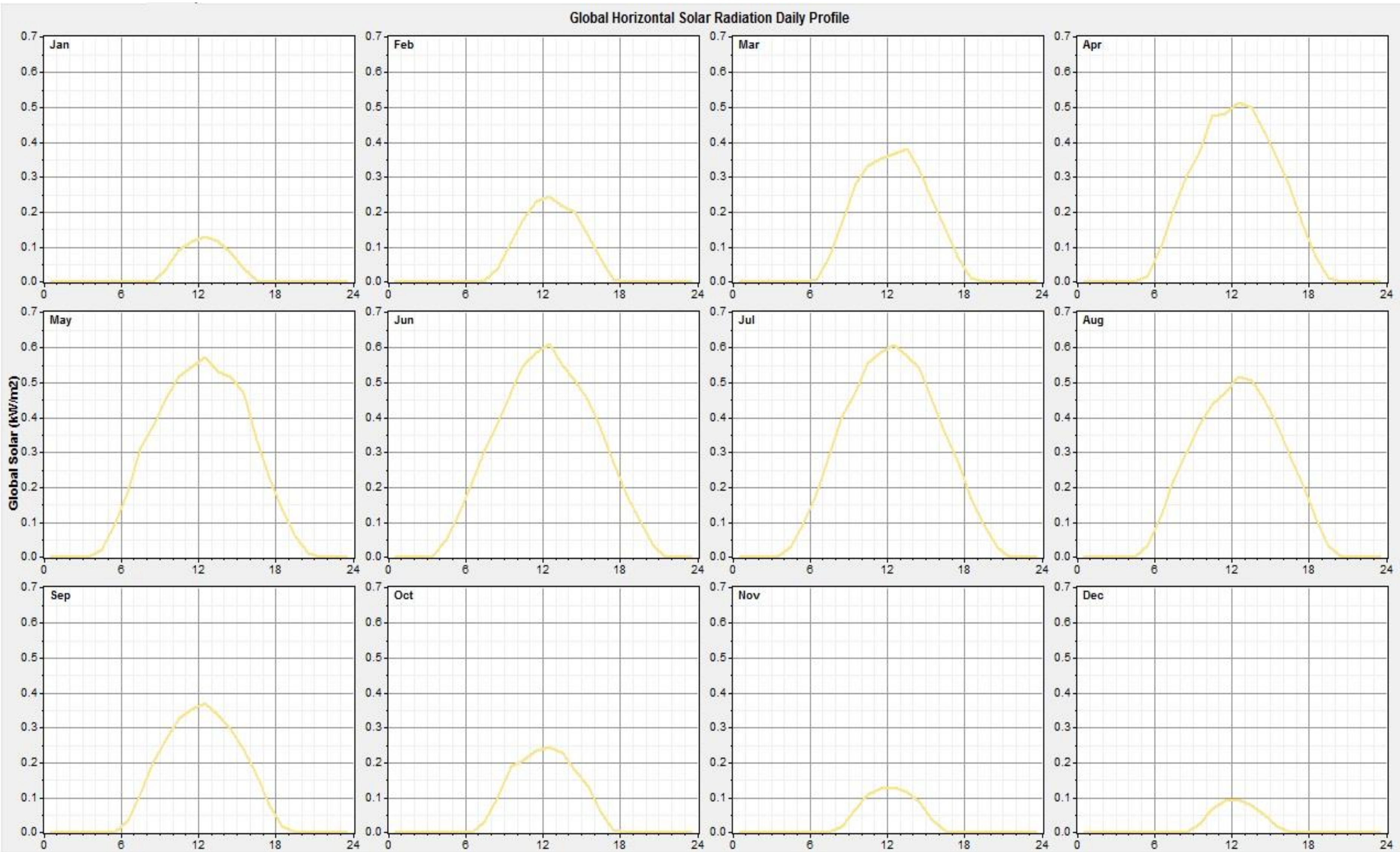
Appendix 1 – Equipment installed in the laboratory 225, building of TPU [20, 21, 22, 23]

Wind generator		**PV panels**		**Battery**		**Controller**		**Invertor**	
Trade mark	Sapsan-1000	Trade mark	FSM-200	Trade mark	ST12-200	Trade mark	TSMPPT-45/60	Trade mark	Map Energia
Manufacturer	Sapsan-Energia, Russia	Manufacturer	Sapsan-Energia, Russia	Manufacturer	Volta, China	Manufacturer	Morningstar Corporation, USA	Manufacturer	MicroArt
Type of generator	on permanent magnets	Nominal power	180 W	Nominal voltage, V	12 V	Current	45A/60A	Max power	9 kW
Nominal power	1000 W	Nominal voltage	24 V	Capacity, Ah	200 Ah	Max input voltage	150V	Peak power (5 sec)	12 kW
Maximum rotations per minute	450	Maximum voltage	36	Length, mm	522 mm	Peak efficiency	99%	Nom power	6 kW
Working voltage	48-56 V	Maximum currect	5,3 A	Width,mm	240	Nominal voltage	12/24/36/48V	Short circuit current	0,4-0,7 A
Impeller		Short-circuit current	6,1 A	Height,mm	219	Voltage interval	8-68 V	Dimensions	33×36×32
Material	fiberglass	No-load voltage	42 V	Height with the terminals, mm	236	Self-consumption	<4 W	Weight	36 kg
Radius	1,5 m	Dimensions	1585x805x35 mm	Weight, kg	55	Weight	4,2 kg		
Amount	3	Weight	16 kg	Lifetime	7	Dimensions	29,1x13,0x14,2 sm		
Minimum speed	2,5 m/s			Guarantee, months	12				
Weight	100 kg								

Appendix 2 – Wind speed daily profile for Tomsk town, Homer software [25, 26]



Appendix 3 – Solar radiation daily profile for Tomsk town, Homer software [24, 26]



Appendix 4 – Statistical data on the prices of equipment [20, 21, 22, 27, 28]

Wind generators				
Trade mark	Producer	Nominal power,W	Price, €	Specific cost, €/kW
ВЭУ-1/2.6	Melnikov Electroveter	1	354	354
ВЭУ-2/3.5	Melnikov Electroveter	2	813	406
ВЭУ-3/5	Melnikov Electroveter	5	2188	438
ВЭУ-10/7	Melnkov Electroveter	10	4792	479
LOW·WIND·48·1	MIkroArt	1	1220	1220
LOW·WIND·48·2.5	MIkroArt	2,5	1940	776
WINDGEN·48·5	MIkroArt	5	6229	1246
TOWER·S·12M	MIkroArt	3	2688	896
EuroWind 300M	Alternative Ukrain Energetics	0,3	500	1667
EuroWind 500	Alternative Ukrain Energetics	0,5	821	1643
EuroWind 600	Alternative Ukrain Energetics	0,6	893	1488
EuroWind 1	Alternative Ukrain Energetics	1	1071	1071
EuroWind 2	Alternative Ukrain Energetics	2	1857	929
EuroWind 5	Alternative Ukrain Energetics	5	8500	1700
EuroWind 10	Alternative Ukrain Energetics	10	9571	957
EuroWind 20	Alternative Ukrain Energetics	20	16714	836
EuroWind 30	Alternative Ukrain Energetics	30	24571	819
EuroWind 50	Alternative Ukrain Energetics	50	66143	1323
EuroWind 100	Alternative Ukrain Energetics	100	118000	1180
PV panels				
Trade mark	Producer	Nominal power,W	Price, €	Specific cost, €/kW
CHN10-36P	Chinaland Solar Energy	10	21,8	2180
CHN20-36M	Chinaland Solar Energy	20	36,4	1820
CHN30-36M	Chinaland Solar Energy	30	49	1633
CHN40-36P	Chinaland Solar Energy	40	69,8	1745
CHN50-36P	Chinaland Solar Energy	50	88	1760
CHN80-36M	Chinaland Solar Energy	80	108,6	1358
CHN150-36P	Chinaland Solar Energy	150	201	1340
Моно-60-12В	MIkroArt	60	93,8	1563
Моно-200-24В	MIkroArt	200	264,6	1323
FSM 30M	Sapsan-Energia	30	41,7	1389
FSM 50M	Sapsan-Energia	50	64,6	1292
FSM 150M	Sapsan-Energia	150	166,7	1111
HG-200S	Sapsan-Energia	200	227,1	1135

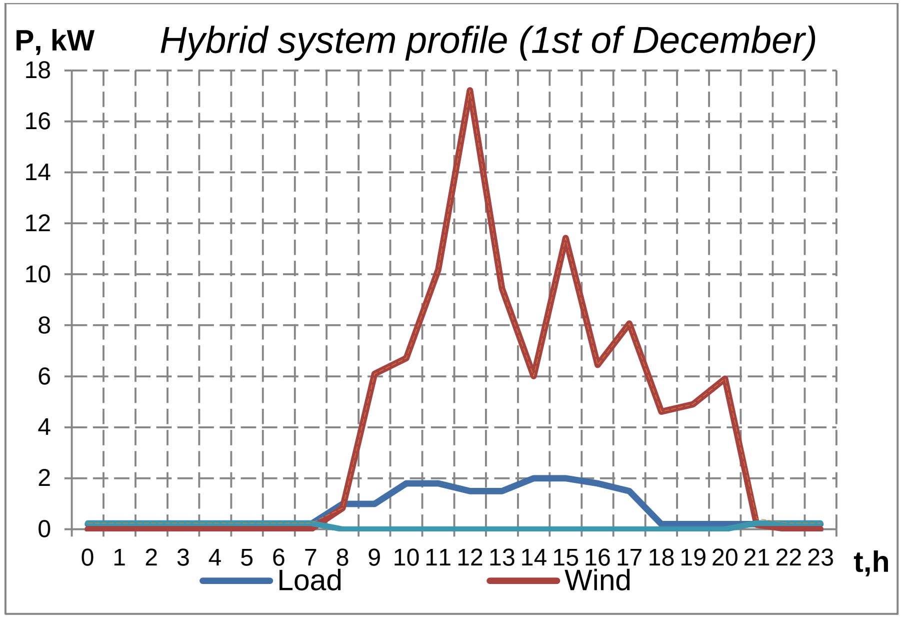
Appendix 4 – Statistical data on the prices of equipment (continuation)

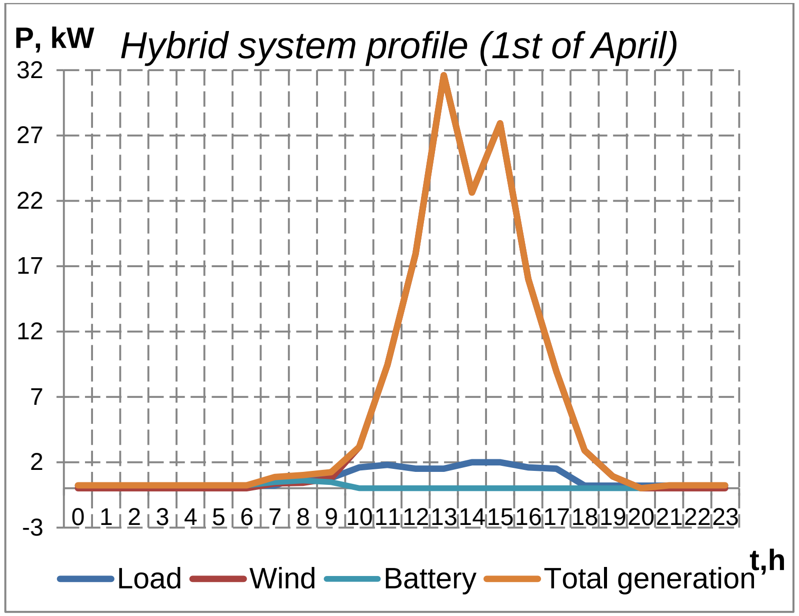
Diesel generators				
Trade mark	*Producer*	*Nominal power,W*	*Price, €*	*Specific cost, €/kW*
ADP·5·230·VYA·S·M	Vepr	5	2964	593
ADP·6·230·VL·S·M	Vepr	6	3387	564
ADP·6·230·VL·BS·M	Vepr	6	3093	515
ADP·8·230·VL·BS·M	Vepr	9	5032	572
ADP·10·230·VL·BS·M	Vepr	11	5661	515
ADP·12·230·VL·BS·M	Vepr	12	5975	498
ADA·10·230RL49·M	Vepr	9	4160	443
АД 8-Т400	Azimut	8	4580	573
АД 10-Т400	Azimut	10	4670	467
АД 12-Т400	Azimut	12	4760	397
АД 15-Т400	Azimut	15	5080	339
АД 20-Т400	Azimut	20	5220	261
АД 60-Т400	Azimut	60	8750	146
Batteries				
Trade mark	*Producer*	*Capacity,Ah*	*Price, €*	*Specific cost, €/Ah*
VOLTA ST12-100	Volta	100	143	1,43
VOLTA ST12-120	Volta	120	181	1,50
VOLTA ST12-150	Volta	150	215	1,43
VOLTA ST12-200	Volta	200	338	1,69
VOLTA ST12-250	Volta	250	390	1,56
DELTA DTM 12120 L	Delta	120	181	1,51
DELTA DTM 12150 L	Delta	150	227	1,51
DELTA DTM 12200 L	Delta	200	301	1,51
DELTA DTM 12230 L	Delta	230	352	1,53
BB Battery MSB300-2FR	BB Battery	300	195	0,65
BB Battery MSB400-2FR	BB Battery	400	289	0,72
BB Battery MSB500-2FR	BB Battery	500	331	0,66
BB Battery MSB600-2FR	BB Battery	600	396	0,66
BB Battery MSB800-2FR	BB Battery	800	720	0,90
BB Battery MSB1000-2FR	BB Battery	1000	800	0,80
BB Battery MSU-2000(FR)	BB Battery	2000	1153	0,58
Diesel generator fuel consumption				
Trade mark	*Producer*	*Fuel consumption, kg/kWh*	*Density of diesel fuel, kg/l*	*Fuel consumption, l/kWh*
ADP·5·230·VYA·S·M	Vepr	0,25	0,86	0,29
ADP·6·230·VL·S·M	Vepr	0,25	0,86	0,29
ADP·6·230·VL·BS·M	Vepr	0,27	0,86	0,31
ADP·8·230·VL·BS·M	Vepr	0,27	0,86	0,31
ADP·10·230·VL·BS·M	Vepr	0,27	0,86	0,31
ADP·12·230·VL·BS·M	Vepr	0,27	0,86	0,31
ADA·10·230RL49·M	Vepr	0,27	0,86	0,31

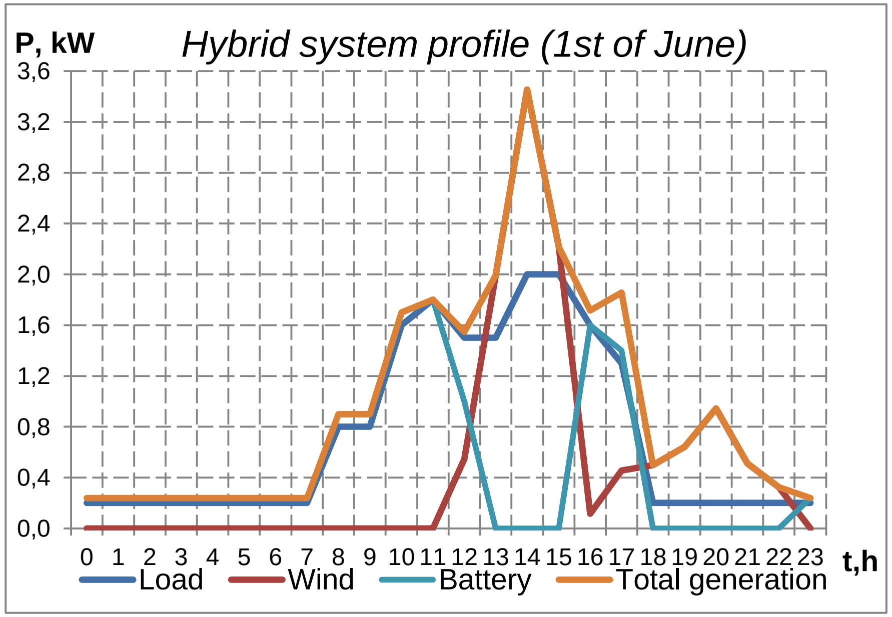
Appendix 5 – The total energy balance, 1st option

1st of December							1st of April							1st of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24
6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0,24	0,24
7	0,2	0	0	0	0,24	0,24	7	0,2	0,383	0	0	0,48	0,863	7	0,2	0	0	0	0,24	0,24
8	1,0	0,826	0	0	0	0,826	8	1	0,42	0	0	0,6	1,02	8	0,8	0	0	0	0,9	0,9
9	1,0	6,10	0	0	0	6,10	9	0,8	0,76	0	0	0,48	1,24	9	0,8	0	0	0	0,9	0,9
10	1,8	6,71	0	0	0	6,71	10	1,6	3,17	0	0	0	3,17	10	1,6	0	0	0	1,7	1,7
11	1,8	10,18	0	0	0	10,18	11	1,8	9,44	0	0	0	9,44	11	1,8	0	0	0	1,8	1,8
12	1,5	17,21	0	0	0	17,21	12	1,5	17,96	0	0	0	17,96	12	1,5	0,55	0	0	1	1,55
13	1,5	9,45	0	0	0	9,45	13	1,5	31,60	0	0	0	31,60	13	1,5	1,99	0	0	0	1,99
14	2,0	6,01	0	0	0	6,01	14	2	22,64	0	0	0	22,64	14	2	3,46	0	0	0	3,46
15	2,0	11,42	0	0	0	11,42	15	2	27,92	0	0	0	27,92	15	2	2,22	0	0	0	2,22
16	1,8	6,45	0	0	0	6,45	16	1,6	16,01	0	0	0	16,01	16	1,6	0,12	0	0	1,6	1,72
17	1,5	8,07	0	0	0	8,07	17	1,5	8,93	0	0	0	8,93	17	1,3	0,46	0	0	1,4	1,86
18	0,2	4,61	0	0	0	4,61	18	0,2	2,89	0	0	0	2,89	18	0,2	0,50	0	0	0	0,50
19	0,2	4,90	0	0	0	4,90	19	0,2	0,92	0	0	0	0,92	19	0,2	0,64	0	0	0	0,64
20	0,2	5,90	0	0	0	5,90	20	0,2	0,00	0	0	0	0,00	20	0,2	0,94	0	0	0	0,94
21	0,2	0,17	0	0	0,24	0,41	21	0,2	0	0	0	0,24	0,24	21	0,2	0,51	0	0	0	0,51
22	0,2	0,00	0	0	0,24	0,24	22	0,2	0	0	0	0,24	0,24	22	0,2	0,32	0	0	0	0,32
23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24	23	0,2	0,00	0	0	0,24	0,24
Sum, kWh	18,7					100,6	Sum, kWh	18,1					147	Sum, kWh	17,7					23,17

Appendix 5 – The total energy balance, 1st option (continuation)



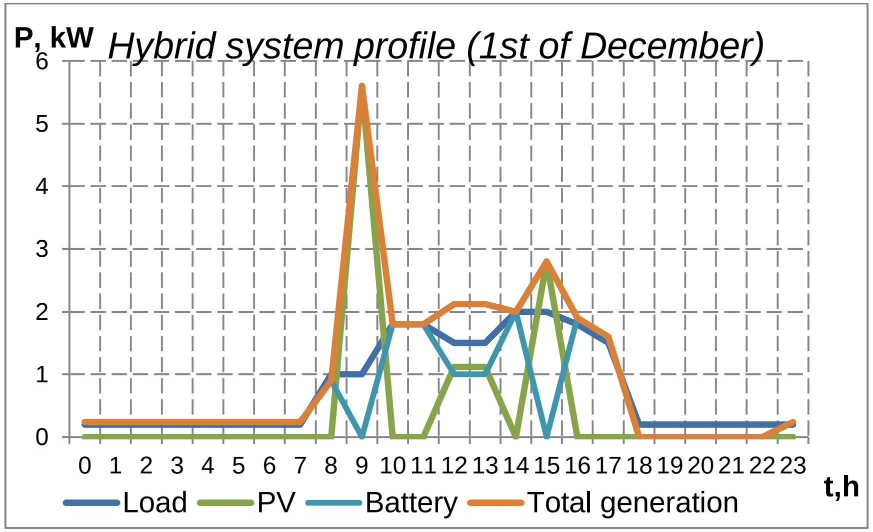


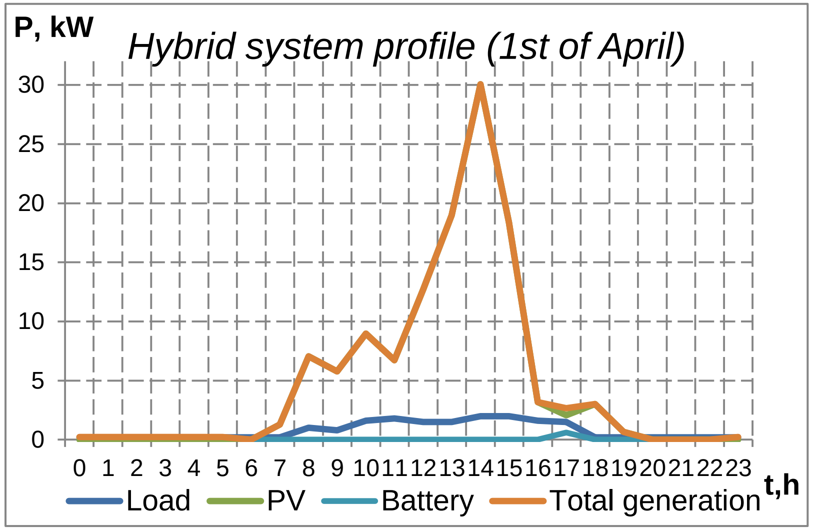


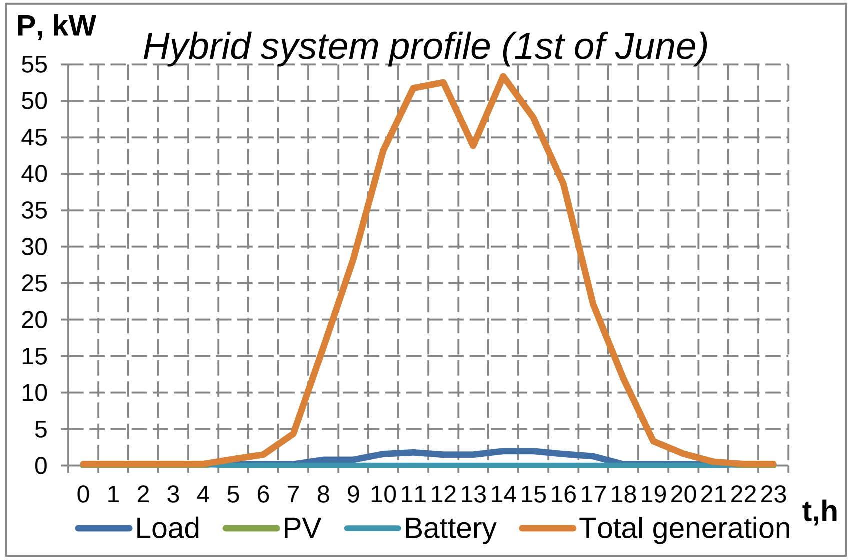
Appendix 6 – The total energy balance, 2nd option

1st of December							1st of April							1st of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24	5	0,2	0	0,90	0	0	0,90
6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0	0	6	0,2	0	1,51	0	0	1,51
7	0,2	0	0	0	0,24	0,24	7	0,2	0	1,29	0	0	1,29	7	0,2	0	4,37	0	0	4,37
8	1	0	0	0	0,9	0,9	8	1	0	7,06	0	0	7,06	8	0,8	0	16,18	0	0	16,18
9	1	0	5,6	0	0	5,6	9	0,8	0	5,77	0	0	5,77	9	0,8	0	28,22	0	0	28,22
10	1,8	0	0	0	1,8	1,8	10	1,6	0	8,96	0	0	8,96	10	1,6	0	43,18	0	0	43,18
11	1,8	0	0	0	1,8	1,8	11	1,8	0	6,72	0	0	6,72	11	1,8	0	51,74	0	0	51,74
12	1,5	0	1,12	0	1	2,12	12	1,5	0	12,71	0	0	12,71	12	1,5	0	52,53	0	0	52,53
13	1,5	0	1,12	0	1	2,12	13	1,5	0	18,98	0	0	18,98	13	1,5	0	43,85	0	0	43,85
14	2	0	0	0	2	2	14	2	0	30,07	0	0	30,07	14	2	0	53,37	0	0	53,37
15	2	0	2,8	0	0	2,8	15	2	0	18,37	0	0	18,37	15	2	0	47,71	0	0	47,71
16	1,8	0	0	0	1,9	1,9	16	1,6	0	3,19	0	0	3,19	16	1,6	0	38,64	0	0	38,64
17	1,5	0	0	0	1,6	1,6	17	1,5	0	2,07	0	0,6	2,67	17	1,3	0	22,12	0	0	22,12
18	0,2	0	0	0	0	0	18	0,2	0	3,02	0	0	3,02	18	0,2	0	11,98	0	0	11,98
19	0,2	0	0	0	0	0	19	0,2	0	0,67	0	0	0,67	19	0,2	0	3,36	0	0	3,36
20	0,2	0	0	0	0	0	20	0,2	0	0	0	0	0	20	0,2	0	1,62	0	0	1,624
21	0,2	0	0	0	0	0	21	0,2	0	0	0	0	0	21	0,2	0	0,56	0	0	0,56
22	0,2	0	0	0	0	0	22	0,2	0	0	0	0	0	22	0,2	0	0	0	0,24	0,24
23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24
Sum, kWh	18,7					24,8	Sum, kWh	18,1					121,1	Sum, kWh	17,7					423,5

Appendix 6– The total energy balance, 2^{nd} option (continuation)



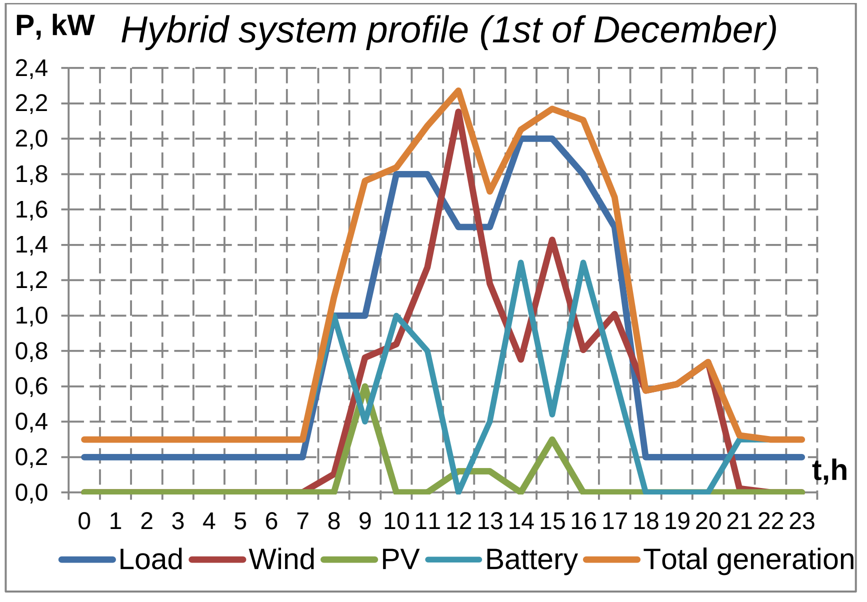


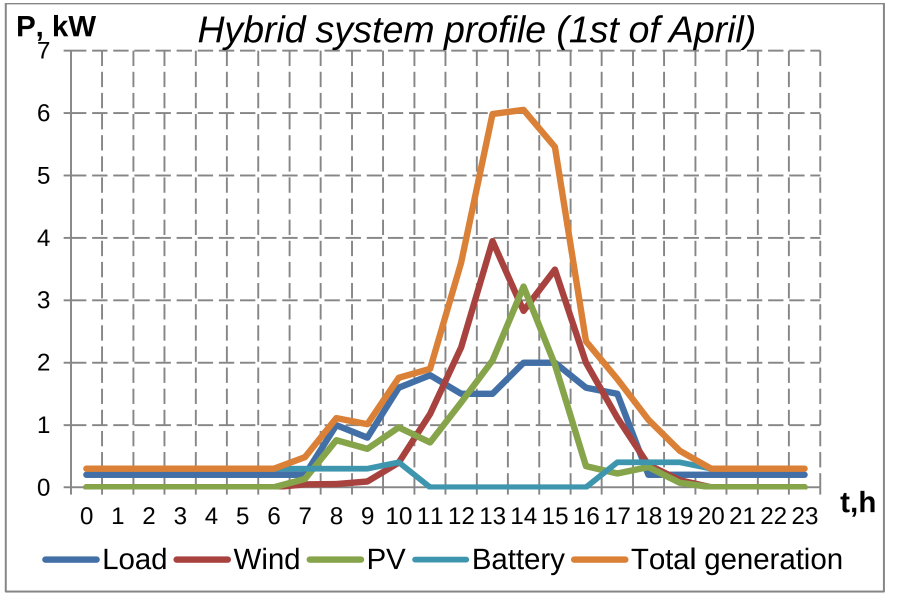


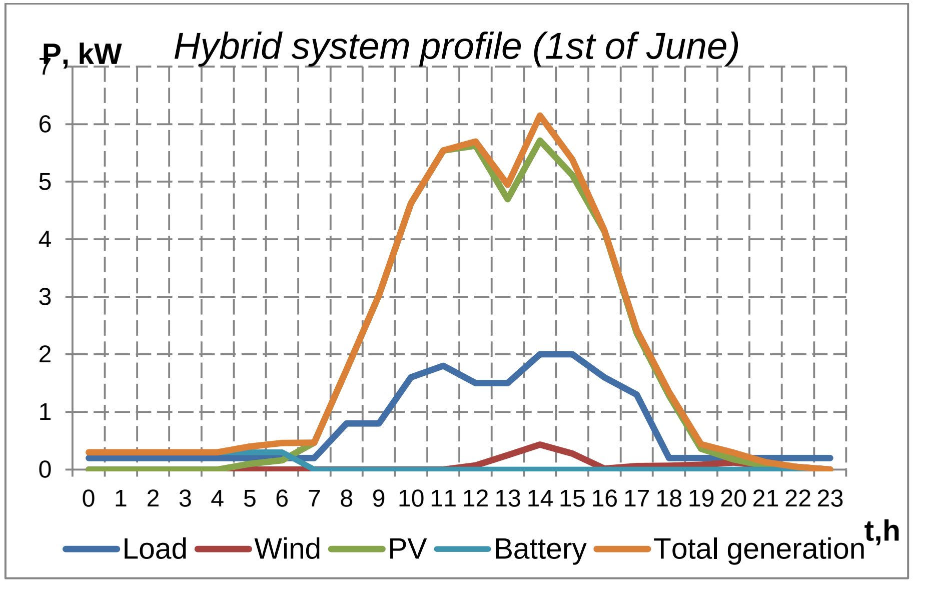
Appendix 7– The total energy balance, 3^{rd} option

1^{st} of December							1^{st} of April							1^{st} of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,3	0,3	0	0,2	0	0	0	0,3	0,3	0	0,2	0	0	0	0,3	0,3
1	0,2	0	0	0	0,3	0,3	1	0,2	0	0	0	0,3	0,3	1	0,2	0	0	0	0,3	0,3
2	0,2	0	0	0	0,3	0,3	2	0,2	0	0	0	0,3	0,3	2	0,2	0	0	0	0,3	0,3
3	0,2	0	0	0	0,3	0,3	3	0,2	0	0	0	0,3	0,3	3	0,2	0	0	0	0,3	0,3
4	0,2	0	0	0	0,3	0,3	4	0,2	0	0	0	0,3	0,3	4	0,2	0	0	0	0,3	0,3
5	0,2	0	0	0	0,3	0,3	5	0,2	0	0	0	0,3	0,3	5	0,2	0	0,10	0	0,3	0,40
6	0,2	0	0	0	0,3	0,3	6	0,2	0	0	0	0,3	0,3	6	0,2	0	0,16	0	0,3	0,46
7	0,2	0	0	0	0,3	0,3	7	0,2	0,05	0,14	0	0,3	0,49	7	0,2	0	0,47	0	0	0,47
8	1	0,10	0	0	1	1,10	8	1	0,05	0,76	0	0,3	1,11	8	0,8	0	1,73	0	0	1,73
9	1	0,76	0,6	0	0,4	1,76	9	0,8	0,10	0,62	0	0,3	1,01	9	0,8	0	3,02	0	0	3,02
10	1,8	0,84	0	0	1	1,84	10	1,6	0,40	0,96	0	0,4	1,76	10	1,6	0	4,63	0	0	4,63
11	1,8	1,27	0	0	0,8	2,07	11	1,8	1,18	0,72	0	0	1,9	11	1,8	0	5,54	0	0	5,54
12	1,5	2,15	0,12	0	0	2,27	12	1,5	2,25	1,36	0	0	3,61	12	1,5	0,07	5,63	0	0	5,70
13	1,5	1,18	0,12	0	0,4	1,70	13	1,5	3,95	2,03	0	0	5,98	13	1,5	0,25	4,70	0	0	4,95
14	2	0,75	0	0	1,3	2,05	14	2	2,83	3,22	0	0	6,05	14	2	0,43	5,72	0	0	6,15
15	2	1,43	0,3	0	0,44	2,17	15	2	3,49	1,97	0	0	5,46	15	2	0,28	5,11	0	0	5,39
16	1,8	0,81	0	0	1,3	2,11	16	1,6	2,00	0,34	0	0	2,34	16	1,6	0,01	4,14	0	0	4,15
17	1,5	1,01	0	0	0,66	1,67	17	1,5	1,12	0,22	0	0,4	1,74	17	1,3	0,06	2,37	0	0	2,43
18	0,2	0,58	0	0	0	0,58	18	0,2	0,36	0,32	0	0,4	1,09	18	0,2	0,06	1,28	0	0	1,35
19	0,2	0,61	0	0	0	0,61	19	0,2	0,12	0,07	0	0,4	0,59	19	0,2	0,08	0,36	0	0	0,44
20	0,2	0,74	0	0	0	0,74	20	0,2	0	0	0	0,3	0,3	20	0,2	0,12	0,17	0	0	0,29
21	0,2	0,02	0	0	0,3	0,32	21	0,2	0	0	0	0,3	0,3	21	0,2	0,06	0,06	0	0	0,12
22	0,2	0	0	0	0,3	0,3	22	0,2	0	0	0	0,3	0,3	22	0,2	0,04	0	0	0	0,04
23	0,2	0	0	0	0,3	0,3	23	0,2	0	0	0	0,3	0,3	23	0,2	0	0	0	0	0
Sum, kWh	18,7					23,99	Sum, kWh	18,1					36,42	Sum, kWh	17,7					48,76

Appendix 7 – The total energy balance, 3rd option (continuation)



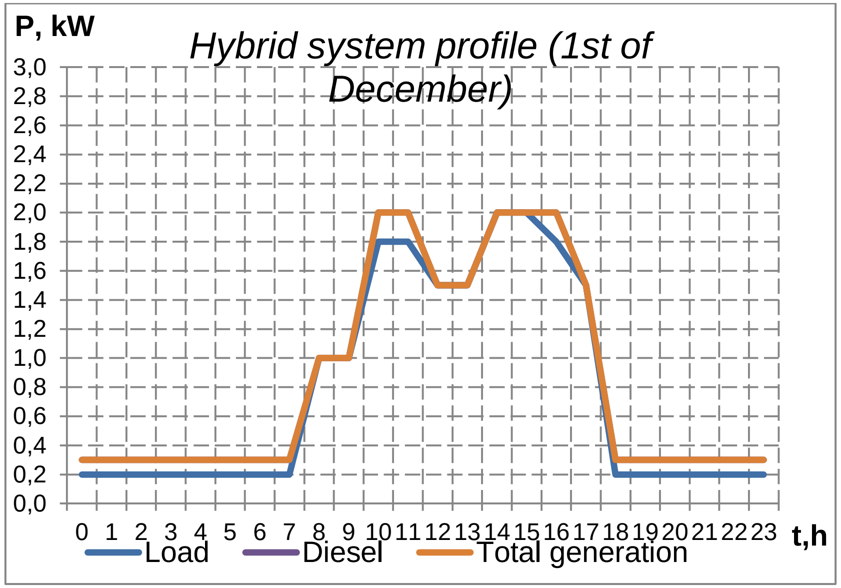


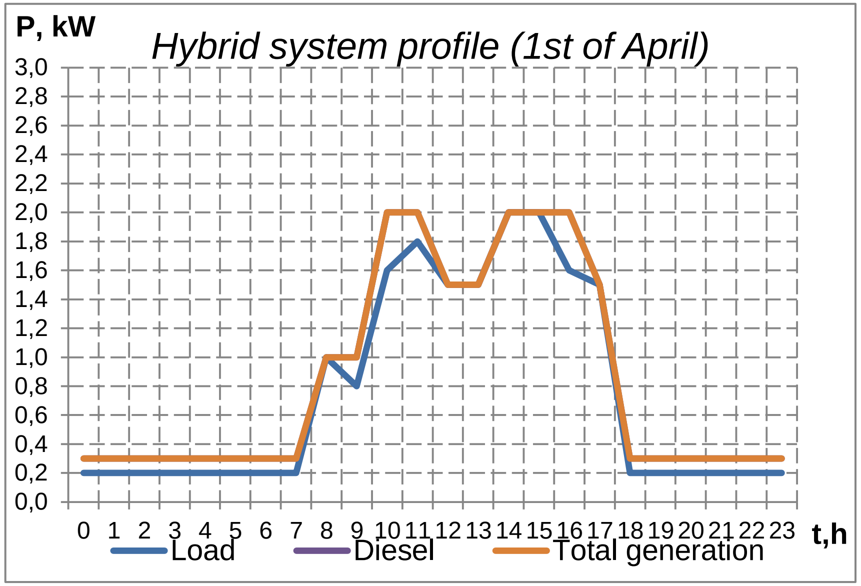


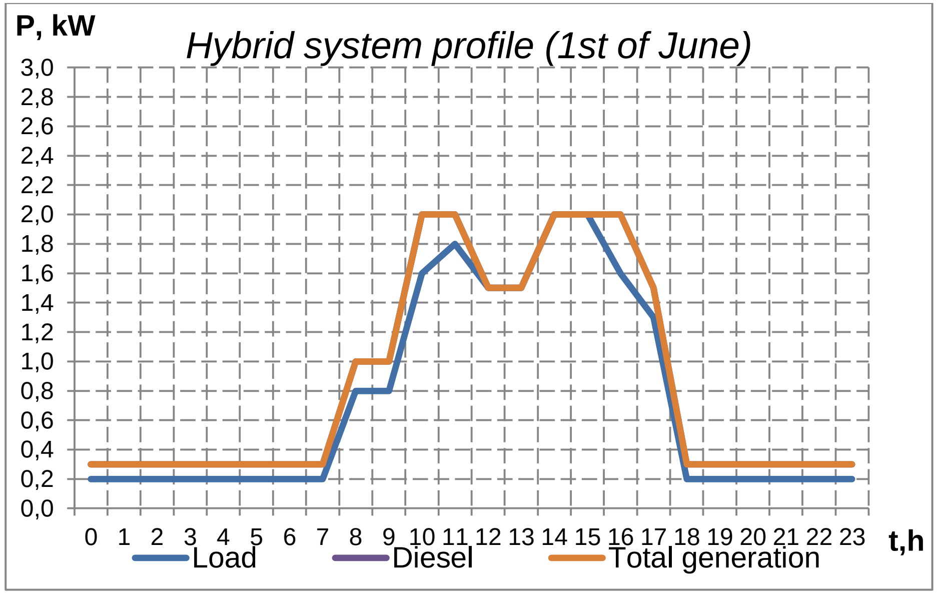
Appendix 8– The total energy balance, 4^{th} option

1^{st} of December							1^{st} of April							1^{st} of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0,3	0	0,3	0	0,2	0	0	0,3	0	0,3	0	0,2	0	0	0,3	0	0,3
1	0,2	0	0	0,3	0	0,3	1	0,2	0	0	0,3	0	0,3	1	0,2	0	0	0,3	0	0,3
2	0,2	0	0	0,3	0	0,3	2	0,2	0	0	0,3	0	0,3	2	0,2	0	0	0,3	0	0,3
3	0,2	0	0	0,3	0	0,3	3	0,2	0	0	0,3	0	0,3	3	0,2	0	0	0,3	0	0,3
4	0,2	0	0	0,3	0	0,3	4	0,2	0	0	0,3	0	0,3	4	0,2	0	0	0,3	0	0,3
5	0,2	0	0	0,3	0	0,3	5	0,2	0	0	0,3	0	0,3	5	0,2	0	0	0,3	0	0,3
6	0,2	0	0	0,3	0	0,3	6	0,2	0	0	0,3	0	0,3	6	0,2	0	0	0,3	0	0,3
7	0,2	0	0	0,3	0	0,3	7	0,2	0	0	0,3	0	0,3	7	0,2	0	0	0,3	0	0,3
8	1	0	0	1	0	1	8	1	0	0	1	0	1	8	0,8	0	0	1	0	1
9	1	0	0	1	0	1	9	0,8	0	0	1	0	1	9	0,8	0	0	1	0	1
10	1,8	0	0	2	0	2	10	1,6	0	0	2	0	2	10	1,6	0	0	2	0	2
11	1,8	0	0	2	0	2	11	1,8	0	0	2	0	2	11	1,8	0	0	2	0	2
12	1,5	0	0	1,5	0	1,5	12	1,5	0	0	1,5	0	1,5	12	1,5	0	0	1,5	0	1,5
13	1,5	0	0	1,5	0	1,5	13	1,5	0	0	1,5	0	1,5	13	1,5	0	0	1,5	0	1,5
14	2	0	0	2	0	2	14	2	0	0	2	0	2	14	2	0	0	2	0	2
15	2	0	0	2	0	2	15	2	0	0	2	0	2	15	2	0	0	2	0	2
16	1,8	0	0	2	0	2	16	1,6	0	0	2	0	2	16	1,6	0	0	2	0	2
17	1,5	0	0	1,5	0	1,5	17	1,5	0	0	1,5	0	1,5	17	1,3	0	0	1,5	0	1,5
18	0,2	0	0	0,3	0	0,3	18	0,2	0	0	0,3	0	0,3	18	0,2	0	0	0,3	0	0,3
19	0,2	0	0	0,3	0	0,3	19	0,2	0	0	0,3	0	0,3	19	0,2	0	0	0,3	0	0,3
20	0,2	0	0	0,3	0	0,3	20	0,2	0	0	0,3	0	0,3	20	0,2	0	0	0,3	0	0,3
21	0,2	0	0	0,3	0	0,3	21	0,2	0	0	0,3	0	0,3	21	0,2	0	0	0,3	0	0,3
22	0,2	0	0	0,3	0	0,3	22	0,2	0	0	0,3	0	0,3	22	0,2	0	0	0,3	0	0,3
23	0,2	0	0	0,3	0	0,3	23	0,2	0	0	0,3	0	0,3	23	0,2	0	0	0,3	0	0,3
Sum, kWh	18,7					20,7	Sum, kWh	18,1					20,7	Sum, kWh	17,7					20,7

Appendix 8 – The total energy balance, 4th option (continuation)



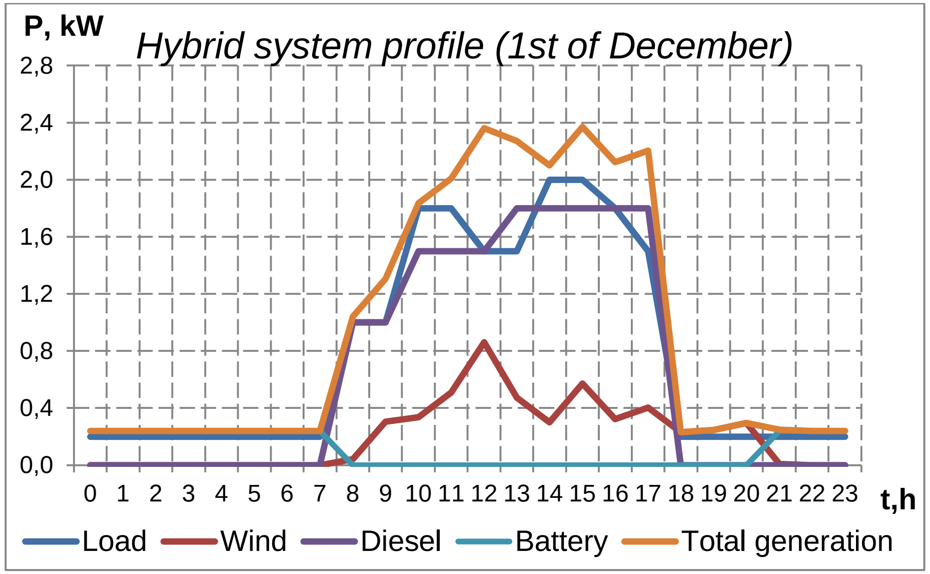


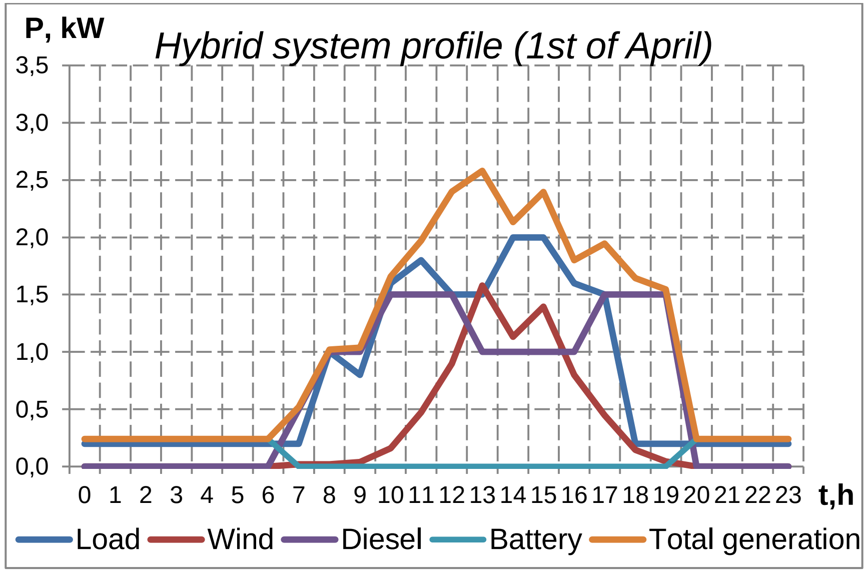


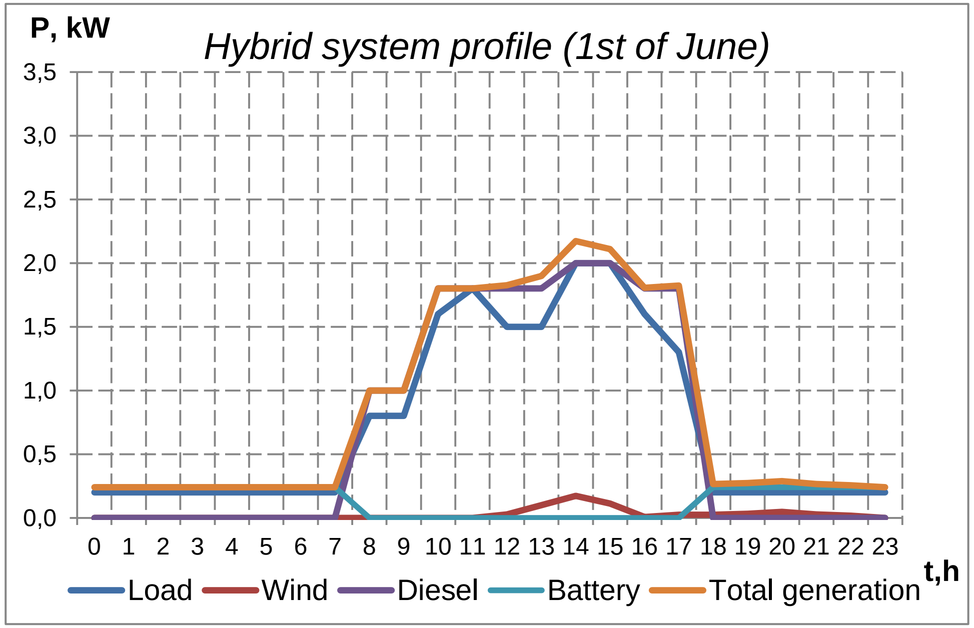
Appendix 9 – The total energy balance, 5th option

1st of December							1st of April							1st of June						
T,h	Load	Wind	PV	Diesel	Battery	Total generation	T,h	Load	Wind	PV	Diesel	Battery	Total generation	T,h	Load	Wind	PV	Diesel	Battery	Total generation
0	0,2	0	0	0	0,24	0,24	0	0,2	0,00	0,00	0,00	0,24	0,24	0	0,2	0,00	0,00	0,00	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0,00	0,00	0,00	0,24	0,24	1	0,2	0,00	0,00	0,00	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0,00	0,00	0,00	0,24	0,24	2	0,2	0,00	0,00	0,00	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0,00	0,00	0,00	0,24	0,24	3	0,2	0,00	0,00	0,00	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0,00	0,00	0,00	0,24	0,24	4	0,2	0,00	0,00	0,00	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0,00	0,00	0,00	0,24	0,24	5	0,2	0,00	0,00	0,00	0,24	0,24
6	0,2	0	0	0	0,24	0,24	6	0,2	0,00	0,00	0,00	0,24	0,24	6	0,2	0,00	0,00	0,00	0,24	0,24
7	0,2	0	0	0	0,24	0,24	7	0,2	0,02	0,00	0,50	0,00	0,52	7	0,2	0,00	0,00	0,00	0,24	0,24
8	1	0,04	0	1	0	1,04	8	1	0,02	0,00	1,00	0,00	1,02	8	0,8	0,00	0,00	1,00	0,00	1,00
9	1	0,30	0	1	0	1,30	9	0,8	0,04	0,00	1,00	0,00	1,04	9	0,8	0,00	0,00	1,00	0,00	1,00
10	1,8	0,34	0	1,5	0	1,84	10	1,6	0,16	0,00	1,50	0,00	1,66	10	1,6	0,00	0,00	1,80	0,00	1,80
11	1,8	0,51	0	1,5	0	2,01	11	1,8	0,47	0,00	1,50	0,00	1,97	11	1,8	0,00	0,00	1,80	0,00	1,80
12	1,5	0,86	0	1,5	0	2,36	12	1,5	0,90	0,00	1,50	0,00	2,40	12	1,5	0,03	0,00	1,80	0,00	1,83
13	1,5	0,47	0	1,8	0	2,27	13	1,5	1,58	0,00	1,00	0,00	2,58	13	1,5	0,10	0,00	1,80	0,00	1,90
14	2	0,30	0	1,8	0	2,10	14	2	1,13	0,00	1,00	0,00	2,13	14	2	0,17	0,00	2,00	0,00	2,17
15	2	0,57	0	1,8	0	2,37	15	2	1,40	0,00	1,00	0,00	2,40	15	2	0,11	0,00	2,00	0,00	2,11
16	1,8	0,32	0	1,8	0	2,12	16	1,6	0,80	0,00	1,00	0,00	1,80	16	1,6	0,01	0,00	1,80	0,00	1,81
17	1,5	0,40	0	1,8	0	2,20	17	1,5	0,45	0,00	1,50	0,00	1,95	17	1,3	0,02	0,00	1,80	0,00	1,82
18	0,2	0,23	0	0	0	0,23	18	0,2	0,14	0,00	1,50	0,00	1,64	18	0,2	0,02	0,00	0,00	0,24	0,26
19	0,2	0,25	0	0	0	0,25	19	0,2	0,05	0,00	1,50	0,00	1,55	19	0,2	0,03	0,00	0,00	0,24	0,27
20	0,2	0,30	0	0	0	0,30	20	0,2	0,00	0,00	0,00	0,24	0,24	20	0,2	0,05	0,00	0,00	0,24	0,29
21	0,2	0,01	0	0	0,24	0,25	21	0,2	0,00	0,00	0,00	0,24	0,24	21	0,2	0,03	0,00	0,00	0,24	0,27
22	0,2	0	0	0	0,24	0,24	22	0,2	0,00	0,00	0,00	0,24	0,24	22	0,2	0,02	0,00	0,00	0,24	0,26
23	0,2	0	0	0	0,24	0,24	23	0,2	0,00	0,00	0,00	0,24	0,24	23	0,2	0,00	0,00	0,00	0,24	0,24
Sum, kWh	18,7					23,04	Sum, kWh	18,1					25,29	Sum, kWh	17,7					20,75

Appendix 9 – The total energy balance, 5th option (continuation)



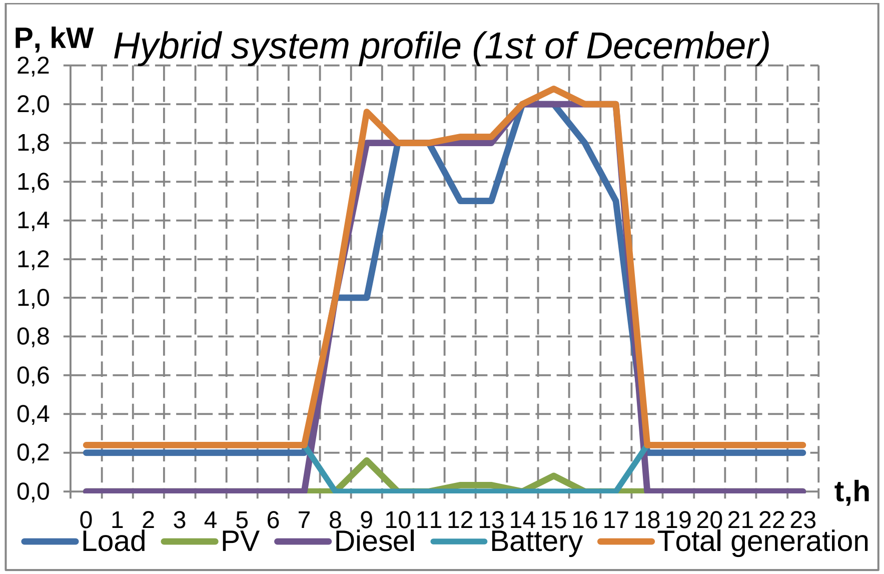


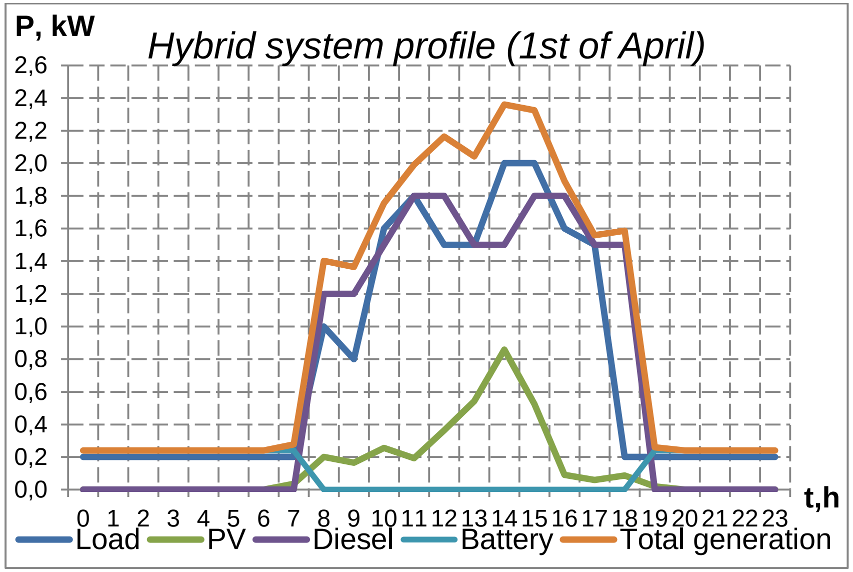


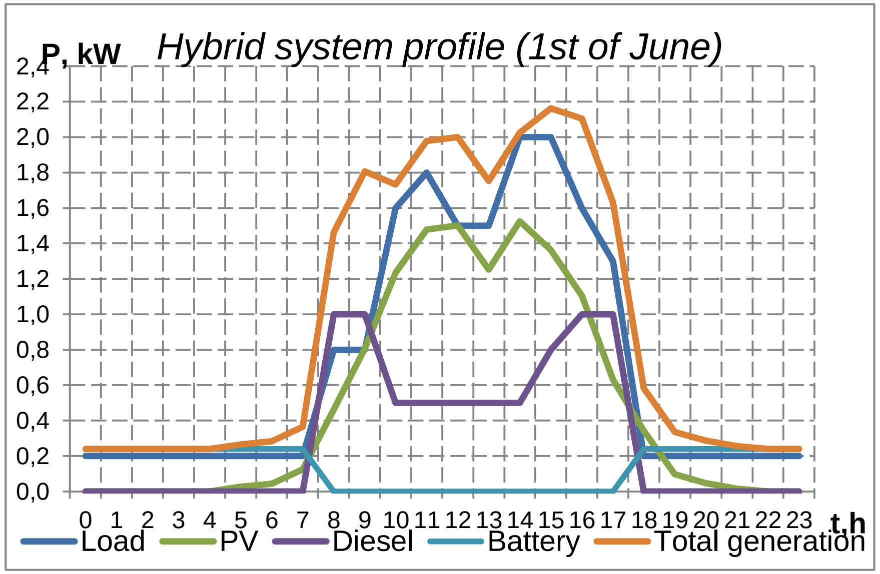
Appendix 10– The total energy balance, 6th option

1st of December							1st of April							1st of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24	5	0,2	0	0,03	0	0,24	0,27
6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0,24	0,24	6	0,2	0	0,04	0	0,24	0,28
7	0,2	0	0	0	0,24	0,24	7	0,2	0	0,037	0	0,24	0,28	7	0,2	0	0,12	0	0,24	0,36
8	1	0	0	1	0	1	8	1	0	0,202	1,2	0	1,40	8	0,8	0	0,46	1	0	1,46
9	1	0	0,16	1,8	0	1,96	9	0,8	0	0,165	1,2	0	1,36	9	0,8	0	0,81	1	0	1,81
10	1,8	0	0	1,8	0	1,8	10	1,6	0	0,256	1,5	0	1,76	10	1,6	0	1,23	0,5	0	1,73
11	1,8	0	0	1,8	0	1,8	11	1,8	0	0,192	1,8	0	1,99	11	1,8	0	1,48	0,5	0	1,98
12	1,5	0	0,032	1,8	0	1,832	12	1,5	0	0,363	1,8	0	2,16	12	1,5	0	1,50	0,5	0	2,00
13	1,5	0	0,032	1,8	0	1,832	13	1,5	0	0,542	1,5	0	2,04	13	1,5	0	1,25	0,5	0	1,75
14	2	0	0	2	0	2	14	2	0	0,859	1,5	0	2,36	14	2	0	1,52	0,5	0	2,02
15	2	0	0,08	2	0	2,08	15	2	0	0,525	1,8	0	2,32	15	2	0	1,36	0,8	0	2,16
16	1,8	0	0	2	0	2	16	1,6	0	0,091	1,8	0	1,89	16	1,6	0	1,10	1	0	2,10
17	1,5	0	0	2	0	2	17	1,5	0	0,059	1,5	0	1,56	17	1,3	0	0,63	1	0	1,63
18	0,2	0	0	0	0,24	0,24	18	0,2	0	0,086	1,5	0	1,59	18	0,2	0	0,34	0	0,24	0,58
19	0,2	0	0	0	0,24	0,24	19	0,2	0	0,019	0	0,24	0,26	19	0,2	0	0,10	0	0,24	0,34
20	0,2	0	0	0	0,24	0,24	20	0,2	0	0	0	0,24	0,24	20	0,2	0	0,05	0	0,24	0,29
21	0,2	0	0	0	0,24	0,24	21	0,2	0	0	0	0,24	0,24	21	0,2	0	0,02	0	0,24	0,26
22	0,2	0	0	0	0,24	0,24	22	0,2	0	0	0	0,24	0,24	22	0,2	0	0	0	0,24	0,24
23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24
Sum, kWh	18,7					21,66	Sum, kWh	18,1					23,62	Sum, kWh	17,7					22,71

Appendix 10– The total energy balance, 6th option (continuation)



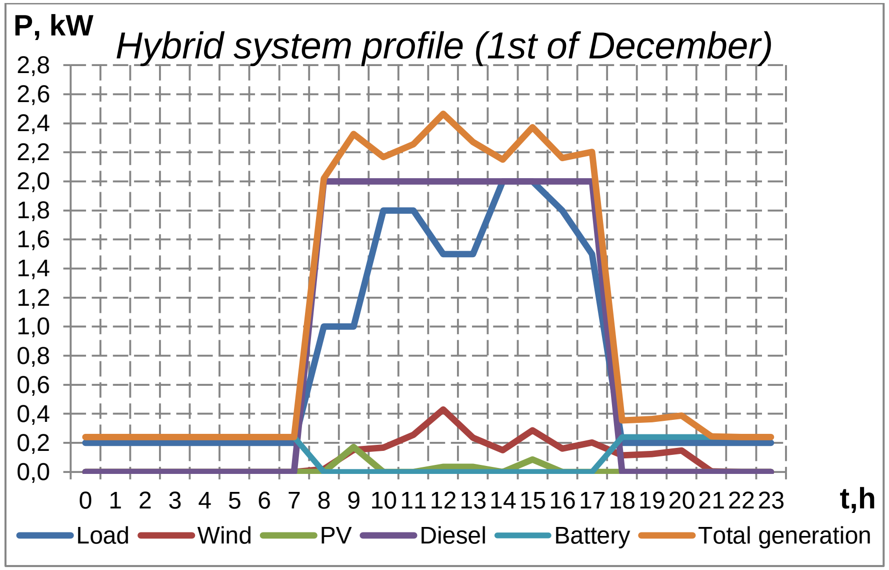


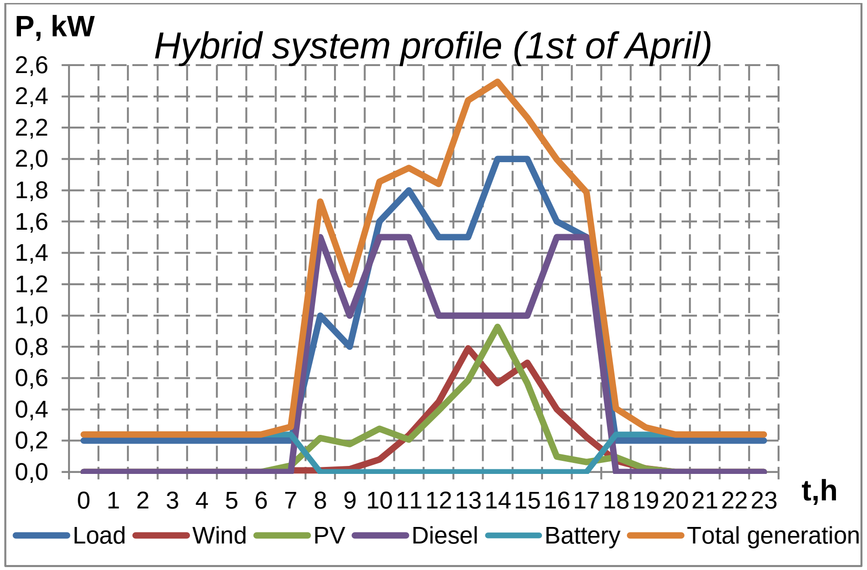


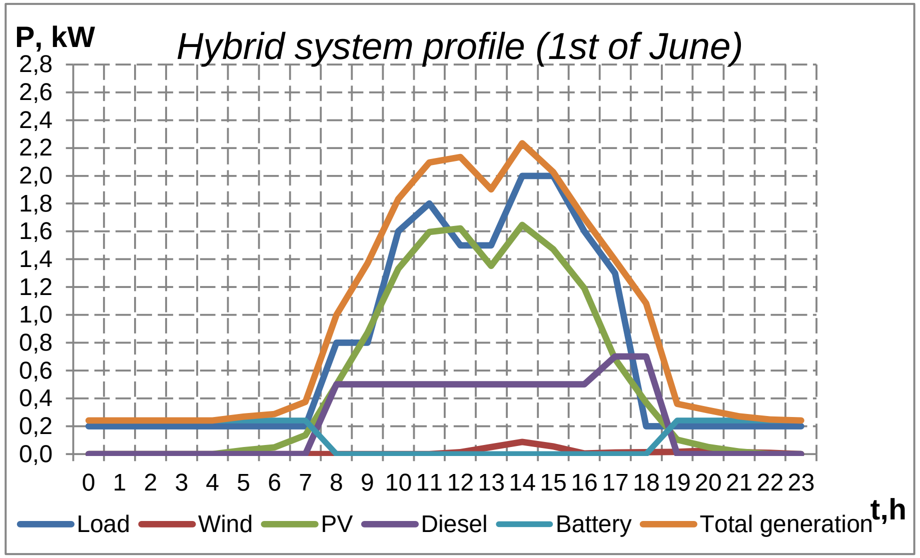
Appendix 11– The total energy balance, 7^{th} option

1^{st} of December							1^{st} of April							1^{st} of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24	5	0,2	0	0,028	0	0,24	0,27
6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0,24	0,24	6	0,2	0	0,047	0	0,24	0,29
7	0,2	0	0	0	0,24	0,24	7	0,2	0,01	0,04	0	0,24	0,289	7	0,2	0	0,135	0	0,24	0,37
8	1	0,021	0	2	0	2,02	8	1	0,01	0,22	1,5	0	1,728	8	0,8	0	0,499	0,5	0	1,00
9	1	0,152	0,173	2	0	2,33	9	0,8	0,02	0,18	1	0	1,197	9	0,8	0	0,871	0,5	0	1,37
10	1,8	0,168	0	2	0	2,17	10	1,6	0,08	0,28	1,5	0	1,856	10	1,6	0	1,332	0,5	0	1,83
11	1,8	0,255	0	2	0	2,25	11	1,8	0,24	0,21	1,5	0	1,943	11	1,8	0	1,597	0,5	0	2,10
12	1,5	0,43	0,035	2	0	2,46	12	1,5	0,45	0,39	1	0	1,841	12	1,5	0,01	1,621	0,5	0	2,13
13	1,5	0,236	0,035	2	0	2,27	13	1,5	0,79	0,59	1	0	2,376	13	1,5	0,05	1,353	0,5	0	1,90
14	2	0,15	0	2	0	2,15	14	2	0,57	0,93	1	0	2,494	14	2	0,09	1,647	0,5	0	2,23
15	2	0,286	0,086	2	0	2,37	15	2	0,70	0,57	1	0	2,265	15	2	0,06	1,472	0,5	0	2,03
16	1,8	0,161	0	2	0	2,16	16	1,6	0,40	0,10	1,5	0	1,999	16	1,6	0,00	1,192	0,5	0	1,70
17	1,5	0,202	0	2	0	2,20	17	1,5	0,22	0,06	1,5	0	1,787	17	1,3	0,01	0,683	0,7	0	1,39
18	0,2	0,115	0	0	0,24	0,36	18	0,2	0,07	0,09	0	0,24	0,406	18	0,2	0,01	0,37	0,7	0	1,08
19	0,2	0,123	0	0	0,24	0,36	19	0,2	0,02	0,02	0	0,24	0,284	19	0,2	0,02	0,104	0	0,24	0,36
20	0,2	0,148	0	0	0,24	0,39	20	0,2	0	0	0	0,24	0,24	20	0,2	0,02	0,05	0	0,24	0,31
21	0,2	0,004	0	0	0,24	0,24	21	0,2	0	0	0	0,24	0,24	21	0,2	0,01	0,017	0	0,24	0,27
22	0,2	0	0	0	0,24	0,24	22	0,2	0	0	0	0,24	0,24	22	0,2	0,01	0	0	0,24	0,25
23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24
Sum, kWh	18,7					26,14	Sum, kWh	18,1					23,1	Sum, kWh	17,7					22,32971

Appendix 11 – The total energy balance, 7th option (continuation)



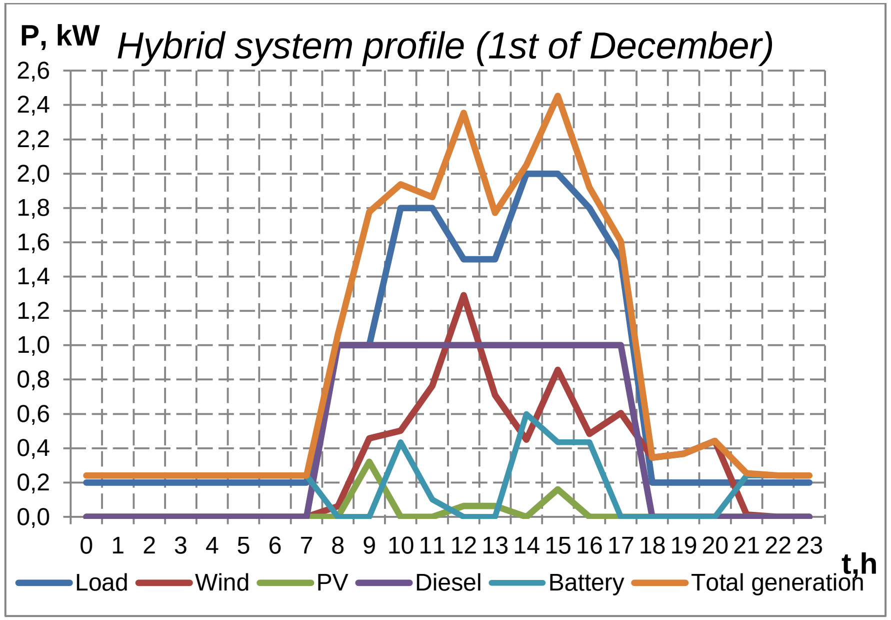


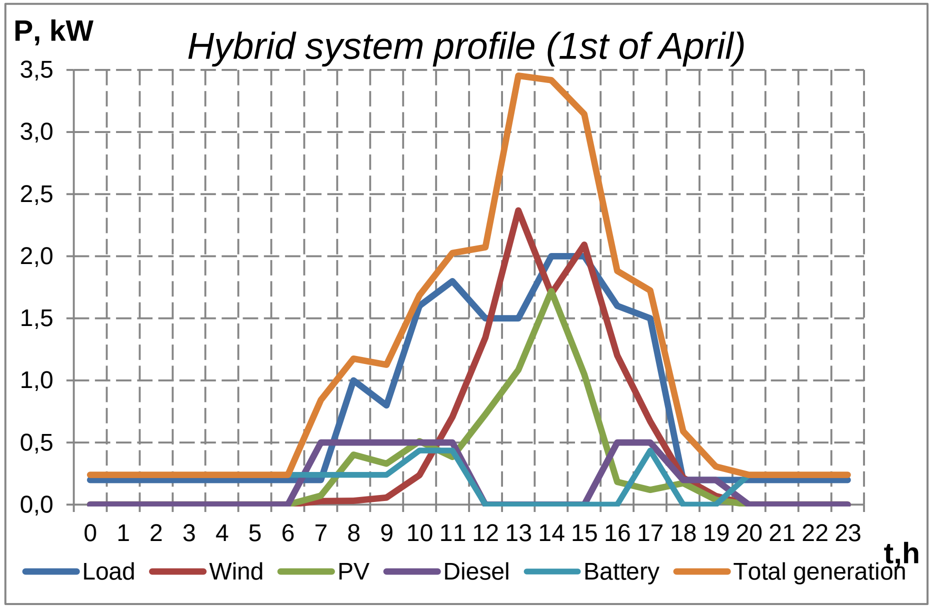


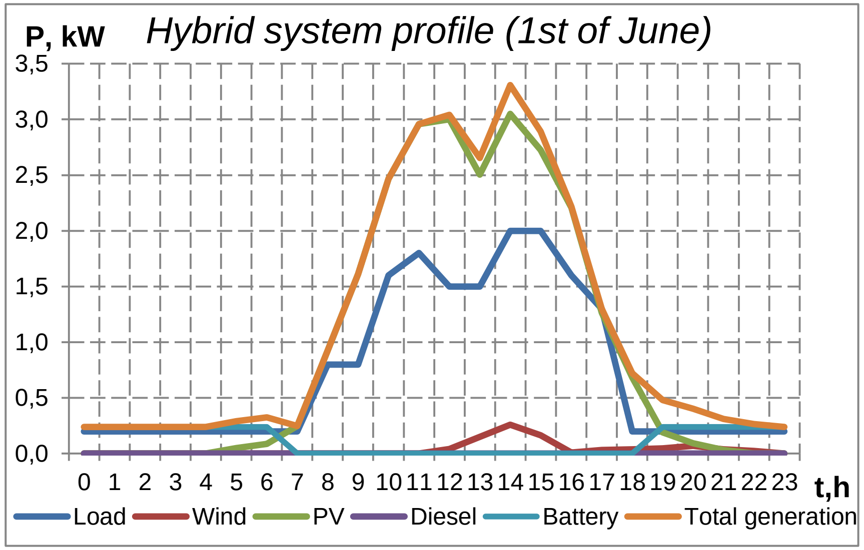
Appendix 12 – The total energy balance, 8th option

1st of December							1st of April							1st of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24	5	0,2	0	0,051	0	0,24	0,29
6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0,24	0,24	6	0,2	0	0,086	0	0,24	0,33
7	0,2	0	0	0	0,24	0,24	7	0,2	0,029	0,074	0,5	0,24	0,842	7	0,2	0	0,25	0	0	0,25
8	1	0,062	0	1	0	1,06	8	1	0,031	0,403	0,5	0,24	1,175	8	0,8	0	0,925	0	0	0,92
9	1	0,457	0,32	1	0	1,78	9	0,8	0,057	0,33	0,5	0,24	1,127	9	0,8	0	1,613	0	0	1,61
10	1,8	0,503	0	1	0,44	1,94	10	1,6	0,237	0,512	0,5	0,44	1,685	10	1,6	0	2,467	0	0	2,47
11	1,8	0,764	0	1	0,1	1,86	11	1,8	0,708	0,384	0,5	0,44	2,027	11	1,8	0	2,957	0	0	2,96
12	1,5	1,291	0,064	1	0	2,35	12	1,5	1,347	0,726	0	0	2,073	12	1,5	0,04	3,002	0	0	3,04
13	1,5	0,709	0,064	1	0	1,77	13	1,5	2,37	1,085	0	0	3,455	13	1,5	0,15	2,506	0	0	2,66
14	2	0,451	0	1	0,6	2,05	14	2	1,698	1,718	0	0	3,417	14	2	0,26	3,05	0	0	3,31
15	2	0,857	0,16	1	0,44	2,45	15	2	2,094	1,05	0	0	3,144	15	2	0,17	2,726	0	0	2,89
16	1,8	0,484	0	1	0,44	1,92	16	1,6	1,201	0,182	0,5	0	1,883	16	1,6	0,01	2,208	0	0	2,22
17	1,5	0,605	0	1	0	1,61	17	1,5	0,67	0,118	0,5	0,4356	1,724	17	1,3	0,03	1,264	0	0	1,30
18	0,2	0,346	0	0	0	0,35	18	0,2	0,217	0,173	0,2	0	0,59	18	0,2	0,04	0,685	0	0	0,72
19	0,2	0,368	0	0	0	0,37	19	0,2	0,069	0,038	0,2	0	0,308	19	0,2	0,05	0,192	0	0,24	0,48
20	0,2	0,443	0	0	0	0,44	20	0,2	0	0	0	0,24	0,24	20	0,2	0,07	0,093	0	0,24	0,40
21	0,2	0,013	0	0	0,24	0,25	21	0,2	0	0	0	0,24	0,24	21	0,2	0,04	0,032	0	0,24	0,31
22	0,2	0	0	0	0,24	0,24	22	0,2	0	0	0	0,24	0,24	22	0,2	0,02	0	0	0,24	0,26
23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24
Sum, kWh	18,7					22,6	Sum, kWh	18,1					26,09	Sum, kWh	17,7					27,86366

Appendix 12– The total energy balance, 8th option (continuation)



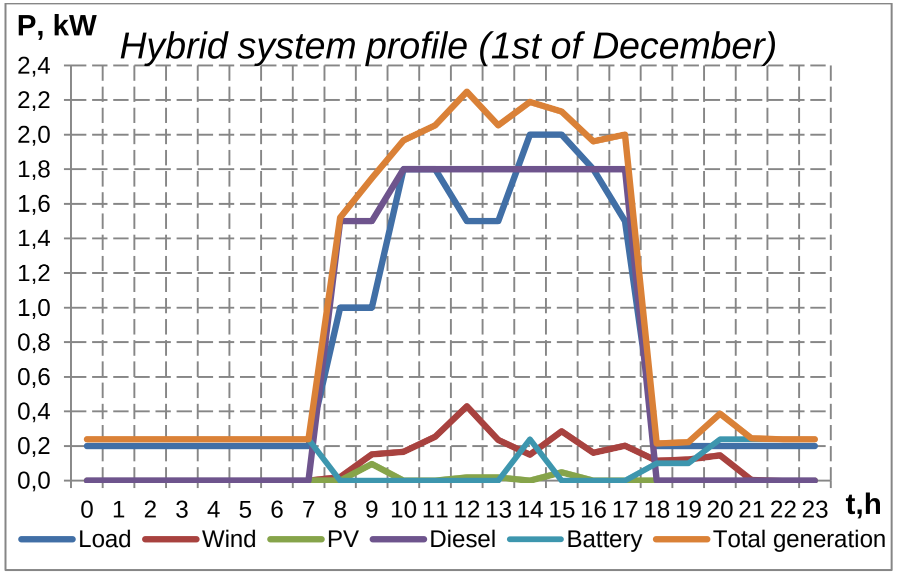


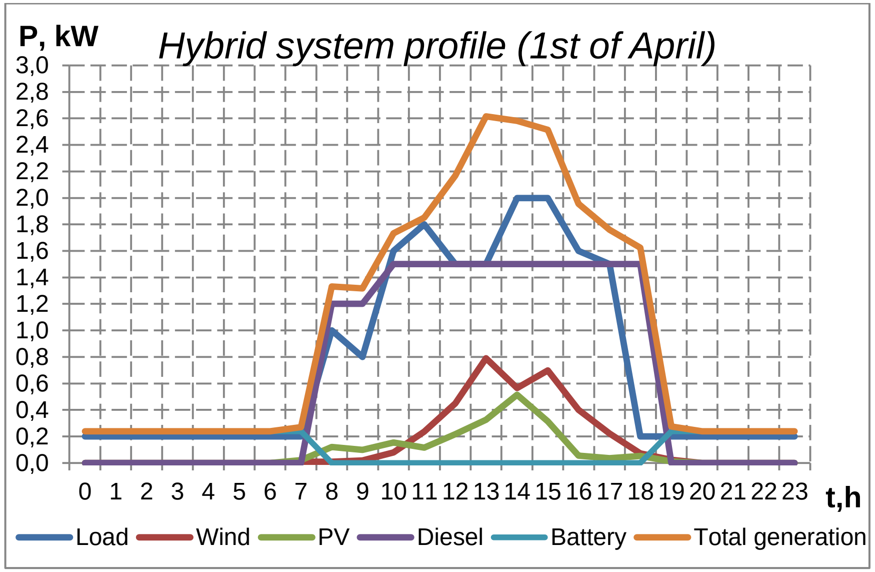


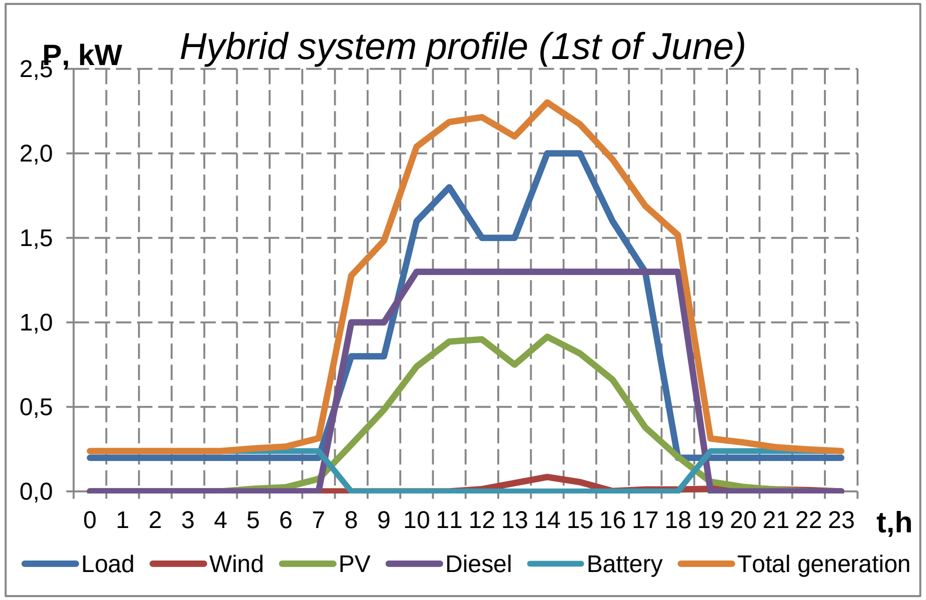
Appendix 13 – The total energy balance, 9th option

1st of December							1st of April							1st of June						
T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration	T,h	Load	Wind	PV	Diesel	Batte-ry	Total gene-ration
0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24	0	0,2	0	0	0	0,24	0,24
1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24	1	0,2	0	0	0	0,24	0,24
2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24	2	0,2	0	0	0	0,24	0,24
3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24	3	0,2	0	0	0	0,24	0,24
4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24	4	0,2	0	0	0	0,24	0,24
5	0,2	0	0	0	0,24	0,24	5	0,2	0	0	0	0,24	0,24	5	0,2	0	0,015	0	0,24	0,26
6	0,2	0	0	0	0,24	0,24	6	0,2	0	0	0	0,24	0,24	6	0,2	0	0,026	0	0,24	0,27
7	0,2	0	0	0	0,24	0,24	7	0,2	0,01	0,022	0	0,24	0,272	7	0,2	0	0,075	0	0,24	0,31
8	1	0,021	0	1,5	0	1,52	8	1	0,01	0,121	1,2	0	1,331	8	0,8	0	0,277	1	0	1,28
9	1	0,152	0,096	1,5	0	1,75	9	0,8	0,019	0,099	1,2	0	1,318	9	0,8	0	0,484	1	0	1,48
10	1,8	0,168	0	1,8	0	1,97	10	1,6	0,079	0,154	1,5	0	1,733	10	1,6	0	0,74	1,3	0	2,04
11	1,8	0,255	0	1,8	0	2,05	11	1,8	0,236	0,115	1,5	0	1,851	11	1,8	0	0,887	1,3	0	2,19
12	1,5	0,43	0,019	1,8	0	2,25	12	1,5	0,449	0,218	1,5	0	2,167	12	1,5	0,01	0,9	1,3	0	2,21
13	1,5	0,236	0,019	1,8	0	2,06	13	1,5	0,79	0,325	1,5	0	2,615	13	1,5	0,05	0,752	1,3	0	2,10
14	2	0,15	0	1,8	0,24	2,19	14	2	0,566	0,516	1,5	0	2,582	14	2	0,09	0,915	1,3	0	2,30
15	2	0,286	0,048	1,8	0	2,13	15	2	0,698	0,315	1,5	0	2,513	15	2	0,06	0,818	1,3	0	2,17
16	1,8	0,161	0	1,8	0	1,96	16	1,6	0,4	0,055	1,5	0	1,955	16	1,6	0,00	0,662	1,3	0	1,97
17	1,5	0,202	0	1,8	0	2,00	17	1,5	0,223	0,036	1,5	0	1,759	17	1,3	0,01	0,379	1,3	0	1,69
18	0,2	0,115	0	0	0,1	0,22	18	0,2	0,072	0,052	1,5	0	1,624	18	0,2	0,01	0,205	1,3	0	1,52
19	0,2	0,123	0	0	0,1	0,22	19	0,2	0,023	0,012	0	0,24	0,275	19	0,2	0,02	0,058	0	0,24	0,31
20	0,2	0,148	0	0	0,24	0,39	20	0,2	0	0	0	0,24	0,24	20	0,2	0,02	0,028	0	0,24	0,29
21	0,2	0,004	0	0	0,24	0,24	21	0,2	0	0	0	0,24	0,24	21	0,2	0,01	0,01	0	0,24	0,26
22	0,2	0	0	0	0,24	0,24	22	0,2	0	0	0	0,24	0,24	22	0,2	0,01	0	0	0,24	0,25
23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24	23	0,2	0	0	0	0,24	0,24
Sum, kWh	18,7					23,35	Sum, kWh	18,1					24,63	Sum, kWh	17,7					24,34437

Appendix 13 – The total energy balance, 9th option (continuation)

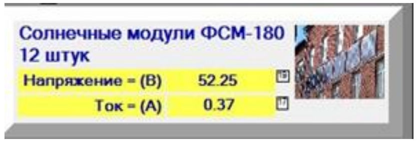






Appendix 14 – Instruments data of a system, laboratory № 225, TPU, 13.09.2014

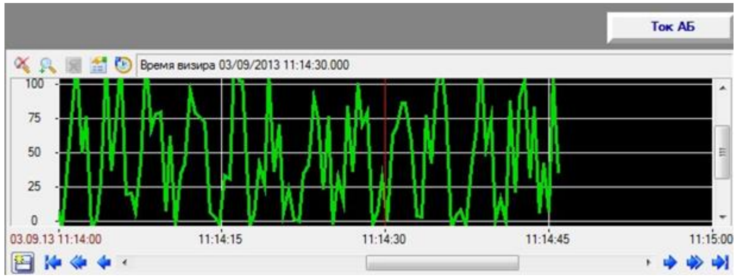
A)



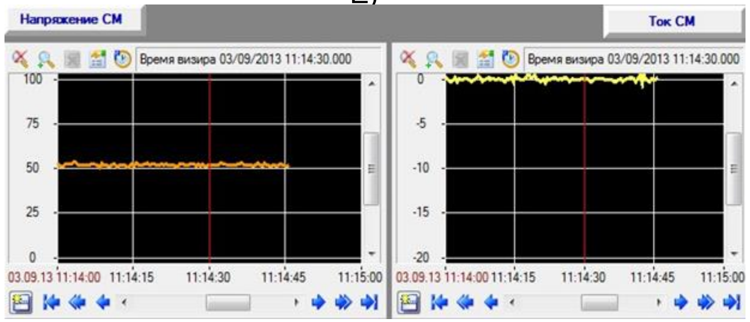
B)

C)

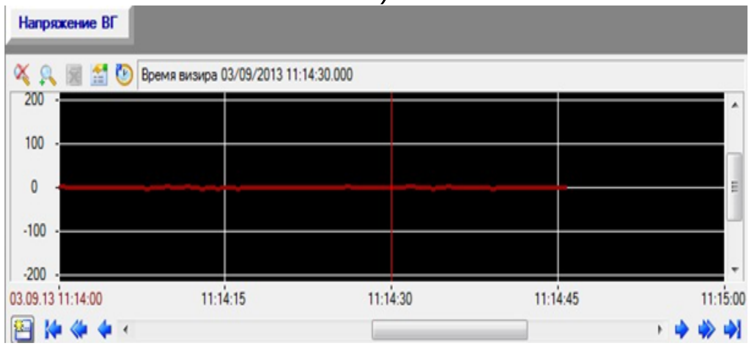
D)



E)



F)



G)

A) Reading of invertor output and network B) Reading of PV panels values C) Reading of battery values D) Reading of wind generator values
E) Oscillogram of battery discharging current F) Oscillograms of voltage and current of PV panels G) Oscillogram of wind generator voltage

Appendix 15 – Economic model of system (8^{th} option)

Primary data		**Investments**			***Operating costs for 1st year***		***Escalation rates***
Minimum price on electricity, €/kWh	0,4721 €	1.	*Wind*		Maintanace, euro	343,2	0,055
Tax rate	0,13		Installed power,kW	3	Fuel price,euro/liter	0,7	
Discount rate	0,11614		Specific cost, €/kW	1700	Fuel consumption,liter/kWh	0,3	
Electricity produced	6642,4		Inv costs, €	5100	Fuel costs for 1st year,euro	340,9	0,065
		2.	*PV*		Nominal wages, euro	591,4	
			Installed power,kW	4	Regional coefficient	1,3	
			Specific costs,€/kW	2200	Wages costs for 1st year, euro	768,8	0,078
			Inv costs, €	8800			
		3.	*Diesel*				
			Installed power,kW	**1**			
			Electricity produced by diesel,kWh	1623,7			
			Specific costs, €/kW	600			
			Inv costs,€	***600***			
		4.	*Battery*				
			Battery capacity,Ah	200			
			Specific costs, €/Ah	1,7			
			Battery cost,€	340			

Appendix 15 – Economic model of system (continuation)

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Capital investments																					
Wind	5100																				
PV	8800																				
Diesel	600																				
Battery	340										340										
Invertor	1390																				
Controller	512										512										
Other equipment	250																				
Design and construction	169,9																				
Total for year	*17161,9*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*852*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Total	***18013,9***																				
Operational costs																					
M&R	0	343	366	389	415	442	470	501	533	568	605	644	686	731	778	829	883	940	1001	1066	1136
Fuel	0	341	363	387	412	439	467	498	530	564	601	640	682	726	773	823	877	934	995	1059	1128
Wages	0	769	829	893	963	1038	1119	1207	1301	1402	1511	1629	1756	1893	2041	2200	2372	2557	2756	2971	3203
Depreciation	*0*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*	*901*
Total operational costs	*0*	*2354*	*2458*	*2570*	*2690*	*2819*	*2957*	*3106*	*3265*	*3435*	*3618*	*3814*	*4025*	*4251*	*4493*	*4753*	*5032*	*5332*	*5653*	*5998*	*6368*
Revenues	0	3136	3326	3527	3741	3967	4207	4461	4731	5018	5321	5643	5984	6346	6730	7138	7569	8027	8513	9028	9574
EBT,euro	0	782	868	957	1050	1148	1249	1356	1467	1582	1703	1829	1959	2096	2237	2384	2537	2696	2860	3030	3207
Taxes,euro	0	156	174	191	210	230	250	271	293	316	341	366	392	419	447	477	507	539	572	606	641
EAT,euro	0	626	694	766	840	918	1000	1085	1173	1266	1362	1463	1568	1676	1790	1907	2030	2157	2288	2424	2565
CF,euro	-17162	1527	1595	1666	1741	1819	1900	1985	2074	2167	1411	2364	2468	2577	2690	2808	2930	3057	3189	3325	3466
Present value of CF, euro	-17162	1527	1429	1338	1252	1172	1097	1027	961	900	525	788	737	689	645	603	564	527	492	460	430
NPV	**0**																				