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Федеральное государственное автономное образовательное учреждение
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**«НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ»
/ NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY**

Институт – Энергетический / Institute – Power Supply
Направление подготовки – Электроэнергетика / Direction – Electric Power
Магистерская программа – Оптимизация развивающихся систем электроснабжения / MA Course – Optimization of developing power supply systems
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МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ / MASTER'S THESIS

Тема работы / Theme
«Автономная система электроснабжения на базе возобновляемых источников энергии» « Analyses and design of wind solar power off grid system to supply inhabited building »

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Томск / Tomsk – 2016

Министерство образования и науки Российской Федерации
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Институт Энергетический
Направление подготовки (специальность) 13.04.02 – «Электроэнергетика и электротехника»
Кафедра Электроснабжения промышленных предприятий

УТВЕРЖДАЮ:
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(Подпись) (Дата) (Ф.И.О.)

ЗАДАНИЕ
на выполнение выпускной квалификационной работы

В форме:

Магистерской диссертации

(бакалаврской работы, дипломного проекта/работы, магистерской диссертации)

Студенту:

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Срок сдачи студентом выполненной работы:	

ТЕХНИЧЕСКОЕ ЗАДАНИЕ:

Исходные данные к работе *(наименование объекта исследования или проектирования; производительность или нагрузка; режим работы (непрерывный, периодический, циклический и т. д.); вид сырья или материал изделия; требования к*	Объект исследования: Системы электроснабжения на основе солнечных фотоэлектрических установок и ветрогенераторов. Цель работы: сравнительный анализ применения установок солнечной фотоэнергетики и ветровых установок в России и в Чешской республике.

продукту, изделию или процессу; особые требования к особенностям функционирования (эксплуатации) объекта или изделия в плане безопасности эксплуатации, влияния на окружающую среду, энергозатрат; экономический анализ и т. д.).	
Перечень подлежащих исследованию, проектированию и разработке вопросов *(аналитический обзор по литературным источникам с целью выяснения достижений мировой науки техники в рассматриваемой области; постановка задачи исследования, проектирования, конструирования; содержание процедуры исследования, проектирования, конструирования; обсуждение результатов выполненной работы; наименование дополнительных разделов, подлежащих разработке; заключение по работе).*	✓ - Аналитический обзор применения возобновляемых энергоисточников, включая энергию солнца и ветра, гибридные системы. ✓ - Определение нагрузок объекта электроснабжения. ✓ - Оценка солнечного и ветрового потенциала рассматриваемых территорий. ✓ Технико-экономическое обоснование принимаемых решений.
Перечень графического материала *(с точным указанием обязательных чертежей)*	Презентация в формате ppt, pdf.

Консультанты по разделам выпускной квалификационной работы

(с указанием разделов)

Раздел	Консультант
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Работа выполнялась на английском языке

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Tomsk Polytechnic University

Institute of Power Engineering

Master Theses

Analyses and design of wind-solar power off grid system to supply inhabited building

Supervisor: Доцент Муравлев Игорь Олегович, к.т.н.

Author: Bc. Marek Vaniš

Analyses and design of wind-solar power off grid system to supply inhabited building

Abstract

The master theses presents, possibility to power supply a inhabited object by using a combination of wind turbines and photovoltaic panels in an off grid system. First part describes the object and the intended location where the object is located. Second part describes natural conditions and its characteristics necessary to take into account when designing photovoltaic and wind generator. Third part describes electrical appliances, and power consumption and load profile of the object. There are three load profiles to be supplied by the off grid system, the current one with resistance boiler, second instead of resistance boiler a heat pump and third no electrical heating profile. In the fourth section is presented a model of PV generator and WECS generator. In the fifth section is designed a wind power plant in combination with photovoltaic panels, then the basic components of the whole system are described. At the end, there is an economic evaluation of all variants.

Key words:

Photovoltaic generator, wind turbine, island systems, off grid

Analyses and design of wind-solar power off grid system to supply inhabited building

Statement

I present this master theses for a defense at the Institute of Power Engineering at Tomsk Polytechnic University. By this I state I have composed this work alone with the use of literature stated at the end of this work.

Table of Contents

1 Introduction

The growing demand for more energy and support of new green energy sources makes us seek new energy sources. The most important application field of this search is renewable energy resources. Wind and solar energy are currently the most popular ones owing to its omnipresence, ease of availability and convertibility to the electric energy. This work covers realization of an off grid hybrid renewable energy system for a home use. This project is implemented in accordance with no available public grid, even though there has been chosen a house currently connected to it. The owner would like to disconnect from the grid and be independent. Batteries in the system are charged by solar power via an MPPT or from the wind. System control relies three phase invertor. Power resources and loads in the system are monitored and controlled in real time by invertors' measurements.

The subsidies all over the world make renewable energy sources cost decrease. The owners of remote properties, had to pay in the past to distribution companies for bringing the question, what is the price, if there is build an off grid system without connection to the public grid. The main aim of this theses is to find the right combination of the PV generator, wind generator and diesel generator including the design of all basic components. There will be taken into account three variants of the load profile. In the end there will be an economical evaluation. To be able to fulfill the main aim is to create models of PV and wind generator.

1.1 Location and short description of supplied object

The supplied object is located at the edge of small town called Krupka. It is situated at the beginning of Ore Mountains. The construction has been finished in 1996. It is built out of autoclaved aerated concrete and hollow bricks. There are new plastic windows with three insolation chambers. There are two floors and under half of the house is basement. Both floors have 180 m^2 of usable area. The house is inhabited full year round.

The closest connection to the gas pipe is 400 m so in the house uses all the equipment electrical. In 1996 was especially because of the house's street built electrical substation and wire connection from about 500 m far.

To heat up the house during the winter season there is an electrical boiler and for storage of the hot water there were installed two 200 l tanks. The radiant floor was installed to save electrical energy used for heating. On the second floor works just half of the heating circuit, the other one is leaking, therefore is not used anymore. Instead of broken branch were installed two radiators which heat up of the other half of second floor is taking care fireplace with heat exchanger, which uses two radiators. In the house there is another electrical water boiler with volume 160 l for the drinkable water. The heating and hot water supply are the biggest energy consumers, it uses about 80 % of the electrical energy during the heating season. There is also many other devices using electrical power, full list will be provided further.

At the end of 2010 there was installed PV system with the installed power 5,08 kWp to complement grid feed in. Until 2013 used to work a subsidy program which allowed to consume the produced power and also to get paid for all transformed power from the sunlight (either consumed or not). The PV plant's yearly yields are between 4,4 MWh and 5,3 MWh. The coefficient of self-production and consumption is yearly between 41 % and 46 %. The rest of the power (54 % to 59 %) is fed into the grid.

1.2 Geographical climatic conditions

For the Czech Republic is typical to have four equally long seasons. Actual weather may differ very much from longtime period average. This variability in weather is caused mainly by different location and mightiness of two main pressure center: Iceland low pressure zone and Azores high pressure zone. Especially in hotter half of the season the high pressure brings hotter and dryer weather, on the other hand the Iceland low pressure area brings more clouds and also precipitations. Differences in weather are due to latitude and longitude are in area in the same size like the Czech Republic negligible. Specifications of Krupka are only due to its location, it spreads out from the foot of Ore Mountains (262 m above sea level) to its top (808 m above sea level). The discussed object is about in about 350 m above sea level.

1.2.1 Precipitation and water sources

The long term average precipitation of the Czech Republic is about 674 mm. In Krupka there is little bit less, 612 mm per year. There are no big rivers or fast creeks in Krupka. There are some streams, but most of them are dried out during summer. There is one small lake in the middle of forest next to the town and a steep hill underneath. There is some potential for small/micro hydro power plant, but it is in hardly accessible area, it is far (5 km) from the judged object. The lake and land around the lake is also owned by the state company Lesy České republiky, s.p. (The Czech Forest Company), which would make bureaucratically difficult.

1.2.2 Sun and wind

The Czech Republic is a landlocked country which is located in the mild climate which is very variable. Each location’s climate differs from each other, mostly because of the altitude. With rising altitude air temperature decreases, on the other hand rises the amount of precipitation and average wind speed. Krupka is situated right next to the area at the edge of economical profitability wind velocity, which is set for the Czech Republic at 5,25 m/s. (1). In the following picture may be seen that, Krupka is located in the area with the wind velocity of 5,0 m/s (black cross in the map in the dark orange area). The experiment of wind velocity measurement will be done, to verify it for the location of the object. Wind velocity may differ quite a lot according to local conditions.

In the next Figure 2 are located suitable locations for the wind turbine placement in the Czech Republic. These are marked within the blue boundaries. There is also marked the place (black double circle), where the object of this work is place. It is right at the border of the suitable area, therefore it is one of the aims if it is a suitable place to build a wind turbine and find the height of the hub. About 3km of the shown location are placed two 2MW turbines.

Colorfully marked areas in the next Figure 2 are anyhow protected areas where the wind turbine may be built only with restrictions and with the respect to landscape and nature. Except for the red areas where it cannot be built at all.

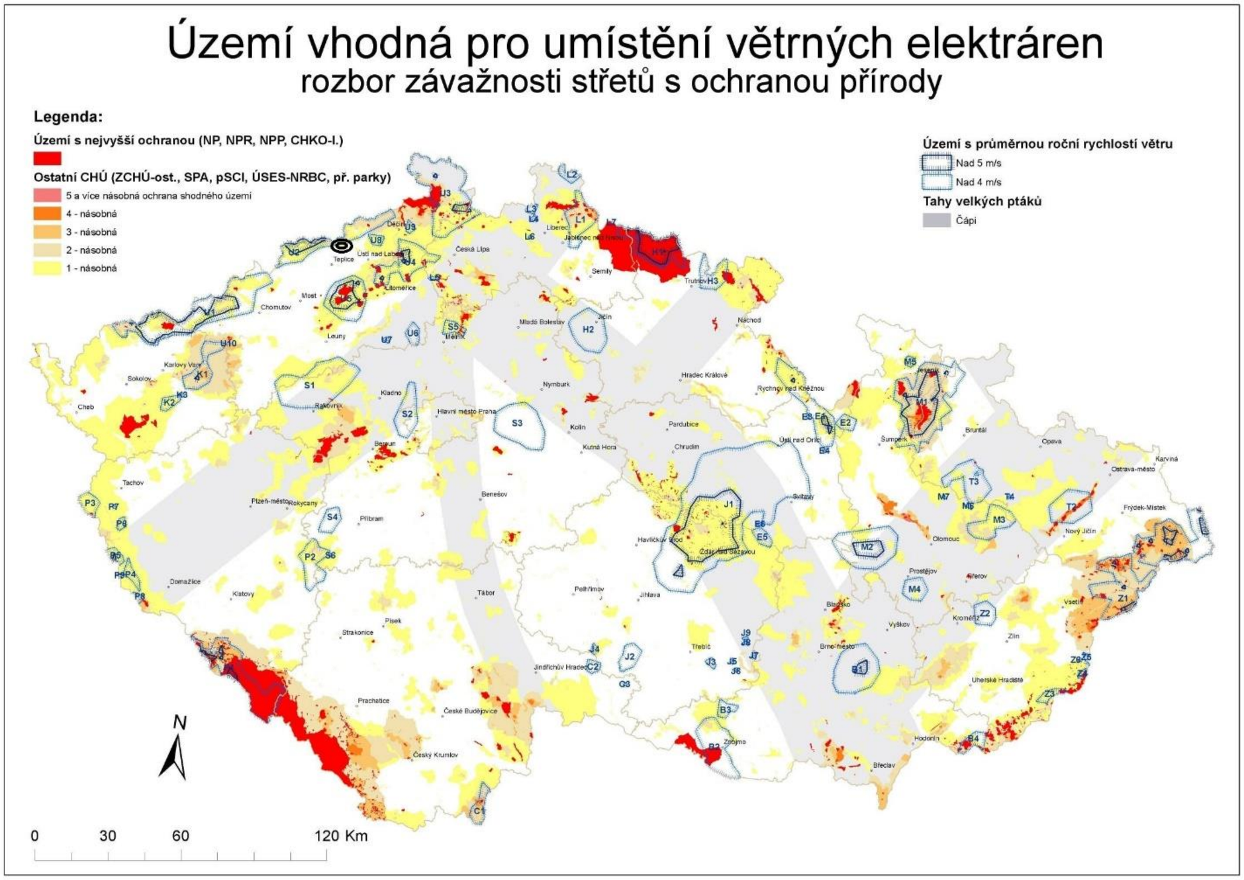


Figure 2 - Locations suitable for Wind energy conversion systems and location of protected nature (source: ERU)

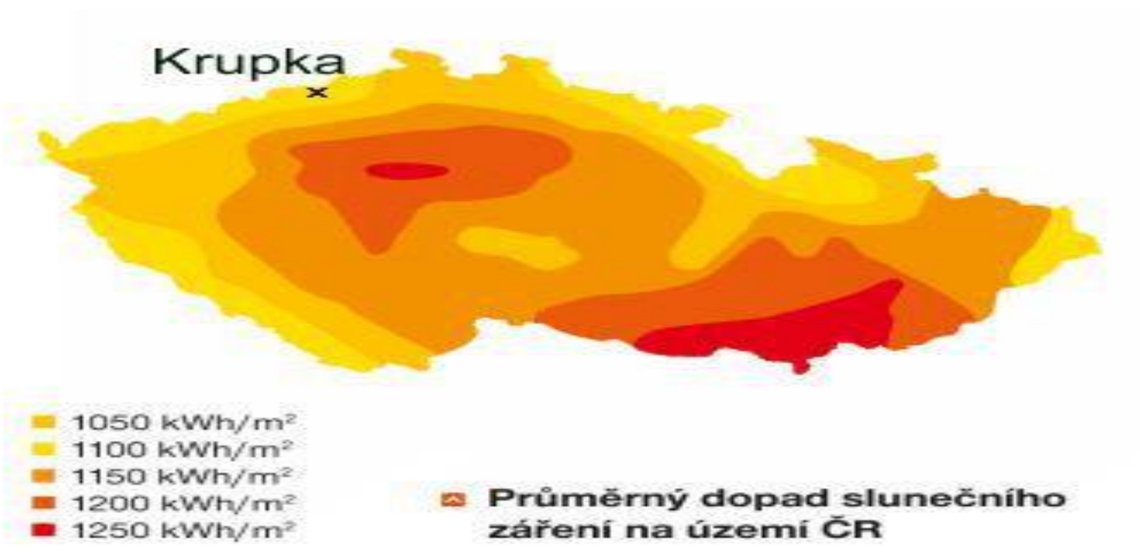


Figure 1 - Average of Sun irradiation in the Czech Republic (1)

The solar irradiation seems to be influenced by altitude but also slightly by latitude. Krupka is located in the area of the black cross in the following picture. In other sources are usually be provided data for this location from 950 kWh /m^2 1050 kWh/m^2 (2) (3). Therefore there will be further calculated with irradiation of 1000 kWh/m^2.

1.2.3 Temperature and heating season (upřesnit pro Krupku a nebo místo v okolí)

According to Czech Ministry of Trade and Industry the heating season is defined with connection to outside temperature. The heating season officially begins the 1st of September and lasts until the 31st of May. The actual heating in the heating season should begin when there is two following days which are under 13˚C in the given location and according to weather forecast and the temperature cannot be expected to rise above 13˚C. Number of heating days is in the Figure 4.

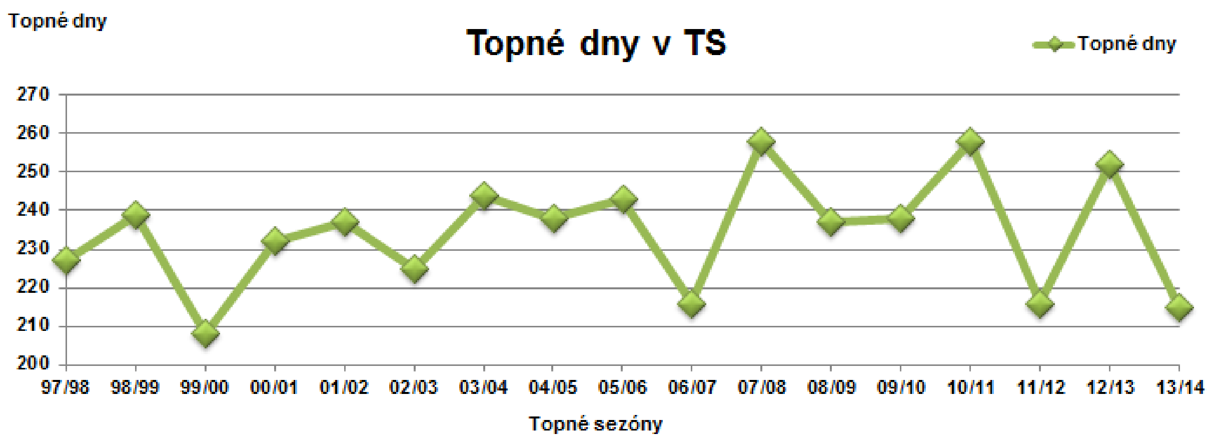


Figure 3 - Number of heating days development during 1997-2014 (Source: Pražská teplárenská)

Average temperature during the heating season is a very simple indicator to find out, but it is quite imprecise since it doesn't include an information if it there had to be turned on the heating.

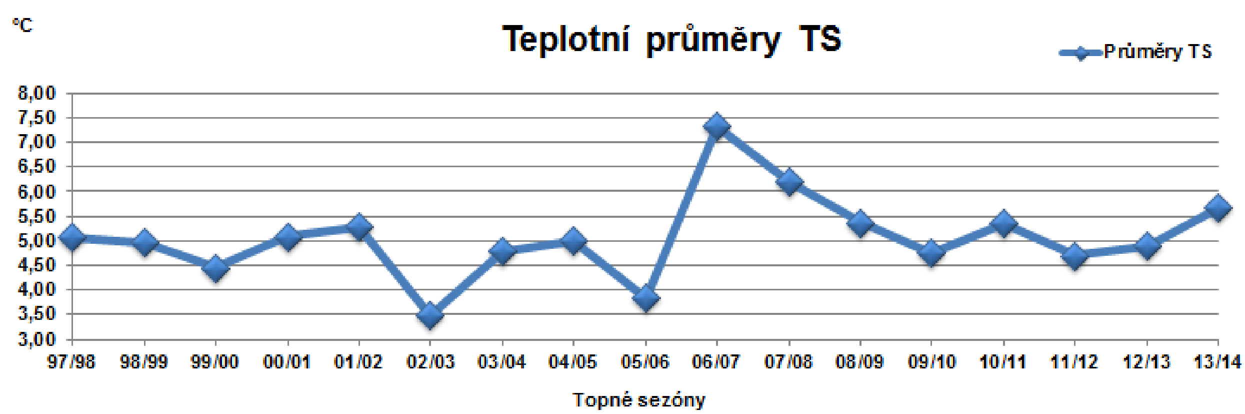


Figure 4 - Temperature averages during a heating season development during 1997-2014 (Source: Pražská teplárenská)

Combining number of days in heating season and outside temperature during the heating season together with inside temperature according to formula:

$$HDD = N * (t_{in} - t_{out})$$

- HDD – heating degree day
- N – number of heating days during heating season
- t_{in} – demanded temperature inside (referential value is 20 degrees)
- t_{out} – temperature outside during the heating season

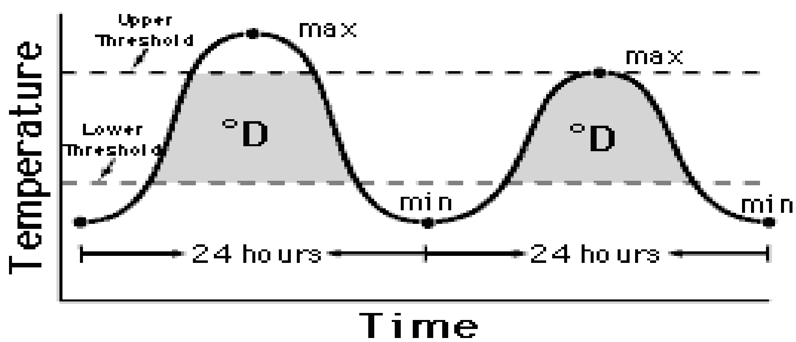


Figure 5 - Heating degree day (Source: University of California and natural resources)

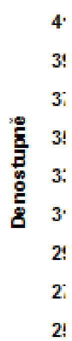


Figure 6 - Heating degree day development during 1997-2014

http://www.thpt.cz/index.php/teploty/demostupne

Out of HDD is possible to calculate how much energy is necessary to heat up the building with following formula:

$$Q_d = \frac{24L_h * e * d * HDD}{t_{in} - t_{out}}$$

- Q_d – heating energy [kWh]
- L_h – building's looses of heat
- e – contemporaneity of heating (usually 0,85 if one or two days every week omitted i.e. schools 0,7)

1.3 Analysis of available electrical power supplies variants

Further will be discussed potential of variants for electrical power supply, each one of them which comes to mind as a possible one. There will be also discussed a heat pump as a source of heat. Since all these are variants which could be used for providing electrical/heat energy to the already standing object which has all its installed devices adapted to AC, there will be taken in account only technologies with AC output, or a DC output with an inverter.

1.3.1 Photovoltaic system

Photovoltaic (PV) system is a system which extracts energy content of a light and transforms it into electrical energy. It is usually done via semiconductor cell. The generated electricity can be used to power a load or can be stored in a battery.

Photovoltaic system usually contents of PV modules (made of PV cells), aluminum construction for fastening modules, DC/AC invertor, DC and AC cables. In some cases batteries and charger which will be discussed separately further.

Principle of PV

Semiconductors are materials which's electrical conductivity depends on inner or outer conditions, which may be changed. By change is usually meant some input of energy – electrical, heat or in this case most importantly the light. The PV cell is a specially designed p-n junction. When a cell is illuminated, electron hole pairs (EHPs) are produced by the interaction of the incident photons with the atom of the cell which comes to excited sate. The electric field created by spare electrons of the cell junction causes the photon generated EHPs to separate with the electrons drifting in the n-region of the cell and the holes drifting into the p-region provided that the EHPs are generated sufficiently close to the p-n junction. (4)

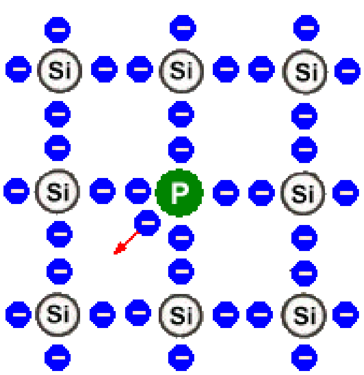


Figure 7 - N-type semiconductor

N-type semiconductor

The silicon has four valence electrons, if it is mixed with an element with five valence electrons (i.e. arsenic, phosphor, antimony) there is an N-type (negative type). The element which has one more electron more is called donor. Four out of five electrons are bond by valence bond with the silicon. The fifth bond is weakly and may move through the crystalline lattice.(5)

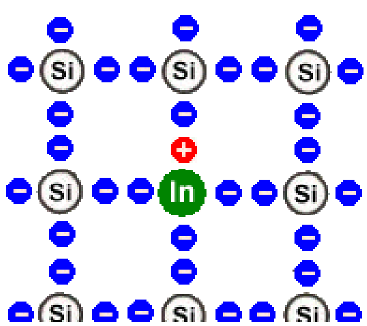


Figure 8 - P-type semiconductor

P-type semiconductor

On the other hand when there is mixed up silicon with an element with three valence electrons. There is a P-type created (positive type). The element with one electron less (indium, gallium, aluminum, boron) which is called acceptor. Three electrons are bond by valence bond with the silicon never the less one electron is missing to make the lattice complete. In that place is created a positive charge gap, which is called hole. When an electron from N-type semiconductor is excited by photons, it jumps into this hole, which brings these holes into movement and therefore hole-conductivity. (5)

Types of PV cells

In the global PV module production in 2013 by technology used leads with two thirds polycrystalline silicon, second is monocrystalline silicon with 24 % of market. There is 10 % of the market left for thin film technology, which is roughly divided on thirds.

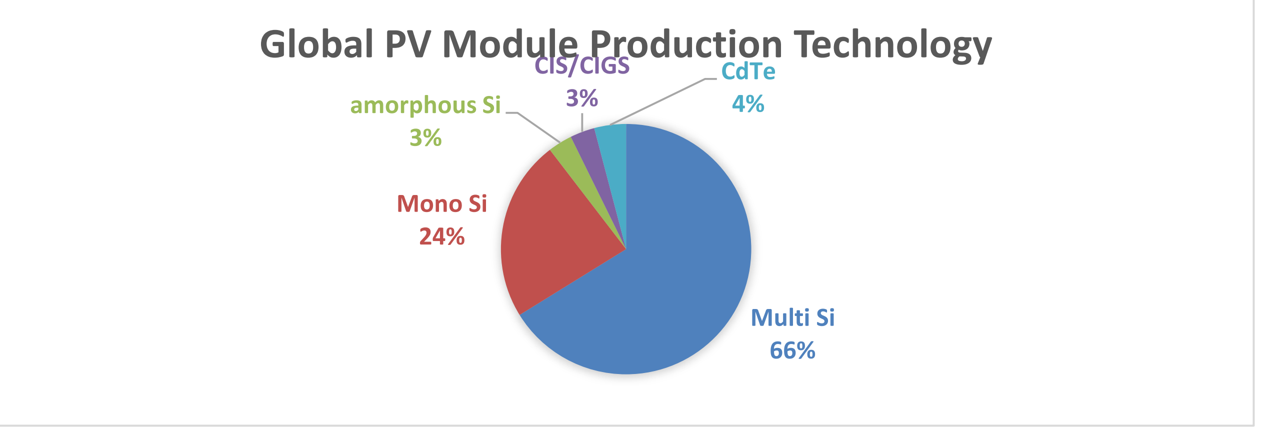


Figure 9 - Global PV module production by technology (Source: pv-tech.org)

Looking at thin film production more closely, CdTe made up 39 % of total thin film production, followed by CIGS (31 %) and thin-film silicon (30 %). There is of course used also other technologies, i.e. GaAs is barely used, but it has its own place in the aeronautics where it is very important. GaAs modules production in MW is too low, therefore it is not shown on the graph.

Characteristics of PV modules

There are many semiconductors which are photo sensitive with the photovoltaic character. A lot of them is used in laboratories for testing. Most of these tested materials are not competitive in mass production for its high production costs, but some of them exceed in efficiency.

A PV module may be seen either as a black box changing light into electricity with a current I and voltage V or for electric purposes as on a following picture described as an electric circuit with four components.

I-U characteristics

Short circuit current (I_{sc}) is a current with zero voltage. Open circuit voltage (V_{oc}) is a voltage when there is no current flow. These two characteristics are very important. The typical I-U characteristics is on the picture. It may be effected by conversion efficiency, temperature, reverse saturation and serial resistance.

The typical U-I characteristics is in the next picture. Maximal power point (MPP) is the biggest possible area under the characteristic U-I curve. Changes follow as the table says

Conversion Efficiency	Shift to higher currents
Temperature	Higher temperature results in lower open-circuit voltage, and higher short-circuit current. Overall result is a shift of the MPP to a lower power.
Reverse saturation current	Higher leakage results in flatter curve.
Serial resistance	Higher losses result in lower voltage

Table 1 - Photovoltaics UI characteristics

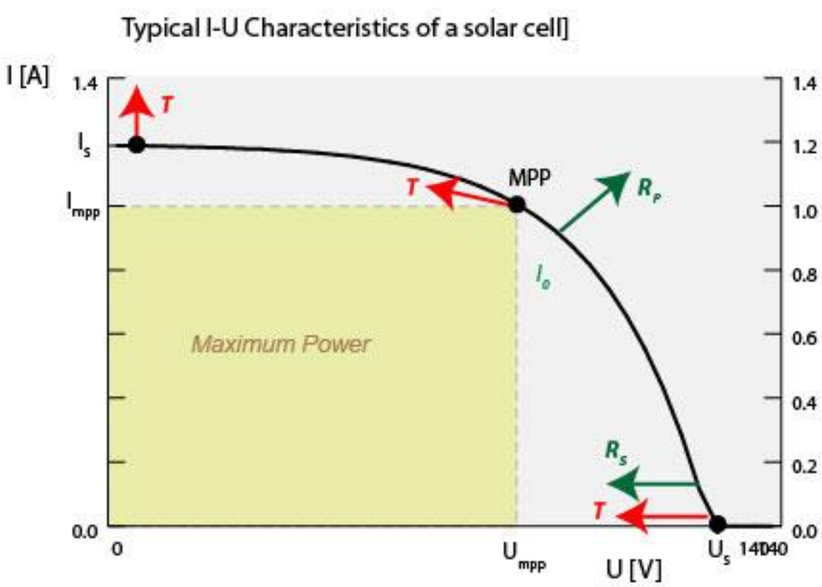


Figure 10 - Typical U-I characteristics of a PV cell (source: Green Rhino Energy)

Temperature coefficient

It is well known that the maximum power output of photovoltaic device changes with temperature. This term is applied to several different photovoltaic cell performance parameters such as open circuit voltage, short circuit current and power. There will be considered only the power coefficient further, which gives an information how much the power output changes according to temperature, using unit's ± percent per kelvin [%/K]

Nominal module efficiency

This is the conversion efficiency that is observed when the module is to light with intensity 1kW/m2. The peak power of the module is related to the module area$A$ $[m^2]$, conversion efficiency η_{nom} [%] and with$H_0 = 1000$ $[W/m^2]$, at standardized conditions usually 25 °C by:

$$P_{peak} = H_0 * \eta_{nom} * A$$

The nominal conversion efficiency can be obtained from the manufacturer's data sheet.

Conversion efficiency (relative module efficiency)

One of the main characteristics of PV module is the efficiency of conversion (transformation) of irradiation to electrical energy. Some of them which are dependent on the irradiance coming from outer space will be mentioned further in Capture 2.1. The efficiency depends on the material (silicon, CdTe, GaAs, CIS/n, CIGS technology (monocrystalline, polycrystalline, and thin film, multilayer) and material's quality and purity which is the module made of, adjustment that has been done (antireflective coating, front a back contacts sizing). (4)

Comparison of PV modules

From comparison of many datasheets came out following indicative table:

	Poly Si	Mono Si	Amorphous Si	CdTe	GaAs	CIS, CIGS
Efficiency (available at the market) [%]	13-16	15-20	6-9	10-16	30	7-13
Area per 1 kWp [m^2]	6-8	5-6	11-17	10-12	3-4	8-14
Usual performance warranty [years]	25	25	25	25	25	25
Temperature coefficient [%/K]	from -0,37 to -0,44	from -0,45 to -0,5	from -0,27 to -0,21	from -0,2 to -0,29	0,21	from -0,31 to -0,39
Price [$/Wp]	0,45 - 0,7	0,5 - 0,95	0,1 - 0,6	0,4	3	0,6

Table 2 - Comparison of PV module technologies

1.3.2 Wind energy conversion system

Wind power is energy extracted from the wind passing through a machine known as the windmill. The windmill in the case when used for electricity generation is usually called wind turbine. The wind turbine transforms the wind energy to mechanical energy, which generator transforms into electrical energy. There are two 2MW wind turbines about 3 km from the house upon the hill.

Wind energy conversion system (WECS) consists of a tower, on which the wind turbine is mounted. A rotor that is turned by the wind and a nacelle which houses the equipment as the generator and/or gearbox.

Characteristics of wind turbine types

Axis of rotation

According to direction of axis, turbines rotate either around a horizontal or vertical axis.

Horizontal	Most of the time it is a propeller looking station, lift turbine which use upward pressure – the wind flows around vanes and spins the rotor. Right behind the rotor, in the same height must be a gearbox and generator.
Vertical	Usually drag turbines which use the resistance of the vane and based on Newton's 3rd law the vane moves. Drag turbines have generally smaller efficiency therefore lift turbines are more frequently used. The advantages of vertical axis turbine is that it does not have to wind up along the wind direction and that the gearbox and generator may be placed at the bottom of the pole. That makes it more stable and easier to build.

Table 3 - Comparison of wind turbine axis of rotation

Size

The categorization according to nominal power is simply micro, small, medium, and big according to following table.

	Micro	Small	Medium	Large
Rotor diameter [m]	≤ 2	≤ 16	≤ 45	> 45
Swept area [m²]	≤ 40	≤ 200	≤ 1600	> 1600
Rated power [kW]	≤ 2,5	≤ 60	≤ 750	> 750

Table 4 - Comparison of wind turbine size (1)

Micro wind generators usually produce DC and are used for battery charging. All other ones usually produce AC and are able to use the produced power for load or feed it into the grid. Of course it depend on the exact generator.

Power

The power of the wind generator is calculated according to the next formula

$$P = \frac{1}{2}\rho v^3 c_p S$$

Where the P is the power, ρ is the air density, v is the wind velocity, c_p is the efficiency of the turbine and S is the area swept by the turbine. The power depends on the third power of the wind velocity and second power of its radius. In the next figure is shown how the average radius influences the rated power of the wind turbine.

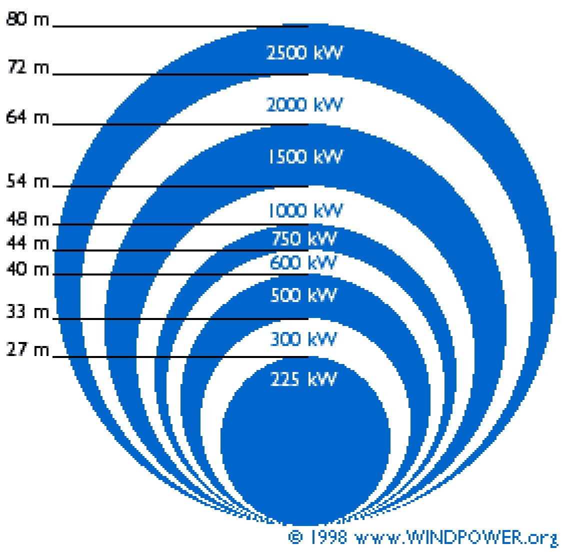


Figure 11 - Radius and rated power of the wind turbine (source: Windpower.org)

1.3.3 Batteries

Power produced by PV-WEC hybrid system usually is not consumed right at the same time when it is produced. It is suitable to consume power produced at the moment and the leftovers to store for later use. At the time when there is not enough power produced form both sources, it may be withdrawn from battery. Even though the cost of batteries rises the total cost no negligibly, it is necessary to use it in an off grid application. The other disadvantage except of battery's high price, is small energetic efficiency, the ratio of input and out of the energy is usually between 70 and 85 %. (6) Two efficiency metrics are used: Colometric efficiency is where current is function of time I (t) and Energy efficiency where voltage is function of time V (t).

Batteries which are used in the off grid system are supposed to store energy for later use. By later use is meant that it is stored for the power demand in several days. It is not possible to store it i.e. from a good year to the bad one, because there is a characteristic of the battery which is called self-discharge, which shows the rate of discharge with no load usually in a month. (7)

Battery characteristics

Primary and secondary batteries

There are two types of batteries. Primary type which is not rechargeable and secondary, which it more interesting in the case of autonomous system, is rechargeable. Why the primary batteries last is that they can be stored up to 10 years and have much higher energy densities than secondary batteries. The market share of primary batteries slowly decreases. The demand of rechargeable increases, because of higher RES production and more electro mobiles produced using rechargeable batteries. The basic most often used batteries are shown on the next picture together with the percentage of worldwide share market. They are Lithium-ion, lead acid, NiMH and others.

From now on, there will be discussed only secondary batteries suitable for off grid power supply.

Capacity

When designed an autonomous system there must be adequate battery capacity chosen. If the capacity of the batteries is too low, it will mean many cycles and bigger discharge, which will result in short life time of the battery. It is also very important to use just one type of battery from the same producer (and the best from the same production series) together. Batteries from different producers or from different series may influence each other because of possible different capacity, voltage and most important is that all batteries must be charged to the same level. Capacity is measured in Ah or kWh. For comparing batteries is used a specific energy which is a capacity divided by weight of the battery. Sometimes instead of specific energy is used a metric which is call energy density. It is very similar to specific energy, it uses volume instead of mass.

Charge and discharge

The dynamic performance of a battery at a point of discharge or a state of charge (SOC) regulates the speed at which current may be put into and taken out. The nominal voltage is not constant, but decreases and rises with during discharging and charging. When the battery is charged, the voltage settles within minutes. For sufficient long charge, the battery voltage saturates at a maximum value. In the overcharge situation, most of the input energy goes to heating loses or side reactions which may damage the battery. On the other side when the battery voltage drops too low, below the cut-off level and kept undercharged, it can cause damage.

The working range of a battery is determined by the state of charge. It is a percentage of how much energy is in the battery. The fully charged is at 100 % SOC, which is in other words 0 % of depth of discharge (DOD) DOD = 100 % - SOC. Batteries usually work within 30-100 % SOC.

Batteries have a special property, which is called self-discharge. The inner resistance causes even when no load is connected, that they discharge themselves.

Cycle life

A cycle is called a process of fully charging and fully discharging the usable capacity of the battery. Repeatability of this cycle is limited and depends on chemistry, depth of charge an discharge cycle, prior history (i.e. storage) and manufacturer. A cycle life determines the time how long the battery will last. An important thing is that after a cycle life of a battery is gone, the battery is not ruined at all, it will have just lower capacity, with which it will function further.

Temperature operating range

Batteries perform poorly at extremely low and high temperatures. These temperatures also can damage the battery. Low temperatures cause ionic diffusion and migration hinder and cause damaging side reaction (plating). High temperature cause faster corrosion and gas generation. To prevent these damaging processes batteries are labeled with lower and upper operation limit. (6)

Secondary battery material comparison

There will be described and compared rechargeable batteries only, especially the batteries suitable for stationary, UPS and traction use. Reversible electrochemical reaction at the two electrodes allow the battery to be charged and discharged within a certain level. One charging and a discharging process is called a cycle. For each battery type will be discussed: electrochemical reaction, aging mechanism and performance including energy and power mass, volume densities, cycle life and cost.

1) Lead Acid based batteries

Lead acid (Pb-acid) battery is older technology which takes 40-45 % of the share in secondary battery market. This is mainly due to its extensive use in starting, lighting and ignition. It is also usable in power storage with high efficiency 75-80 %.

Reversible reaction at both electrodes is shown below. For the direction from the left to the right stands for discharge. For the direction from the right to the left stays for the charging process. This reaction produces -0,3 V on the cathode and 1,6 V on the anode.

Negative electrode (cathode)

$$Pb + HSO_4^- \rightleftarrows PbSO_4 + H^+ + 2e^-$$

Positive electrode (anode)

$$PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightleftarrows PbSO_4 + 2H_2O$$

Under certain operation conditions reaction in previous equations are supplemented with side reaction or the other processes that may reduce the efficiency of the cell and/or cause long term degradation, which reduce its life:

- Corrosion – The anode is covered with PbO_2 can be corroded by the H_2SO_4 solution (electrolyte) leads to oxidation which increase the resistance in the anode
- Gas generation – During overcharge, the hydrogen accumulates at the negative electrode and the oxygen at the anode, which generates the pressure in the battery. This pressure is taken care by special valve in VRLA batteries. Which constitutes in a water loss that can dry out the separator and increase the acid concentration.

- Sulfation – Discharging the cell creates $PBSO_4$ crystals at both, anode and cathode. Charging converts the crystals back to the active material. Sulfation becomes a problem when some of the crystals stay after the charging process. Sulfation lowers battery capacity. Sulfation happens in the high temperatures when the battery is discharged (in low-voltage state) for long time period. The cathode is more prone to sulfation than positive.
- Active-material and physical degradation – The previous three processes decrease the amount of active material and also produce the mechanical stress, which may cause physical damage to the cell.
- Separator (membrane) metallization – Through a process of charge and discharge the $PbSO_4$ is consumed and produced. The $PbSO_4$ may flood separator pores and during the charge may be converted to dendritic, metallic lead. This can cause short circuit through the separator.

Further are described these types of Pb-acid batteries in detail: Starter batteries, VRLA (AGM and gel batteries).

A. Starter batteries

The first type is Classical type known as Starter batteries from cars, they have flooded electrodes. There must be some maintenance by checking the amount of distilled water which dilutes the sulfate acid. Compared to other batteries it is cheap on the other hand it is not very suitable for usage to work together with RES power distribution system, because it is designed to produce high current for a short time (starting the engine) and right away get recharged again.

B. VRLA

AGM (Absorbed Glass Mat) and gel batteries are both classified as maintenance free batteries, both are often also marked as VRLA (Valve Regulated Lead Acid). They have a special valve which regulates the usual working pressure and also is a safety valve.

B.a. AGM

AGM batteries contain liquid electrolyte which is soaked into a special glass mat as the full name says. The lattice of the battery are close each other but also there is the glass mat between them which holds the electrolyte. The advantages of AGM are that it can supply high power even at low temperatures, high durability against vibration, longer lifetime even with high discharge cycles, very slow self-discharge, higher capacity at the same weight as classical batteries and absolutely no maintenance.

B.b. Gel batteries

The gel battery is constructed almost the same way as the regular starter battery, only the electrolyte is stored in the form of thick gel. The electrolyte is inbound into silicon suspension. Similarly as the AGM battery if the gel battery is tipped, the electrolyte will not leak out. Advantages compared to AGM battery is that the gel has lower sensitivity to higher temperature, higher durability against vibration, and better lifetime even with high discharge cycles, slower self-discharge, about the same capacity at the same weight. The gel battery has better recombination of hydrogen and oxygen gasses back to water.

2) Nickel-Metal Hydride

Nickel-Metal Hydride (Ni-MH) batteries offer high performance at higher cost than VRLA batteries. They have very good cycle life and capacity and a rapid recharge capability. The main drawback is their self-discharge faster. Following reversible reaction produces on anode -0,83 V and 0,52 V on cathode.

$$\text{Anode: } NiOOH + H_2O + e^- \rightleftarrows Ni(OH)_2 + OH^-$$

$$\text{Cathode: } MH + OH^- \rightleftarrows M + H_2O + e^-$$

During overcharge these reactions continue, create oxygen, water and hydrogen. Typically it is not fully reversible. The hydrogen at its partial absorption back into the active material causes even faster self-discharge, within order of days.

- Hydrolyses – It is the process of consuming the water and producing hydrogen, the water loss is the inducer of the cell dry-out, increases the cell's internal resistance and the electrolyte concentration.
- Corrosion – The corrosion accelerates the water loss by changing the balance between positive and negative electrodes.
- Decrepitation – NiMH cells also age through decrepitation of the active materials by inducing the stresses. The insertion and disinsertion of hydrogen in these materials case lattice expansion a contraction that induces the inner pressure.

3) Lithium based batteries

Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the biggest specific energy per unit of weight. Lithium metal oxide $LiMO_2$ where M represents a metal, mainly the cobalt - Co respectively iron and phosphorus – LiFePO_4 (also called LFP). Similar to the lead-architecture, lithium-ion uses a cathode, an anode and electrolyte as conductor. During discharge (direction from left to the right in the equation), the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. The reaction produces a theoretical cell voltage 4,1 V which is much higher compared to Pb-acid cell. Example of lithium based battery's electrochemical equations follows on anode and cathode.

$$\text{Cathode reaction } Li_xC \rightleftarrows C + xLi^+ + xe^-$$

$$\text{Anode } Li_{1-x}CoO_2 + xLi^+ + xe^- \rightleftarrows LiCo_2$$

The power and capacity of Li-ion fades with increasing cycling. Power fade is primarily due to increase of internal resistance and impedance. Both causes ohmic loses and energy waist, produces heat and start aging. In Li-ion batteries degrade anode, cathode and electrolyte. These processes are complex, coupled and dependent on cell chemistry, design and manufacturer.

On the cathode the main aging causes are:

- Solid-electrolyte interface (SEI) layer growth – The SEI layer grows on the cathode and together with high temperature leads to an impedance rise.
- Lithium corrosion – Lithium as a metal corrodes over time, which causes capacity fade due to irreversible loss of mobile lithium.
- Contact loss – The SEI layer disconnects from the negative electrode, the contact loss and also increase impedance.
- Lithium plating – At low temperature the lithium can plate on cathode, which causes high charge rates, low cell voltage and irreversible loss of cyclable lithium. (6)

1.3.4 Engine generator

The diesel generator backs up the whole supply system. In the periods of time when the Sun's irradiation and the wind is low, the power is needed too. In the object there are installed some power consuming devices which have high priority of running. Which means the user of the object wants to have these devices running whenever. The power must be therefore available all the time. At this time the power supply is kept by the engine generator. In the case there is in some part of the year or the whole year the sun or wind is insufficient, it may be replaced by the gen-set.

In the off grid system with lead acid and NiMH batteries there must be a diesel generator installed even if there is enough power produced by PV-WEC system. The reason is that some lead acid and NiMH batteries must be charged at least once a month up to 100 % of state of charge (SOC) to keep them in the right shape, reduce the memory effect and maintain long life time.

1.3.5 Grid

In the case there is a grid close to supplied object, the diesel generator may be replaced by it. Which will be efficient in case the grid is not stable, or the power distribution to remote location is too expensive, although cheaper than diesel fuel cost and its distribution. In the case the system is anyhow connected to the grid than it is not considered off grid system and is reasonable only when power produced in the hybrid system is cheaper or more reliable than the grid. There may be inhabitant's personal beliefs and ecological reasons of disconnection form the grid.

1.3.6 Hybrid system

Hybrid system is a system which use more than one energy resource. Integration of two (or more) systems makes hybrid system more stable in terms of power production. Hybrid solar-wind application may be applied in the area, where all-year energy will be consumed. It is possible to combine wind-solar hybrid with diesel generator to supply peaks in demand and in the case there are batteries implemented, some types must be charged once in some period of time onto 100 % of their capacity so it lasts longer and do not get damaged.

Photovoltaic solar module and small wind turbines depend on climate and weather conditions, therefore neither of them is sufficient alone. A number of renewable energy expert claim to have a satisfactory hybrid energy resource if both wind and solar power are integrated within a one hybrid system. The assumption for their satisfactory outcome is that in the hybrid system is installed in climate where in the summer time, when the sun beams are strong enough, wind velocity is relatively small. In the winter time, when sunny days are relatively shorter, wind velocity is on the other hand high. (8).

2 Analysis of general natural conditions for models of electric energy sources

2.1 Solar irradiation potential

Production of electric energy from the solar panel is dependent on the intensity of solar irradiation. The intensity of the solar irradiation varies by following factors. First of all, the location of the power station, the angle at which the solar irradiation comes to mounted panels, the season of the year, the amount of sunny hours, shades and temperature. Each will be described further

2.1.1 Solar irradiance

The Sun is irradiating vast amount of energy to all directions. The total quantity of emitted is approximately 63 MW/m^2 as the energy travels through space it is intercepted by planets and other objects or interstellar gas and dust. As the Sun's rays spread out into space the radiation becomes less intense and by the time the rays reach the edge of the Earth's atmosphere they are considered to be parallel.

Figure 12 - The Sun's rays incident on the Earth. I0 = irradiance on a plane perpendicular to the Sun's rays(9)

Intensity of solar radiation

The intensity of solar radiation striking these objects is determined by a physical law known as the Inverse Square Law. This law states that the intensity of the radiation emitted from the Sun varies with the squared distance from the source (10)

$$E = \frac{I}{r^2}$$

Where E is called illuminance and I pointance, r is a distance from the emitting subject. (11)

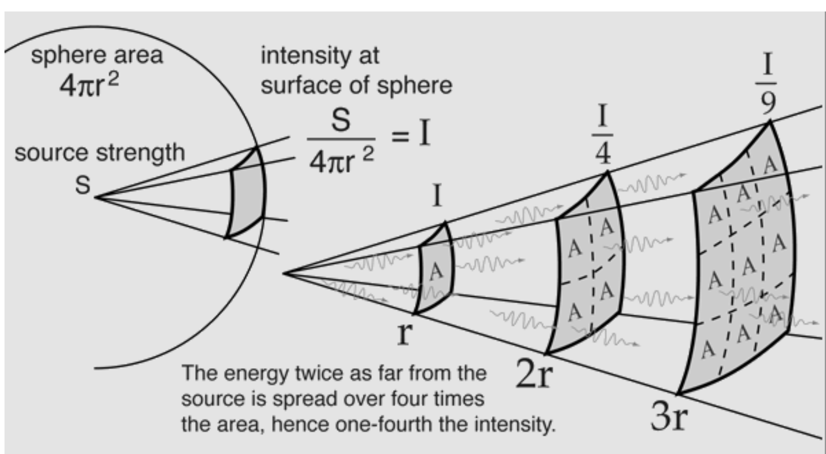


Figure 13 - diffusion of radiation is geometrically related to distance traveled (9)

Yearly variation of solar radiation during the year

Since the Earth runs around the Sun on eclipse the distance from the Sun varies during the year and because of that varies the intensity of irradiance obtained through the year. (9)

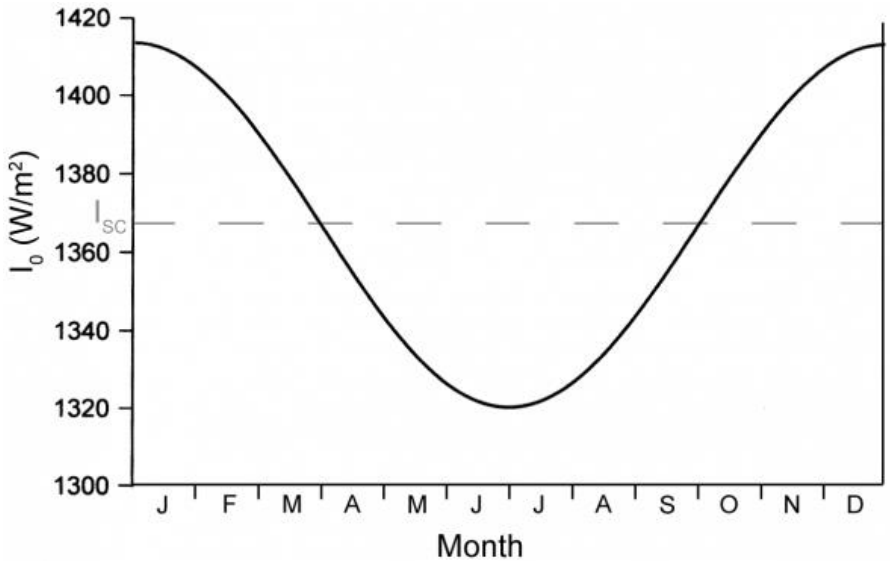


Figure 14 - The variation of extraterrestrial irradiation I0 over the course of a year. The dashed line shows the value of the solar constant (Isc)

The cosine effect

The value I_0 from the **figure number (solar irradiance)** is the same no matter where you are on the Earth's surface, however not all points on the Earth's surface are perpendicular to the Sun's rays. A useful quantity to calculate is the solar irradiance incident on an imaginary surface that is parallel to a horizontal plane on the Earth's surface. The irradiance on such a surface is smaller than I_0 because of the *cosine effect* and is the maximum amount of solar energy that could be collected on a horizontal plane at the Earth's surface if the atmosphere did not scatter and absorb any radiation.

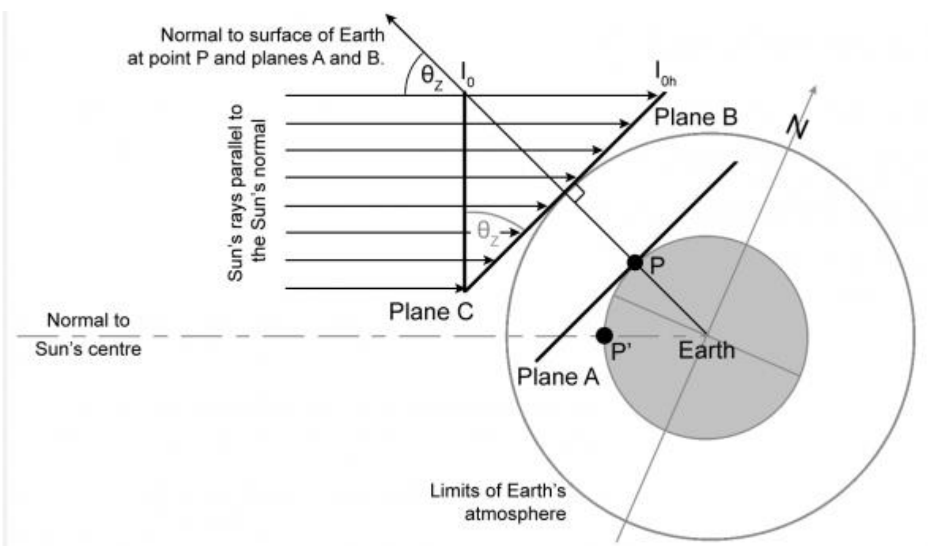


Figure 15 - The cosine effect (9)

- plane A, a horizontal plane at the point P on the Earth's surface;

- plane B, a surface parallel to plane A but on the edge of the Earth's atmosphere, often referred to as the horizontal plane;
- Plane C, a surface perpendicular to the Sun's rays, often referred to as the normal plane.

I_0 is the irradiance intensity on the normal plane and the irradiance intensity on the horizontal plane can be calculated from:

$$I_{0h} = \cos \emptyset_z$$

Given the amount of energy radiated by the Sun and the average Earth-Sun distance of 149.5 million kilometers, the amount of radiation intercepted by the outer limits of the atmosphere can be calculated to be around 1,367 kW/m^2 that is the energy of radiation which obtains space stations. Only about 50 % of the solar energy is intercepted by Earth. (10)

Atmospheric effects on incoming solar radiation

Three atmospheric processes modify the solar radiation passing through the atmosphere on its way to Earth's surface. These processes are caused by interaction of gases and other particles found in the atmosphere.

Scattering

The process of scattering occurs when small particles and gas molecules diffuse part of the incoming solar radiation in random directions. Scattering reduces the amount of incoming radiation which finally reaches the Earth's surface because a significant proportion of scattered radiation is redirected back to space.

The significance of scattering is dependent on two factors: wavelength of the incoming radiation and the size of the scattering particle or gas molecule. In the Earth's atmosphere, the presence of a large number of particles with a size of about 0.5 microns results in shorter wavelengths being preferentially scattered. This factor also causes our sky to look blue because this color corresponds to those wavelengths that are best diffused. If scattering did not occur in our atmosphere the daylight sky would be black.

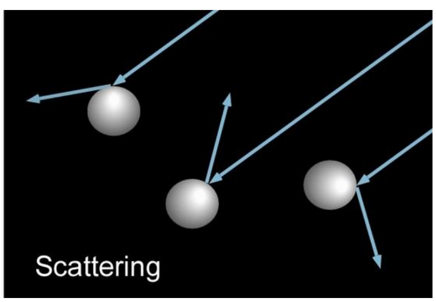


Figure 16 - Scattering (12)

Reflection

Reflection is a process where sunlight is redirect by 180 ° after it strikes an atmospheric particle. It differs from scattering because this redirection causes a 100% loss of the insolation. Most of the reflection in our atmosphere occurs in clouds when light is intercepted by particles of liquid and frozen water. The reflectivity of a cloud can range from 40 to 90 %.

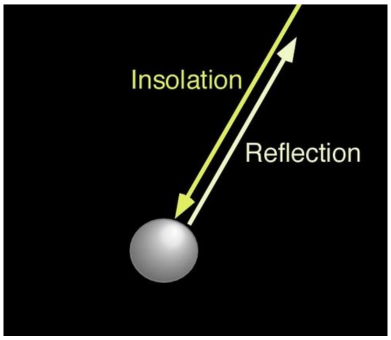


Figure 17 – Reflection (12)

Absorption

In this process, radiation is absorbed by an atmospheric particles, transferred into heat energy. This heat energy may be further emitted into the surrounding area as long wave emission

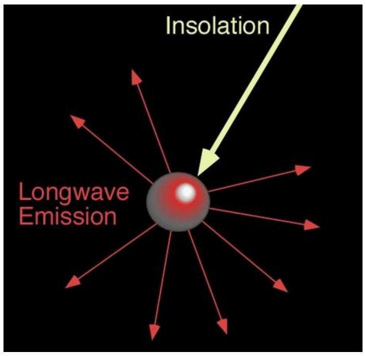


Figure 18 – Absorption (12)

The budget of solar radiation

Previous atmospheric effects participates on the total energy budget as follows in the Figure 19 - Insolation budget:

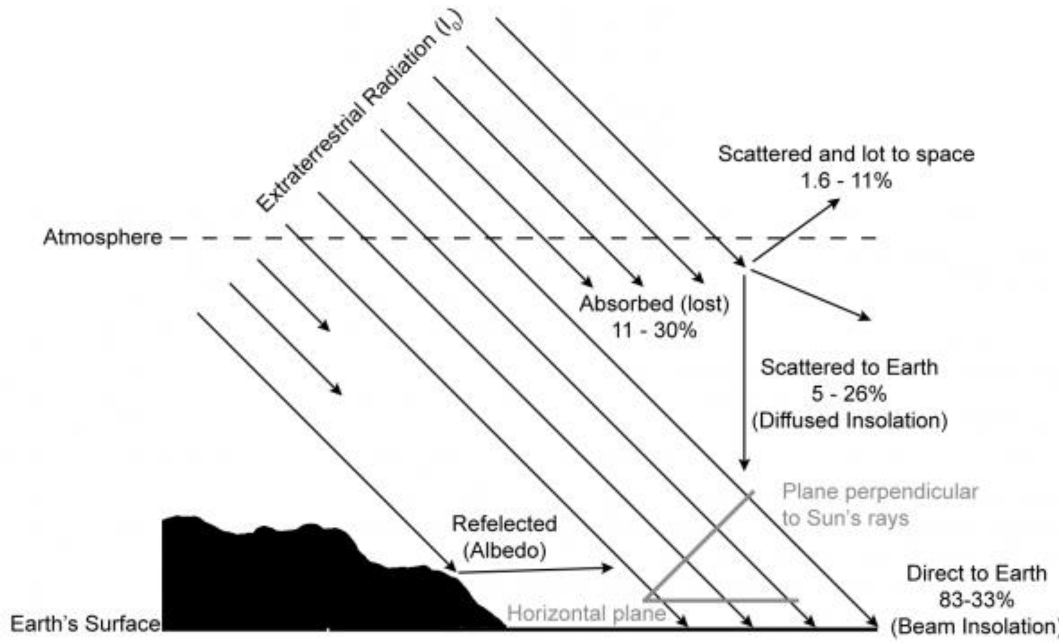


Figure 19 - Insolation budget (9)

The total budget insolation:

- Absorbed 11-30 %
- Scattered and lot to space 1,6-11 %
- Scattered and lot to Earth 5-26 %
- Direct sun (beam) rays 33-83 %

(9)

Sunshine duration

Day time duration of sunlight is based on theoretical maximum when the sun is above the horizon. The year last 8760 hours, and we can assume the day light last a half of it. That means it is 4380 hours per year not counting cloudy hours. Although there are some physical and astronomical effects, which are changing this estimation. Namely, atmospheric refraction allows the Sun to be still visible even when it physically sets below the horizon. Because of that average daytime is longest in polar areas, where the Sun is the most of the time around the horizon. Places on the Arctic Circle have the longest annual daytime of 4647 hours, while the North Pole receives 4575. The real sunshine including cloud shades follows well known general geographical pattern where dry areas have more sun – subtropical latitudes, higher latitudes have more unstable weather with more clouds.

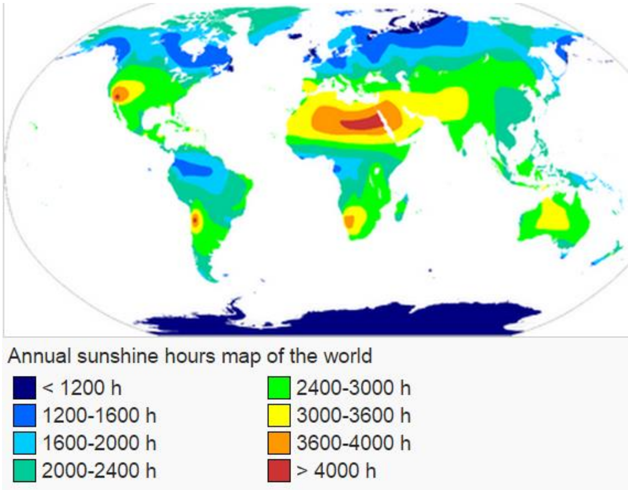


Figure 20 - Sunshine duration (13)

2.1.2 Optimal angle and orientation

Optimal angle of the PV panel depends on two variables, declination angle of sun during across the year and the hour of a day and latitude of the location.

Declination angle

The Earth's axis of rotation is tilted 23,25 ° measured with respect to the plane of the orbit which the Earth goes on around the Sun. The angle between the equatorial plane and a line joining the centers of the Sun and the Earth is called the *declination angle* (δ). As the Earth orbits the Sun the declination angle changes throughout the year. The equation used to calculate the declination angle in degrees on any given day is:

$$\delta = 23{,}45 \sin\left[\frac{360 * (284 + n)}{365}\right]$$

Where n is number of days from the beginning of June (n=1 on the 1^{st} January).

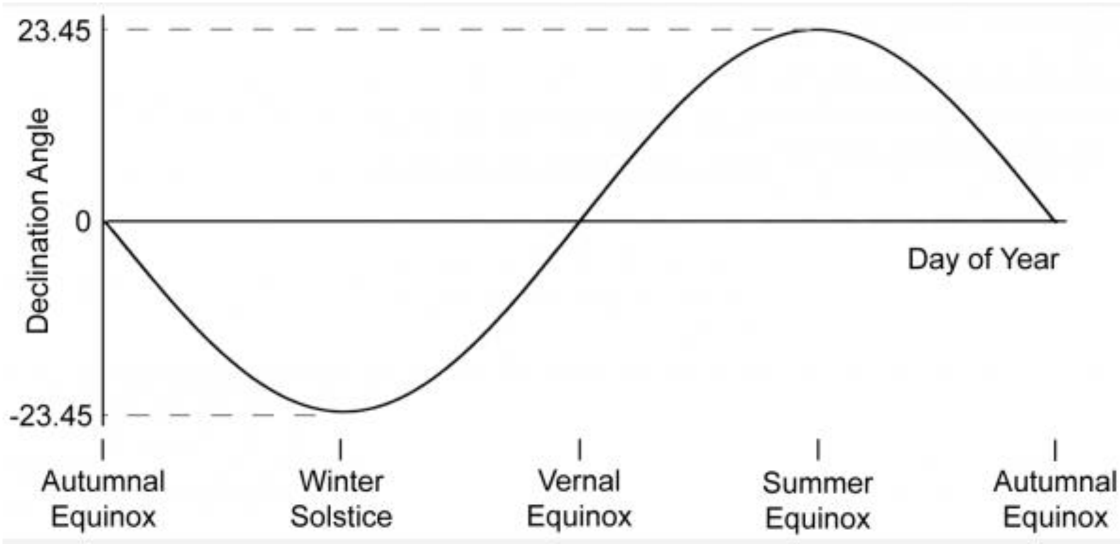


Figure 21 - Declination angle during the year (14)

The declination is zero at the equinoxes (March 22 and September 22). Highest peaks are at winter and summer solstice (20. or 21. June, 22. or 23. September)

Hour angle

Hour angle is defined as the angle of local longitude coordinate and latitude coordinate at which is the Sun during the hour of the day. The fact that the Earth rotates around its axes in 24 hours, simplifies the approximate calculation . 1 rotation = 360 degrees, therefore the hour angle (ω_s) where ST true solar time (local time without summer/winter changes).

$$\omega_s = (ST - 12) * 15°$$

The hour angle is negative from dusk, rises to zero at solar noon – when the point P in the Figure 22 faces exactly Sun. During the afternoon rises to positive. The angle is the same for all places on Earth with the same longitude. (14)

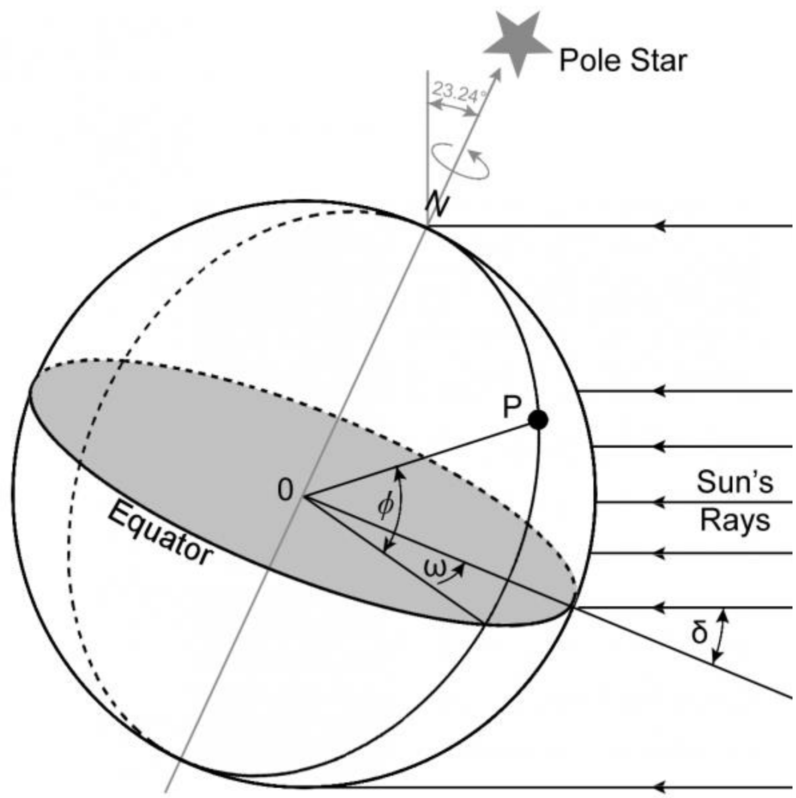


Figure 22 - Hour angle (9)

2.1.3 Shade

The shade affects the solar system. There has been defined two types of shades, the soft and hard one.

Hard shape is defined like a solid object placed in front of the PV cells a way is blocking the sunlight by clear a definable shape (i.e. chimney, tree). Soft shade is when an undefinable shape of shade is observed (i.e. smoke). It is important to take in account which shade is observed because each causes a different effect on a PV cells

The Soft shade causes higher scattering, reflection and absorption as described in chapter 0 never the less the voltage stays almost the same because the voltage depends more on temperature and the electron band-gap in the materials than on the light itself. The current will drop dramatically and therefor the power.

The Hard shade causes the drop of voltage – the cells which are shaded are bypassed by diodes to minimize the losses and that way allowing at least some current from other modules to flow through. Without bypasses the current of the whole panel would drop to the level of the most shaded cell.

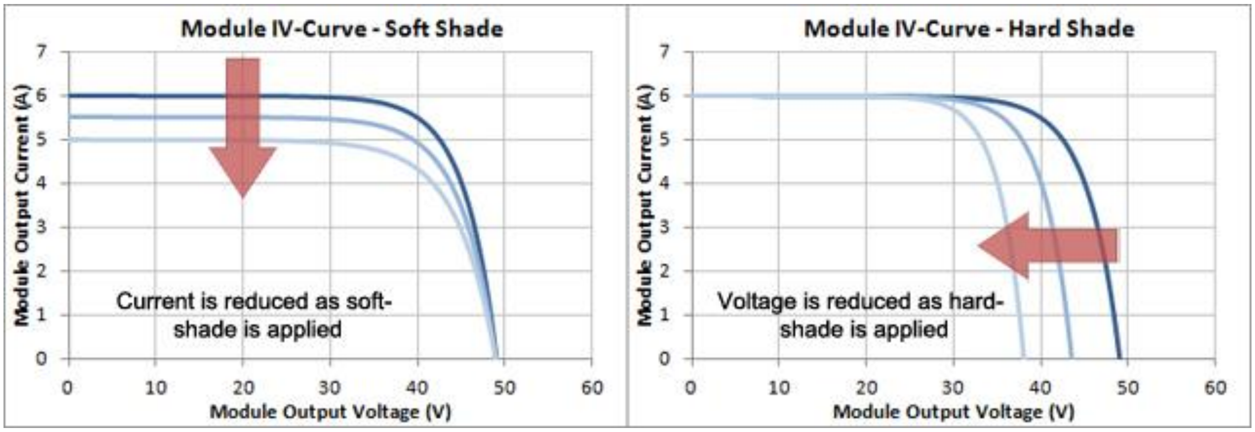


Figure 23 - Effect of soft and hard shade on PV cell (15)

As the sort of a shade is also considered dust and snow.

Dust

In some places of the world may the dust affect and therefore decrease the efficiency of PV panel output power by 40 %. Especially in desert areas. In milder conditions has been conducted an experiment which shows as a result an equation with which is possible within 95 % reliability calculate the affection of dust on the efficiency of PV panel.

$$\Delta\eta = 1{,}1429 + 345{,}96\ \mathrm{X}$$

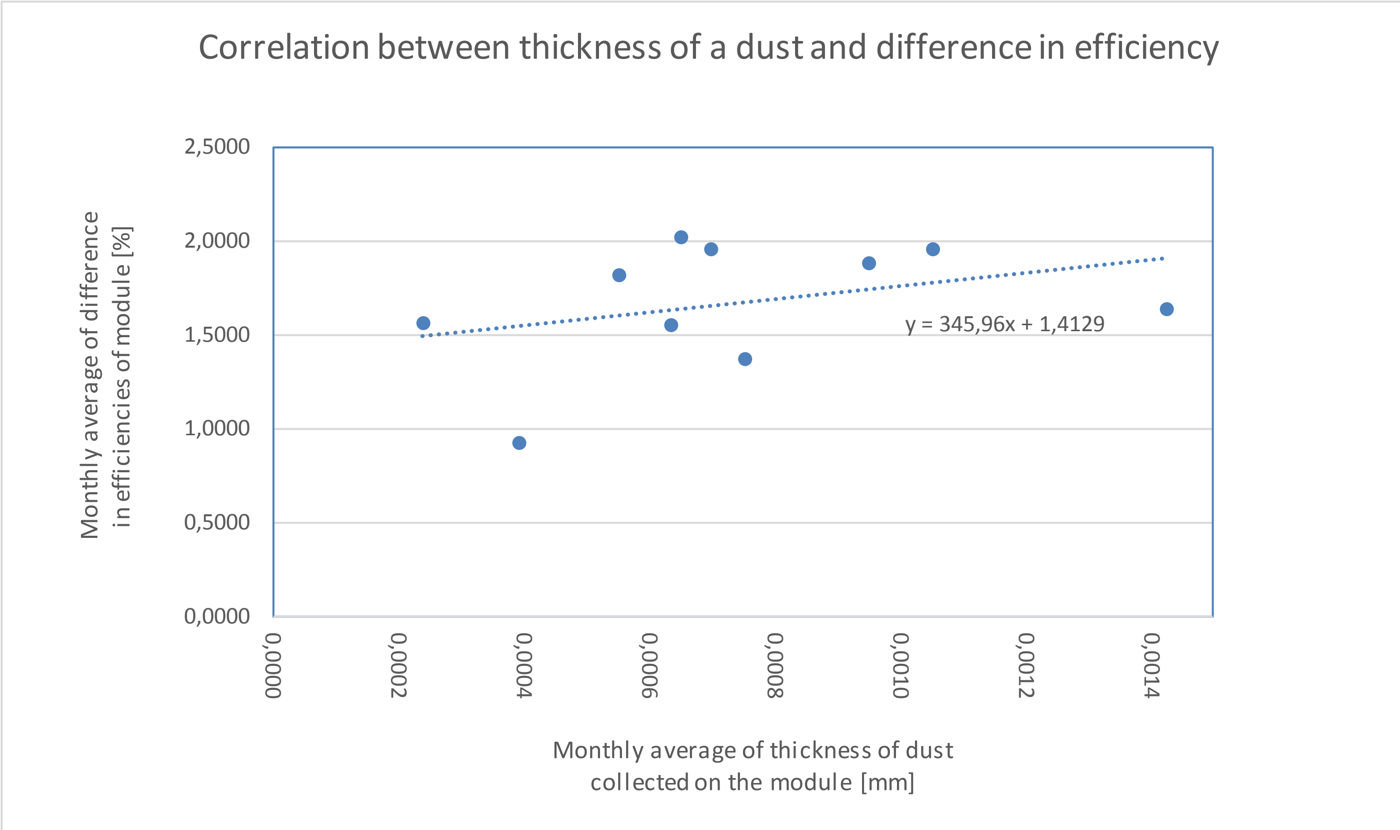


Figure 24 - Effect of dust on efficiency of PV cell (16)

Also according (17) is under greater irradiation the effect of dust slightly reduced but not negligible.

Snow

Freshly fallen snow can reflect up to 95 %

According to several researches, the snow self-clearing can occur from -10 $^{\circ}$C on panels inclined from 28 $^{\circ}$. Depending on inclination the yearly losses attributable to snow are from 0,3 % to 2,7 % (yearly measure at inclination 28 $^{\circ}$) (18)

2.1.4 Temperature

The effect of operating temperature on efficiency is well documented. As all semiconductor devices, solar cells are temperature sensitive. With higher temperature the band gap is reduced, which could be seen as increase of the electrons energy in the material. Therefore in higher temperature is needed lower energy to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap.

The temperature affects the current (I) and voltage (V) of the cell. The maximum power of is defined as maximal fill factor.

$$P_{max} = V_{max} * I_{max} = (FF)V_{oc} * I_{sc}$$

It turns out that both the open circuit voltage and the fill factor decrease substantially with temperature (as the thermally excited electrons begin to dominate the electrical properties of the semi-conductor), while the short-circuit current increases, but only slightly. Thus, the net effect leads to a linear relation in the form.

$$\eta_c = \eta_{Tref}\left[1 - \beta_{Tref}\left(T_c - T_{ref}\right)\right]$$

Where $\eta_c$efficiency of cell is, η_{Tref} is reference efficiency of tilted panel, β_{Tref} is reference temperature coefficient on modules tilted plane, T_c and is cell operating temperature, reference value temperature.

Values η_{Tref} and β_{Tref} are usually given by the manufacturer.

(19)

2.1.5 Usable area and efficiency

In some cases the area suitable for placing PV panels according to rules mentioned above so the yield will be optimal is limited i.e. when the PV system is built on a roof of a house for its own purposes, the panels cannot be placed all the way to the edge of the roof. It is necessary to place panels at some distance from the edge because of gusts, recommended distance is five times the height of the panel from roof. (20).

It is also necessary to take in account shades of chimneys, lightning conductors, dormer windows etc. which can significantly reduce usable area. The limited area forces to use more expensive high efficiency PV cells, to get sufficient yields.

In the case the roof is not tilted enough or even is slightly tilted northward it is necessary to use construction which will make the tilt and azimuth's direction make optimal. This construction will increase the actual efficiency of panels but on the other hand will decrease the usable area. As shown in the Figure 25 each row of panels needs to be placed 2,83 m from the one before. Otherwise would panels before shaded on panels behind. In the figure is shown the day when the Sun is the lowest on 48° latitude. Angle of tilt is 35°, angle of the roof is 0°, height of a panel is 1,65 m.

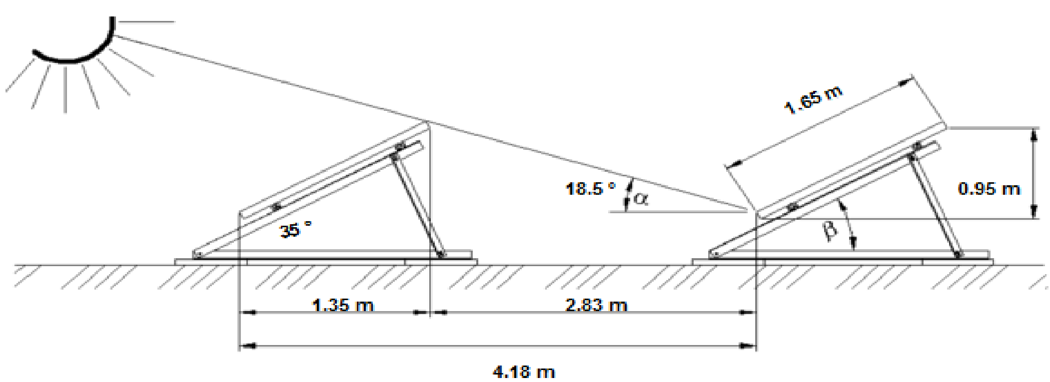


Figure 25 - Angles and distances for tilted panels (Source: Schletter)

2.2 Wind power potential

Winds is driven by temperature differences in the atmosphere and thus pressure differences therefore wind can be also seen as energy of Sun. In the global scale – Geostrophic winds (1000 m above ground level) are not very much influenced by surface of the earth. Surface winds (up to 100 m) are very much influenced by the ground surface. The wind will be slowed down by the earth's surface roughness and obstacles. Since most wind turbines are situated up to 100 m above ground level, surface winds will be further described more closely.

2.2.1 Global and Local wind characteristics

Global and local wind influence each other, even though global winds are important in determining the prevailing winds in a given area, local climatic conditions may overcome an influence of global wind directions. Local winds are always superimposed upon the larger scale wind systems, i.e. the wind direction is given by the sum of global and local effects. When larger scale winds are light, local winds may dominate the wind patterns.

Global wind characteristics

The wind rises from the equator and moves north and south in the higher layers of the atmosphere. Around 30°; latitude in both hemispheres the Coriolis force -since the globe is rotating, any movement on the Northern hemisphere is diverted to the right, if we look at it from our own position on the ground. (In the southern hemisphere it is bent to the left. This apparent bending force is known as the Coriolis force which prevents the air from moving much farther. At this latitude there is a high pressure area, as the air begins sinking down again. As the wind rises from the equator there will be a low pressure area close to ground level attracting winds from the North and South. At the Poles, there will be high pressure due to the cooling of the air. (21)

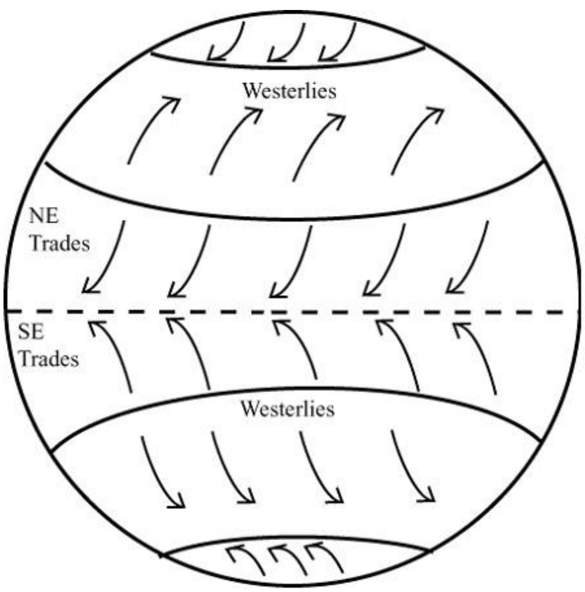


Figure 26 - Global wind directions (9)

Prevailing Wind Directions

Latitude	90-60°N	60-30°N	30-0°N	0-30°S	30-60°S	60-90°S
Direction	NE	SW	NE	SE	NW	SE

Table 5 - Global wind directions (9)

Local

There is many exerting factors of the local wind. As it was written above, the wind is driven by differences in temperature ergo pressure differences. Typical for this situations is following.

The land mass is heated by the Sun faster than the sea during the day. The air rises and flows to the sea, that way creates a low pressure at ground which attracts the cold air, this is called see breeze. Since at night the water keeps warmth longer than landmass (creates low pressure zone) the wind blows opposite direction, this is called land breeze.

In general in high heights above ground level, about 1 km, the wind is almost not influenced by the surface of the earth. In the lower layers of the atmosphere, wind speeds are affected by the friction against the surface of the earth. The wind shear shows how the friction influences the wind speed in different heights.

Mountain areas have specific patterns in weather. When the south facing slope (on the northern hemisphere), the air heated up by sunshine – the density of air decreases and the air moves upwards following the surface of the slope. If the valley floor is sloped, the air may move down or up the valley, as a canyon wind (22)

Obstacles

Obstacles like forest, trees, rock formations or buildings may decrease wind speed and direction of the wind significantly. These obstacles often also create turbulences in the adjacent area. The degradation of the wind velocity depends on the porosity of the obstacle. Porosity is defined as the open area divided by the total area of the object facing the wind.

A building is obviously solid with no porosity, on the other hand a tree in winter with no leaves may let more than half of the wind through. In summer, however, the foliage may be very dense, so as to make the porosity less than one third. The slowdown effect on the wind from an obstacle increases with the height and length of the obstacle. The effect is stronger close to the obstacle, and close to the ground.

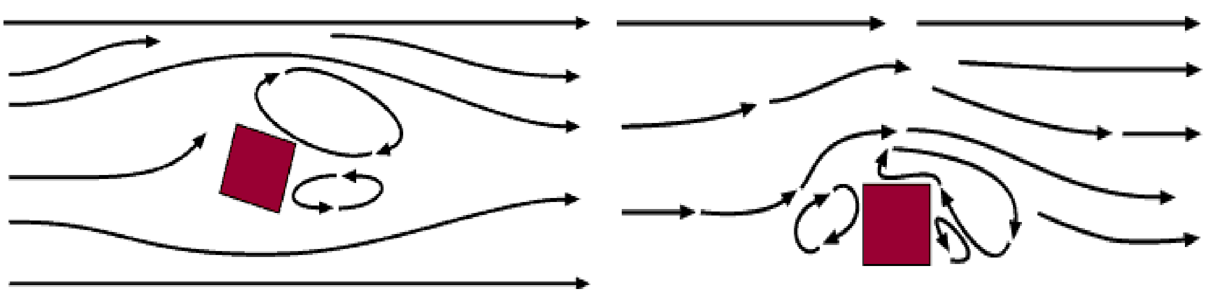


Figure 27 - Influence of an obstacle on wind direction and its regrouping

Roughness

In general the more rough the earth's surface is, the more is the speed of the wind slowed down. Roughness takes in account obstacles and the heterogeneity of the earth. In the wind industry, there is usually referred to roughness classes or roughness lengths, when they evaluate wind conditions in a landscape. A high roughness class of 3 to 4 refers to landscapes with many trees and buildings, while a sea surface is in roughness class 0.

Roughness Classes and Roughness Length Table

Rough-ness Class	Roughness Length m	Energy Index (per cent)	Landscape Type
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 1250 meters
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 500 meters
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 meter tall sheltering hedgerows with a distance of approx. 250 meters
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	18	Larger cities with tall buildings
4	1.6	13	Very large cities with tall buildings and skyscrapers

Table 6 - Roughness classes description (22)

Wind shear

The fact that the wind profile is twisted towards a lower speed as we move closer to ground level, is usually called wind shear. Wind shear may also be important when designing wind turbines. If you consider a wind turbine at a certain height (i.e. 50 m), but the anemometer is placed in another height (i.e. 10 m), the wind shear is the coefficient which corrects the wind speed in these heights.

The wind shear coefficient is calculated according to the next formula:

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^a$$

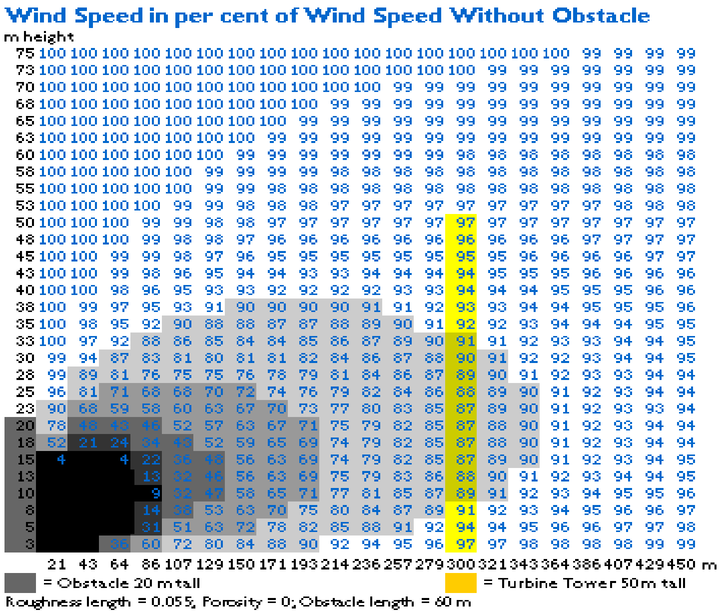
Where v is wind speed at height h, v_0 is reference speed, i.e. a wind speed we already know at height h_0, h is height above ground level for the desired velocity v, a is the roughness length in the current wind direction according to the following table.

Roughness class	Description of landscape	a
0	Open spaces, sand, water	0,12
1	Open space with rare bushes, hedges a trees	0,15
2	Agricultural land with scattered buildings and trees	0,18
3	Closed landscape with trees, many bushes and neighbor buildings	0,24

Table 7 - Wind sheer coefficients (23)

Wind shade

The wind shade map is often used to plot the wind velocity of behind some object.



Wind Speed in per cent of Wind Speed Without Obstacle

m height	21	43	64	86	107	129	150	171	193	214	236	257	279	300	321	343	364	386	407	429	450 m
75	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99
73	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99
70	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99
68	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99	99	99
65	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99	99	99	99
63	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99	99	99	99	99
60	100	100	100	100	100	100	99	99	99	99	99	99	99	98	98	98	98	98	98	98	98
58	100	100	100	100	100	99	99	99	99	98	98	98	98	98	98	98	98	98	98	98	98
55	100	100	100	100	100	99	99	98	98	98	98	98	98	98	98	98	98	98	98	98	98
53	100	100	100	100	99	99	98	98	98	97	97	97	97	97	97	97	97	97	98	98	98
50	100	100	100	99	99	98	98	97	97	97	97	97	97	97	97	97	97	97	97	97	97
48	100	100	100	99	98	98	97	96	96	96	96	96	96	96	96	96	96	97	97	97	97
45	100	100	99	99	98	97	96	95	95	95	95	95	95	95	95	96	96	96	96	97	97
43	100	100	99	98	96	95	94	94	93	93	94	94	94	94	95	95	95	96	96	96	96
40	100	100	98	96	95	93	93	92	92	92	92	93	93	94	94	94	95	95	95	96	96
38	100	99	97	95	93	91	90	90	90	90	91	91	92	93	93	94	94	95	95	95	96
35	100	98	95	92	90	88	88	87	87	88	89	90	91	92	92	93	94	94	94	95	95
33	100	97	92	88	86	85	84	84	85	86	87	89	90	91	91	92	93	93	94	94	95
30	99	94	87	83	81	80	81	81	82	84	86	87	88	90	91	92	92	93	94	94	95
28	99	89	81	76	75	75	76	78	79	81	84	86	87	89	90	91	92	93	93	94	94
25	96	81	71	68	68	70	72	74	76	79	82	84	86	88	89	90	91	92	93	94	94
23	90	68	59	58	60	63	67	70	73	77	80	83	85	87	89	90	91	92	93	93	94
20	78	48	43	46	52	57	63	67	71	75	79	82	85	87	88	90	91	92	93	94	94
18	52	21	24	34	43	52	59	65	69	74	79	82	85	87	88	90	91	92	93	94	94
15	4		4	22	36	48	56	63	69	74	79	82	85	87	89	90	91	92	93	94	95
13				13	32	46	56	63	69	75	79	83	86	88	90	91	92	93	94	94	95
10				9	32	47	58	65	71	77	81	85	87	89	91	92	93	94	95	95	96
8				14	38	53	63	70	75	80	84	87	89	91	92	93	94	95	96	96	97
5				31	51	63	72	78	82	85	88	91	92	94	94	95	96	96	97	97	98
3			36	60	72	80	84	88	90	92	94	95	96	97	97	98	98	98	98	99	99

Figure 28 - Wind speed in per cent of Wind speed without an Obstacle (22)

In the Figure there is an example of wind speed map. There is depicted a 20 m tall building with porosity 0, it is 60 m long. The roughness length is 0,055. The wind turbine is in a 50 m hub height and 300 m far. The blue numbers indicate the wind speed in per cent of the wind speed without the obstacle. At the top of the yellow wind turbine tower the wind speed has decreased to 97 per cent of the speed without the obstacle. This means a loss of wind energy of some 9,3 % (exactly $1.03^3 - 1$).

The wind turbine itself also casts wind shade usually called wake effect in the downwind direction. Which is important for wind parks. (22)

Hill effect

Upon hills, one may also experience that wind speeds are higher than in the surrounding area. It is due to the fact that the wind becomes compressed on the windy side of the hill, and once the air reaches the ridge it can expand again as its soars down into the low pressure area on the lee side of the hill. Also on the other hand it may be noticed that the wind becomes very irregular, once it passes through the wind turbine rotor. If the hill is steep or has an uneven surface, the wind may get significant amounts of turbulence, which may negate the advantage of higher wind speeds.

Tunnel effect

The air becomes compressed on one side of mountains or buildings, and in case there is a tunnel between them the speed of wind coming through increases considerably between these obstacles. This is known as a "tunnel effect". So, even if the general wind speed in open terrain may be 6 m/s it can easily reach 9 m/s in a natural tunnel.

2.2.2 Wind energy land register

Wind registers are made to visualize wind conditions of some area and to sum up climatic conditions potential especially velocity and direction of the wind. As specialized tool helping with design wind power plants are made from the beginning of 1980. There are many models to calculate the wind map.

The most modern ones are calculated by either from meteorological stations data and already standing wind power generators close to them. (23)

2.2.3 Wind rose

The wind rose is a graph and compass showing of cardinal points and prevailing wind direction and velocity. If presented in a circular format, the modern wind rose shows the frequency of winds blowing from particular directions over a specified period. The length of each "spoke" around the circle is related to the frequency that the wind blows from a particular direction per unit time. Each concentric circle represents a different frequency, rising from zero at the center to increasing frequencies at the outer circles. A wind rose plot may contain additional information, in that each spoke is broken down into color-coded bands that show wind speed ranges as showed in example figure below. In the figure is shown that the most powerful wind comes from south, second most powerful from North West and so on. (24)

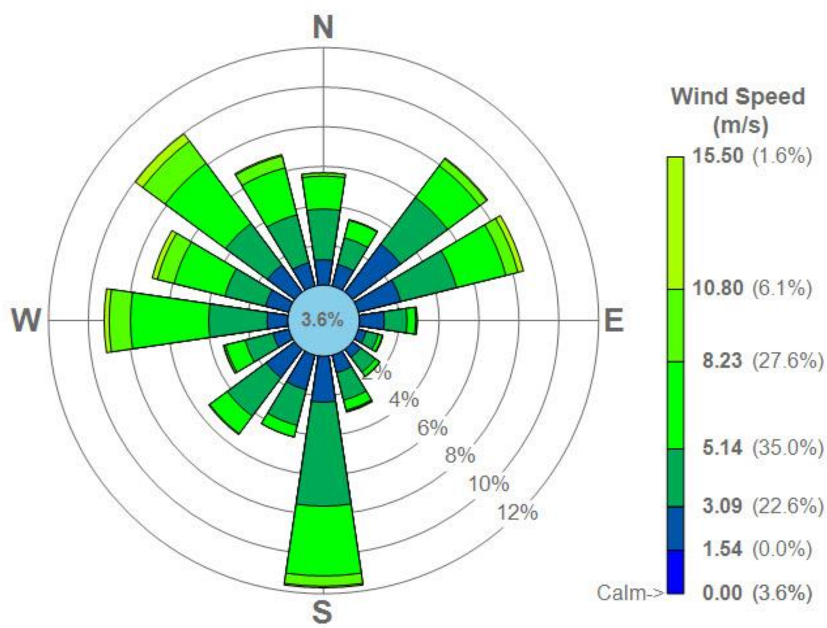


Figure 29 - Wind rose (24)

2.2.4 Energy in the wind – air density, rotor area, wind velocity

There are three most influential factors of the energy in the wind. The formula for wind power passing perpendicularly through a circuit are is:

$$P = \frac{1}{2}\rho v^3 \pi r^2$$

Where P is power [W], ρ is density of air [kg/m^3], v is the wind velocity [m/s], π is the mathematic constant which gives the ratio of perimeter to its ratio [], r is the radius (half of a diameter) of the area[m]. (22)

Air density

The rotor converts to electrical power the kinetic energy of the wind and the kinetic energy of a moving object is proportional to its mass, therefore the kinetic energy of wind depends on its density – the mass per unit of volume. The denser the air is, the more energy it contains. At regular atmospheric pressure and 15 °C the density of air is 1,225 [kg/m^3]. The density may change with the pressure of air (i.e. with rising elevation above sea level the pressure declines), humidity or specific gas contamination and temperature. (25)

Area

Since the power in the formula above rises with the second power of diameter, it is a very influential factor. A swept area is an area which is calculated in the formula above, it is an area which is created by the circle of the end of blades as they sweep through the air.

Wind velocity

The wind velocity is the most important of all from the energy content of the wind, because according to formula it rises with third power. The energy varies with the third power because of the second Newton's law of motion. The wind turbine we uses the energy from braking the wind, and if we double the wind speed, we get twice as many "one second slices" (the dark blue cylinder in the following figure) of wind moving through the rotor every second, and each of those slices contains four times as much energy.

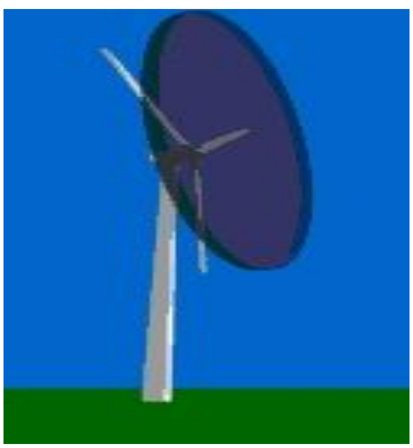


Figure 30 - One second slice of wind (24)

2.2.5 Weibull distribution

There has been many various mathematical methods developed to assist in prediction of the power output production. The most appropriate for this purpose is a statistical function known as Weibull distribution. This function is used to determine the wind distribution in the selected site. The Weibull distribution function has been proposed as a more generally accepted model for this purpose. Since there has been a measured the wind speed for just a short time period. It has been used data from further meteorological station so the recalculation according to obstacles a roughness length had to be done.

As said in chapter 2.2.4the most influential factor of power produced of all is wind velocity, because of that it is important to describe variations in wind velocity. This is the most needed information in the wind power industry. Engineers need it to optimize wind turbine's characteristics and minimize costs and on the other hand investors need it to estimate the electricity generation consequently economic indicators of an investment.

If the wind speed measured it may be noticed that the most powerful winds are rare, while moderate and light wind are common. The wind variation is usually described by Weibull distribution. Statistically described the Weibull distribution for an average wind speed 7 m/s and shape parameter of 2 look as in the following figure. The area under the curve is always exactly 1, since the probability that the wind will be blowing at some wind speed including zero must be 100 %. The vertical line in the blue area at the point 6,6 m/s is dividing the area into two equal halves.

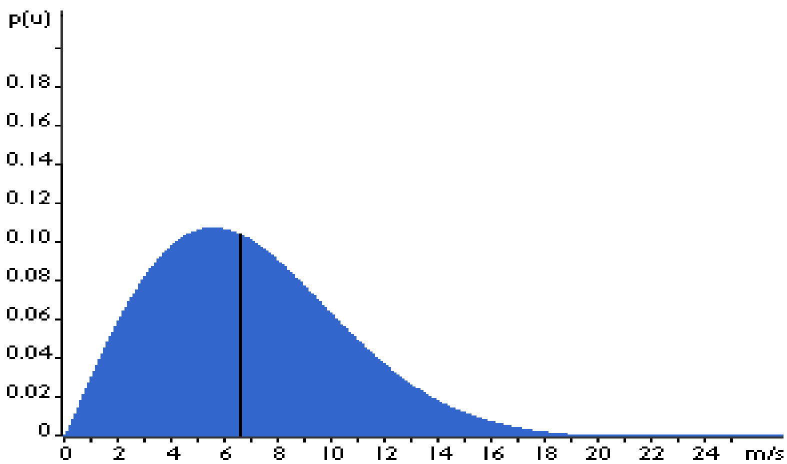


Figure 31 - Weibull distribution (24)

This is very important in the case the investor or designer has just simplified meteorological data in this case mean wind speed. Since the wind speed influences yielded power with third power of wind velocity, using mean wind speed would be inaccurate. The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface. The Weibull distribution may thus vary, both in its shape, and in its mean value.

The distribution of wind is skewed. If the shape parameter is exactly 2, as in the Figure, the distribution is known as a Rayleigh distribution. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution.

It may be very unprecise to calculate wind power from a mean wind velocity especially in a case when the average is taken in longer time period. It is impossible to use the power at mean wind speed to figure out how much power will be produced by the wind turbine. It is impossible in wind energy industry to calculate wind power without Weibull distribution.

According to Weibull distribution it is possible to recalculate the average wind speed back it its probable wind speeds which were used to calculate the average. The probability density is calculated according to the following formula (26).

$$p(x) = \left(\frac{k}{C}\right)\left(\frac{x}{C}\right)^{k-1} exp\left[-\left(\frac{x}{C}\right)^{k}\right]$$

Where $k > 0, x \geq 0$ and $C > 0$, k is the shape factor specified by the user and ranges usually form 1 to 3. For a given average wind speed a lower shape factor indicates relatively wide distribution, higher shape represents narrow distribution around the average. A lower shape factor leads to higher energy production for a given average wind speed. C is the scale factor which is calculated from following formula.

$$C = \frac{\bar{x}}{\Gamma\left(1 + \frac{1}{k}\right)}$$

Where $\bar{x}$the average is wind speed and Γ is the gamma function.

2.2.6 Mean power of wind

The reason why it should be understood well about wind speeds is their energy content. As in the example with bottles. We cared about their content in terms of volume. Now, the volume of a bottle varies with the cube of the size, just like wind power varies with the cube of the wind speed. Let us take the Weibull distribution of wind speeds, and for each speed we place a bottle on a shelf each time there is a 1 % probability of getting that wind speed. The size (height) of each bottle corresponds to the wind speed, so the weight of each bottle corresponds to the amount of energy in the wind.

3 Electric power consumer's specification

Power consumer demand and structure is analyzed in detail in this chapter. There is a list of all electrical devices with power with nominal power inputs and other details. There will be power compared typical power consumers (Standardized load profile) with the same consumption throughout the year with measured values. The main characteristics which will be used for sizing generators and batteries are power consumed per average day during heating season and the overall highest power input. There will be several ways to calculate it and compare it with measured values. There is also a PV generator on the roof of the object.

3.1 Present electric power system structure

There is quite many electrical devices used. Although there is many of them, just few of them have major impact on power consumption. There is just 7 devices (out of 35) which consume over 2 % of the overall consumption. These are in the descending order: heating 1st degree of heating (lower power and temperature), heating 2nd degree of heating (higher power and temperature), water heater, lightning, stove and oven.

I have assumed the difference between summer and winter load profile, which will be examined further in 413.1.2 on the page 41. There also has been an assumption about differences in load profile of week-days and weekends, there was assumed there will be higher consumption on weekends. This assumption has been rejected by the data analysis, which has confirmed the difference between week-day and weekend with opposite result. During some random hours of the average summer week-day is consumed more and some hours less kWh than during average weekend day. Similarly during average winter week-day and average weekend day. This differences between weekends and week-days are in this case not important and will not be further examined.

3.1.1 List of appliances

A list of all appliances follows. To calculate a yearly consumption in kWh there was a used either time of use or number of cycles.

Device	Number of devices	Power [W]	Time of use [h]	Number of cycles	Consumption [kWh]	% of consumption
TV	1	188	1095	0	205,86	1,25
Satellite	1	30	1095	0	32,85	0,20
Radio inside	1	20	2190	0	43,80	0,26
Radio outside	1	20	600	0	12,00	0,07
DVD	1	80	52	0	4,16	0,03
Alarm system	1	23	8760	0	201,48	1,22
Weather station	1	5	8760	0	43,80	0,26
DVR+cameras	1	36	8760	0	315,36	1,91
Videotelephone	3	3	8760	0	26,28	0,16
Mobile phone	4	4	3	1460	17,52	0,11
Office notebook 1	1	90	2190	0	197,10	1,19
Office notebook 1 (back up)	1	90	40	0	3,60	0,02
iPad	1	40	3	16	1,92	0,01
Printer	2	4,8	730	0	3,50	0,02
Router	2	12	8760	0	210,24	1,27
Notebook 3	1	90	730	0	65,70	0,40
Notebook 4	1	90	730	0	65,70	0,40
Notebook 5	1	90	104	0	9,36	0,06
Speakers	3	30	356	0	10,68	0,06
Sewing machine	1	100	20	0	2,00	0,01
Refrigerator	1	31	8760	0	269,00	1,63
Dishwasher	1	700	1	365	255,50	1,55
Oven	1	2350	208	0	488,80	2,96
Stove	1	2000	547,5	0	1095,00	6,62
Kettle	1	2000	0,1	730	146,00	0,88
Washing machine	1	1200	1	200	240,00	1,45
Vacuum cleaner	1	2100	0,5	52	54,60	0,33
Iron	1	1800	1	52	93,60	0,57
Minor kitchen appliance	1	1500	0,5	52	39,00	0,24
Minor bathroom appliances	1	1200	0,3	365	131,40	0,79

FVE invertor	1	2	8760	0	17,52	0,11
Heating 1st degree	1	6000	1120	0	6720,00	40,65
Heating 2nd degree	1	9000	320	0	2880,00	17,42
Water boiler	1	0	365	0	2122,48	12,84
Light	52	15	650	0	507,00	3,07
Total					**16532,81**	**100,00**

3.1.2 Load profile and seasonal influences

According to latest four electric bills the total consumption per one year was from 15,6 MWh to 18,3 MWh. As showed in **Ошибка! Источник ссылки не найден.Ошибка! Источник ссылки не найден.** the heating and water boiler consume about 70 % of overall energy, and most of it of course in the heating season. There is several ways how to set the load profile. I will compare calculated and measured load profile.

Over past four years there have been used two tariffs. The change has been done in attempt to save energy. Both tariffs are used when electrical heating is used. Tariff D25d (also called Accumulation) is used for accumulation of heat in the hot water, the accumulation is done during 8 hours with lower charge. Than water heater is turned on by centralized ripple control. The other tariff D45d (Convector) is usually used for 20 hours per day for convection heating.

Standardized load profile is used to recalculate yearly sum of consumption back into 8760 hour values over coefficients which are calculated according to subjects with same tariff but really measured. This standardized load profile suits to a group of subjects and may be used for a typical representative of the group. This standardized load profile is recalculated according to temperature of the year into the adjusted load profile.

Following load profiles have been done based on the data which take in account the production of photovoltaic generator. The consumption has been already lowered by energy produced by PV generator and used in the object.

On the examined object I have also measured the input power since 1st of October 2012. Therefore the standardized load profile will be also examined from this time period to be able to compare both of them.

Winter as a heating season is defined from November until March. Of course there is heating used outside of this time period, but most of the time there is used fireplace with heat-water exchanger. The use of the fireplace may be nicely seen in the Figure 38 where the winter of 2014 begins out of the sudden, even though when it is compared with heating degree days which begun gradually. Within this definition of summer and winter season there is less than 10 % heating days in the summer season and less than 10 % non-heating days in the winter.

Comparison of standardized and measured load profile

D25d

Tariff D25d was used from 1. 10. 2012 until 31. 7. 2013. There will be described this whole time period, average winter and summer day, day with the lowest power consumption and the day with the highest consumption.

Description of time period 1. 10. 2012 – 31. 7. 2013

In the next Figure 33 there are one hour averages in both load profiles. There were expected some differences between standardized load profile and measured maybe a bit smaller than as in the case of tariff D25d. The correlation coefficient is 0,84 which means that most of the time when the data in standardized load grows, the measured data input also increases.

The number of heating degree days and average month temperature are in Figure 32. There are monthly values for temperature, number of heating degree days and number of days which are according to the Czech norm described in the paragraph 1.2.3. These values were measured in the weather station in the city about 18 km far, which is called Ústí nad Labem.

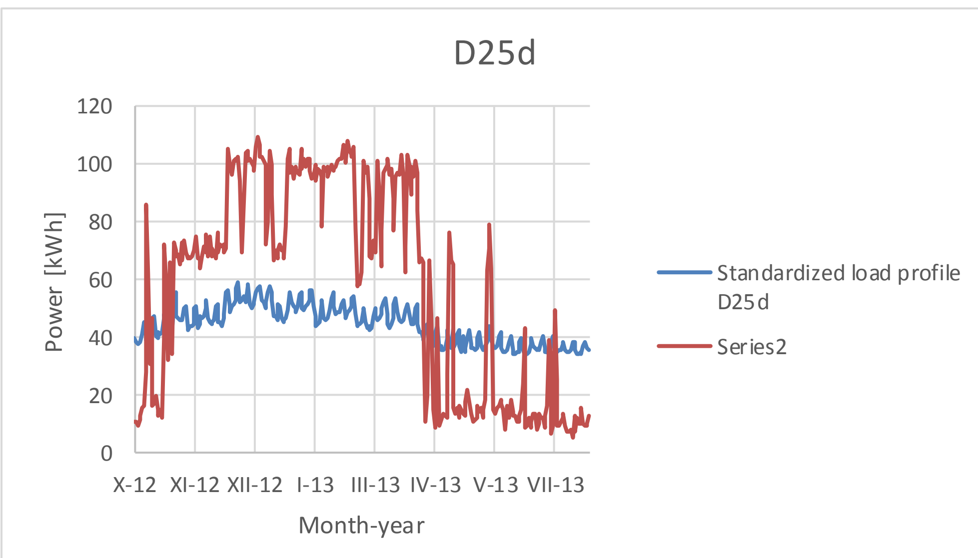


Figure 32 - Comparison of standardized and measured profile D25d

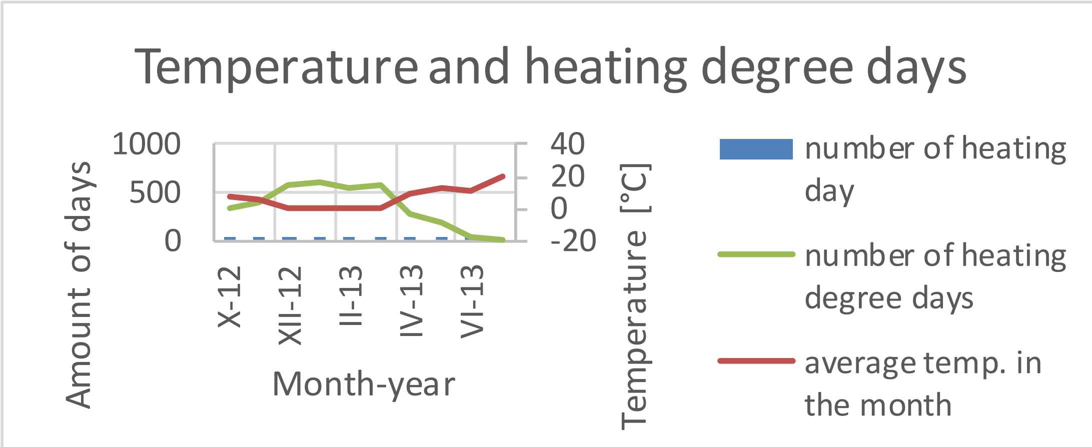


Figure 33 - Temperature and heating degree days for the time period of D25d

In the next Table 8 there is a correlation among data sets, which were supposed to be dependent on each other. There is positive relation between number of heating degree days and both load profiles. So when the number of heating degree days increases the data in both profile increases too, which is explained as power used for heating when there is a cold weather. There is slightly better correspondence between measured data and the number of heating days.

The negative correlation among average temperature and both load profiles is explained as higher power consumption used for heating when exactly as in the previous situation. Only the temperature decreases and the power consumed increased.

	Standardized load profile	**Measured load profile**
Number of heating degree days	0,95	0,97
Average temp. in each of the month	-0,93	-0,94

Table 8 - Table of correlation coefficients among data sets

Average winter and summer day

Average winter and summer day's profile is quite similar, there is an afternoon and night peak, which exactly follows the 8 hours of low rate schedule of the tariff. This time period there is a water boiler accumulating the heat in the summer and winter. In the winter during this 8 hour period there is also running the heating boiler, which accumulates the heat in water tanks, therefore the profile is quite similar but 2-3 times higher consumption. The total consumption in an average winter day is 49,6 kWh according to standardized profile and 87,91 kWh according to measured profile. During a summer day it is 38,79 kWh according to standardized profile and 28,05 kWh according to measured profile.

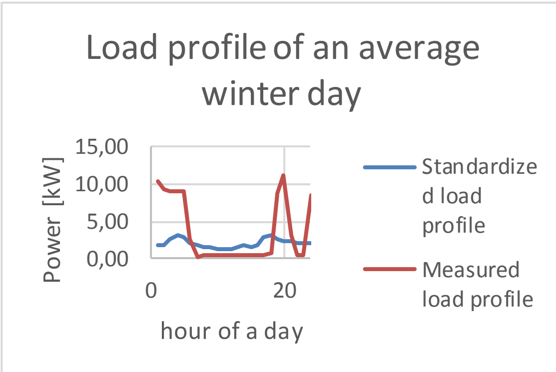


Figure 34 - Comparison of the standardized and measured load profile in an average winter day with tariff D25d

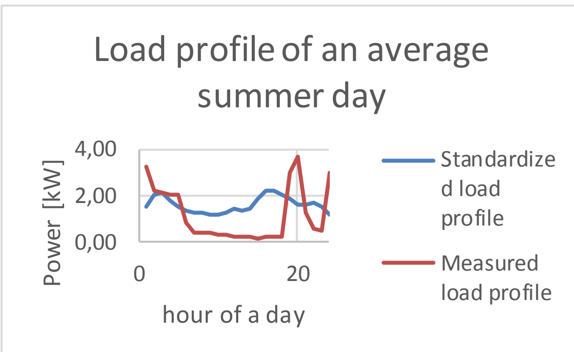


Figure 35 - Comparison of the standardized and measured load profile in an average summer day with tariff D25d

Day with highest and lowest power consumption

The day with highest consumption was supposed to be in winter, according to the standardized and measured values it has been in December for the tariff D25d. During the low rate schedule there is an input close to the maximal value, probably the water and heat boiler was running as may be seen in the Figure 36. The day with the lowest consumed energy is on the other hand in summer with high sunshine power, when the photovoltaic generator produces more power than consumed as in the Figure 37

	Measured	Standard
sum	17558	17558
min value [kWh/day]	6	34
max value [kWh/day]	110	59
date of min day	20.07.2013	18.06.2013
date of max day	22.12.2012	09.12.2012

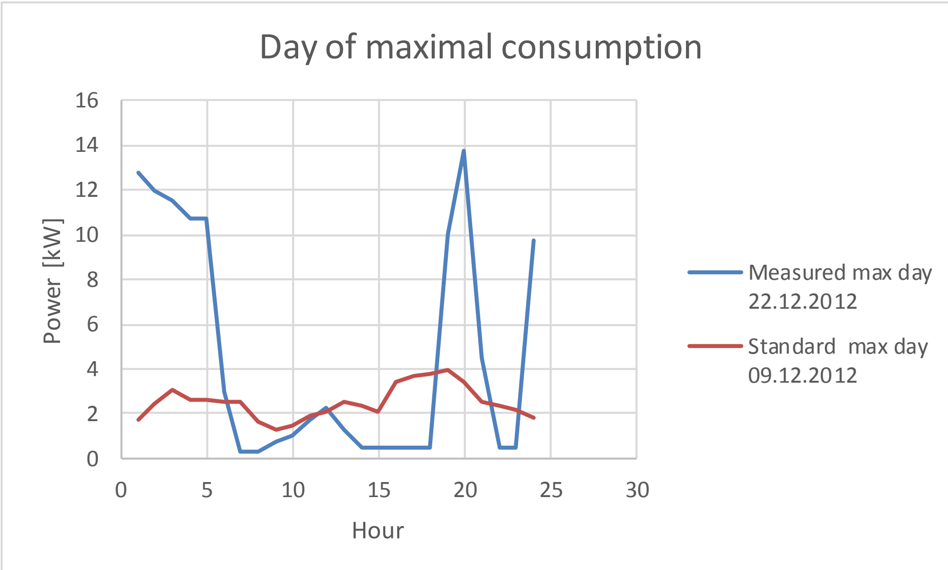


Figure 36 - Day with maximal power consumed with tariff D25d

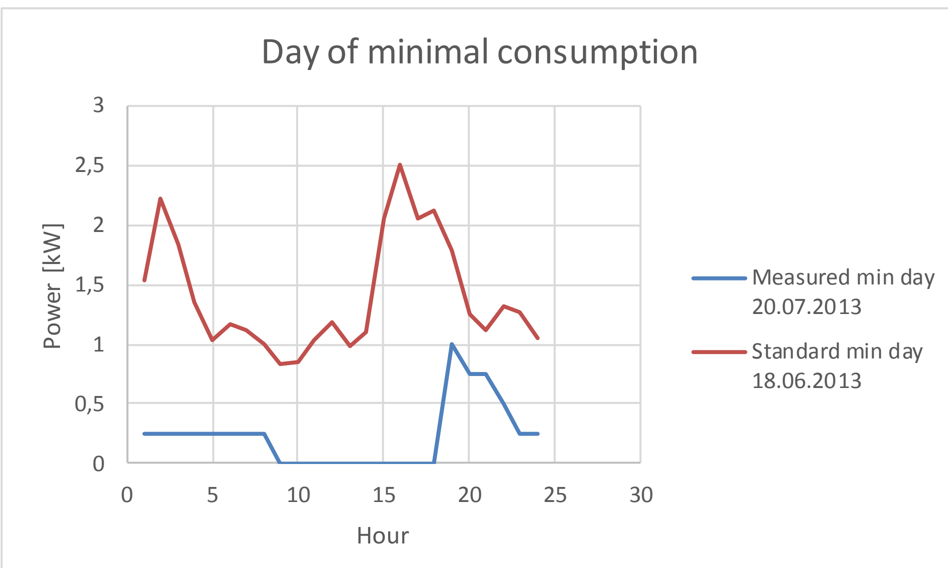


Figure 37- Day with minimal power consumed with tariff D25d

	Measured max day	**Standard max day**	**Measured min day**	**Standard min day**
hour\date	22.12.2012	09.12.2012	20.07.2013	18.06.2013
1	12,75	1,70	0,25	1,54
2	12	2,41	0,25	2,22
3	11,5	3,06	0,25	1,84
4	10,75	2,65	0,25	1,36
5	10,75	2,64	0,25	1,03

6	3	2,49	0,25	1,17
7	0,25	2,48	0,25	1,12
8	0,25	1,64	0,25	1,00
9	0,75	1,31	0	0,84
10	1	1,44	0	0,84
11	1,75	1,94	0	1,03
12	2,25	2,08	0	1,18
13	1,25	2,54	0	0,98
14	0,5	2,38	0	1,10
15	0,5	2,07	0	2,06
16	0,5	3,39	0	2,50
17	0,5	3,68	0	2,05
18	0,5	3,76	0	2,12
19	10	3,98	1	1,79
20	13,75	3,38	0,75	1,25
21	4,5	2,49	0,75	1,12
22	0,5	2,33	0,5	1,31
23	0,5	2,13	0,25	1,27
24	9,75	1,78	0,25	1,06

D45d

There are two year data sets in the next Figure 38, there also may be nicely represented that the fireplace can heat up the object in the case it is necessary. Both years the beginning of boilers heating season is replaced by fireplace, especially in 2014. This information will be taken in account in the further chapter especially in dimensioning of generators in winter.

Description of time period 1. 8. 201 – 31. 7. 2015

In the next Figure 38 there are one hour averages in standardized and measured load profiles. There were expected some differences between standardized load profile but these both profiles correspond quite a little bit better than in case of tariff D25d. The correlation coefficient is 0,88 which means that most of the time when the data in standardized load grows up, the measured input in the same period of time also increases.

The number of heating degree days and average month temperature are in. There are monthly values for temperature, number of heating degree days and number of days which are according to the Czech norm described in the paragraph 1.2.3. These values were measured in the weather station in the city about 18 km far, which is called Ústí nad Labem.

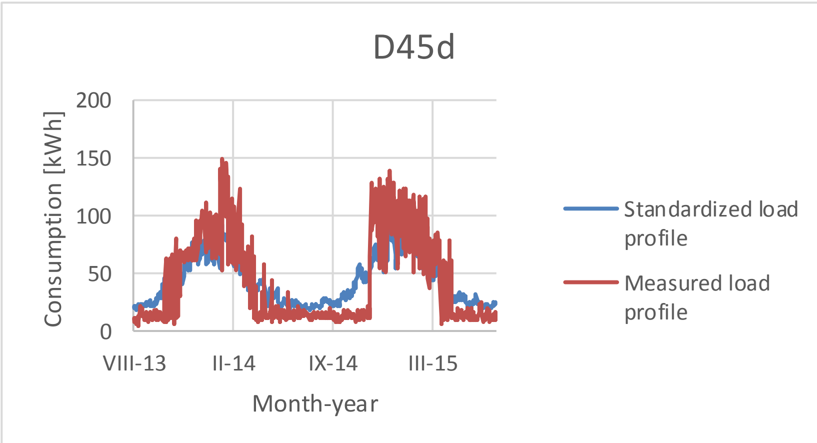


Figure 38 – Comparison of Standardized and measure load profile with tariff D45d

The number of heating degree days in the average month temperature are in Figure 39. There are monthly values for temperature, number of heating degree days and number of days which are according to the Czech norm described in the paragraph 1.2.3. These values were measured in the same weather station as the ones in the Figure 33, in the close town called Ústí nad Labem. The **Ошибка! Источник ссылки не найден.** shows the correlation of the data

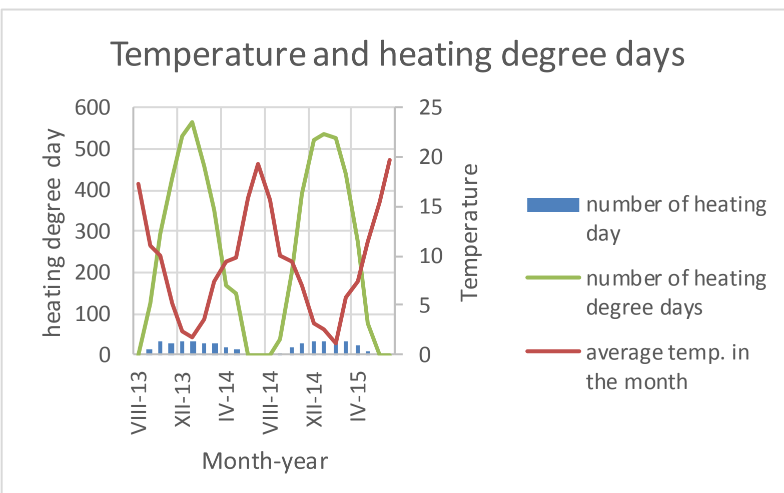


Figure 39 - Temperature and heating degree days for the time period of D45d

	Standardized load profile	Measured load profile
number of heating degree days	0,98	0,95

Average temp. in the month	-0,93	-0,87

Average winter and summer day

Load profile of an average winter day nicely follows the hours of low rate part of the schedule. Since there is just four hours of high rate, here are the hours of schedule of high rate 9-10 am, 11-12 am, 13-14 pm, and 16-17 pm. In this high rate schedule, there is the lowest consumption of the whole day.

During average winter day is consumed 66,49 kWh according to standardized load profile and 80,89 kWh according the measured values.

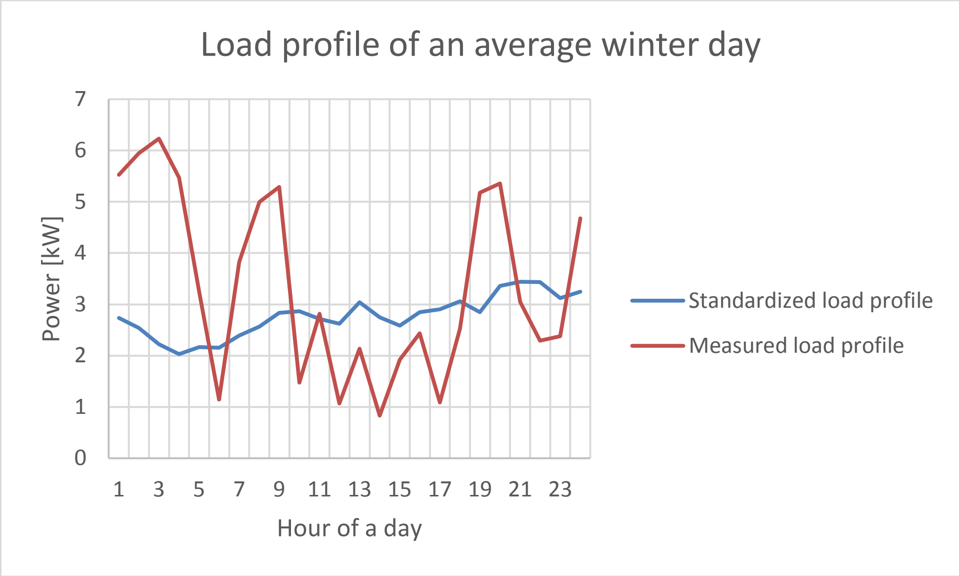


Figure 40 - Comparison of the standardized and measured load profile in an average summer day with tariff D45d

The Figure 41 compares the standardized and measured load profile of an average summer day. Similarly as in the Figure 35 in the measured data may be seen the influence of the photovoltaic generator during the day.

During the average summer day there is used 32,7 kWh according to standardized load profile and 17,72 kWh according to measured load profile.

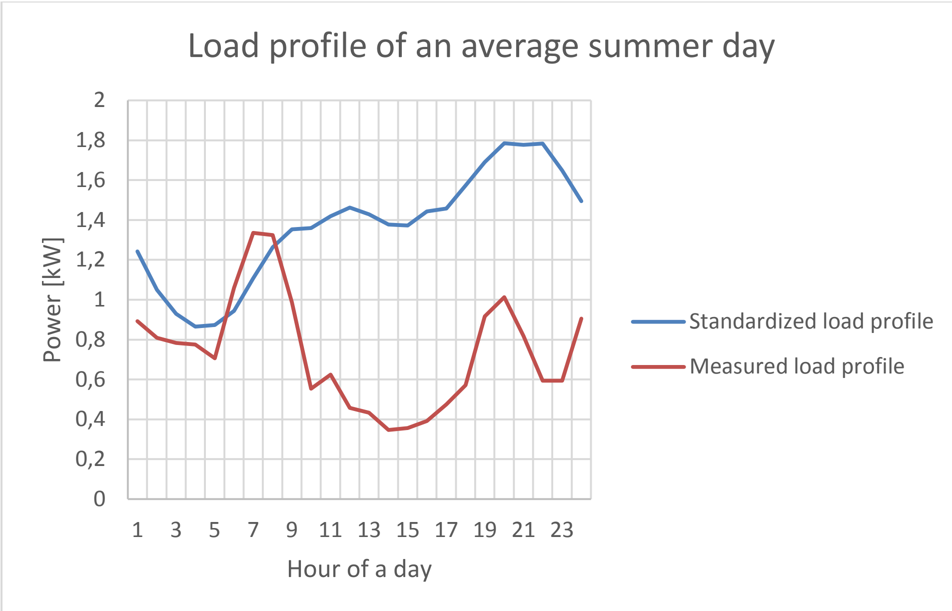


Figure 41 - Comparison of the standardized and measured load profile in an average winter day with tariff D45d

Day with highest and lowest power consumption

In the tariff D45d there are two year data sets as an example I have evaluated both seasons 2013/2014 and 2014/2015 in the table but plotted in just the first one it the graph (they are very similar to each other without any major differences). The sum of measured values differs by 2 kWh of yearly consumption because the measurement has been done by with accuracy of 0,25 kWh. The deviation is a mathematical round up error. In the season of 2014/2015 the deviation is 40 kWh per year. The deviation of 2 kWh respectively 40 kWh in one season is statistically not significant in consumption of 15,6 MWh in 2013/2014 respectively 16,4 MWh in 2014/2015.

2013/2014	**Measured**	**Standard**
sum	15629	15627
min value [kWh/day]	5,5	18,3
max value [kWh/day]	150	93
date of min day	10.08.2013	21.07.2014
date of max day	27.01.2014	26.01.2014

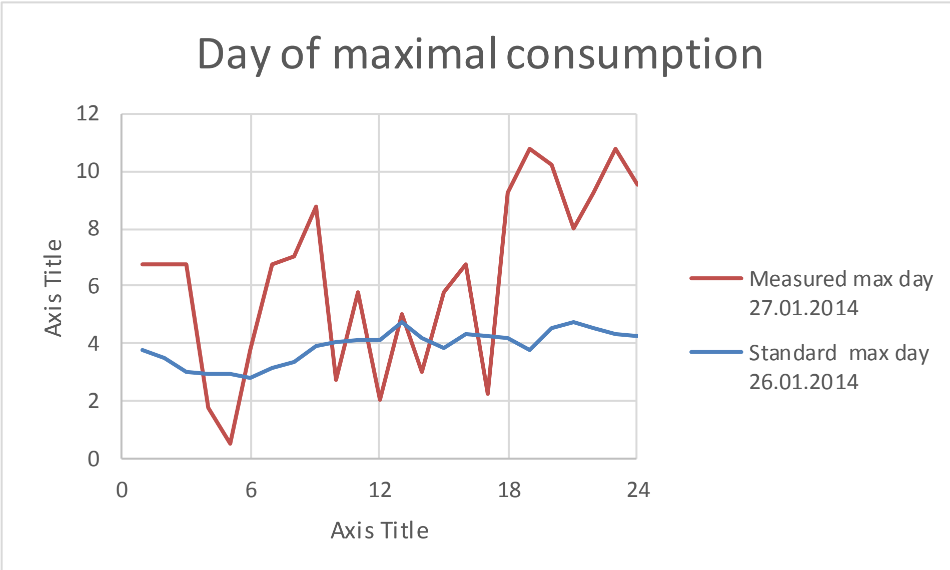


Figure 42 - Day with maximal power consumed with tariff D45d

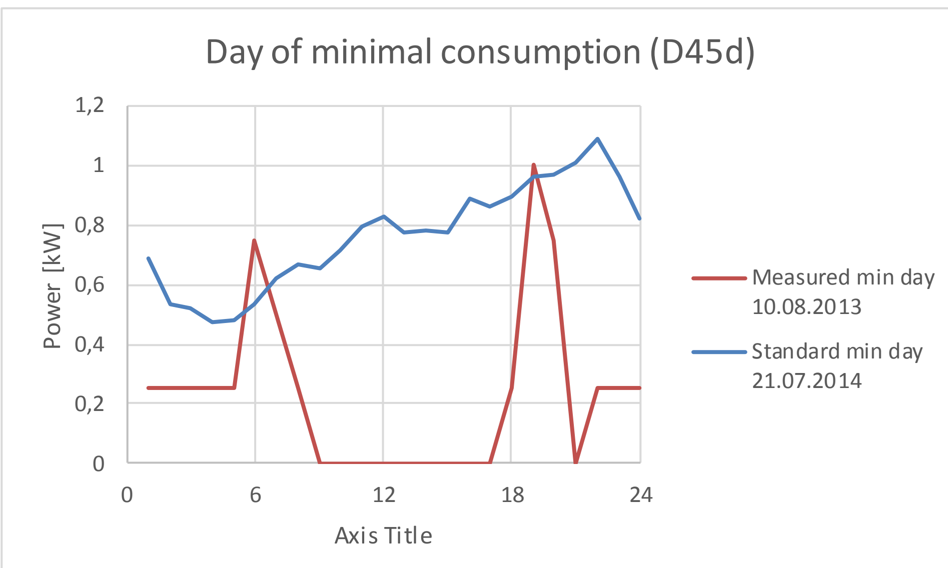


Figure 43 - Day with minimal power consumed with tariff D45d

3.1.3 Influence of the photovoltaic generator to current load profile

As mentioned before, there is installed 5 kWp generator on the roof of the object. The photovoltaic generator was installed in 2010. I have started collecting data from September 2011. During one year period it has produced from 4,4 to 5,3 MWh. There is about 76 % of the yearly energy produced in the summer (non-heating) season.

There were used 22 PV panels 230 Wp each, total 5,06 kWp. The invertor Piko Kostal 5.5 is connected to the home grid into three phases evenly distributing the power generated. Since the inverter is an older device there was in 2013 also installed a Wattrouter M (SolarControls s.r.o), which is used to distribute the power from PV generator straight to several appliances according to some desired rules. These rules may be defined by the power generated, the time setting and priority of connected devices. The Wattrouter provides optimization of the power which is generated to be also consumed in the object and not to be fed into the public grid.

To the Wattrouter there are two various modes used, summer and winter. The setting is done that there is always with the highest priority to feed the power into the hot water boiler, in the summer there is second the heating boiler of the swimming pool and during the winter the heating boiler for the house. Even there is all this setting done, there is consumed about 44 % of the energy produced.

Characteristic values of the data sets follow in the **Ошибка! Источник ссылки не найден.**. If not written differently, values are for all data from 1. 10. 2012 to 31.7.2015.

	A+ Consumption daily [kWh]	A- Export daily [kWh]	Yield power PV gen. daily [kWh]	Consumption of yield from PV gen. [kWh]	Sum of consumption form PV and A+ [kWh]	Ratio of power consumed/produ
overall maximal value	148,00	26,00	32,71	22,39	148,60	
overall average value	47,93	6,98	12,37	5,39	53,32	0
overall sum	49559,25	7220,00	12791,93	5571,93	55131,18	
summer maximal value	103,25	26,00	32,71	22,39	109,28	
summer average value	20,45	9,78	17,15	7,36	27,82	0
winter maximal value	148,00	23,75	32,56	14,51	148,60	
winter average value	83,25	3,40	6,24	2,85	86,09	0

A+ Consumption daily [kWh]	A- Export daily [kWh]	Yield power PV gen. daily [kWh]	Consumption of yield from PV gen. [kWh]	Sum of consumption form PV and A+ [kWh]

	A+ Consumption daily [kWh]	**A- Export daily [kWh]**	**Yield power PV gen. daily [kWh]**	**Consumption of yield from PV gen. [kWh]**	**Sum of consumption form PV and A+ [kWh]**	**Ratio of power consumed/produced**
overall maximal value	148,00	26,00	32,71	22,39	148,60	
overall average value	47,93	6,98	12,37	5,39	53,32	0,44
overall sum	49559,25	7220,00	12791,93	5571,93	55131,18	
summer maximal value	103,25	26,00	32,71	22,39	109,28	

summer average value	20,45	9,78	17,15	7,36	27,82	0,43
winter maximal value	148,00	23,75	32,56	14,51	148,60	
winter average value	83,25	3,40	6,24	2,85	86,09	0,46

To depicture how much of the yield of PV generator is consumed compared with the consumption from the gird is shown in the

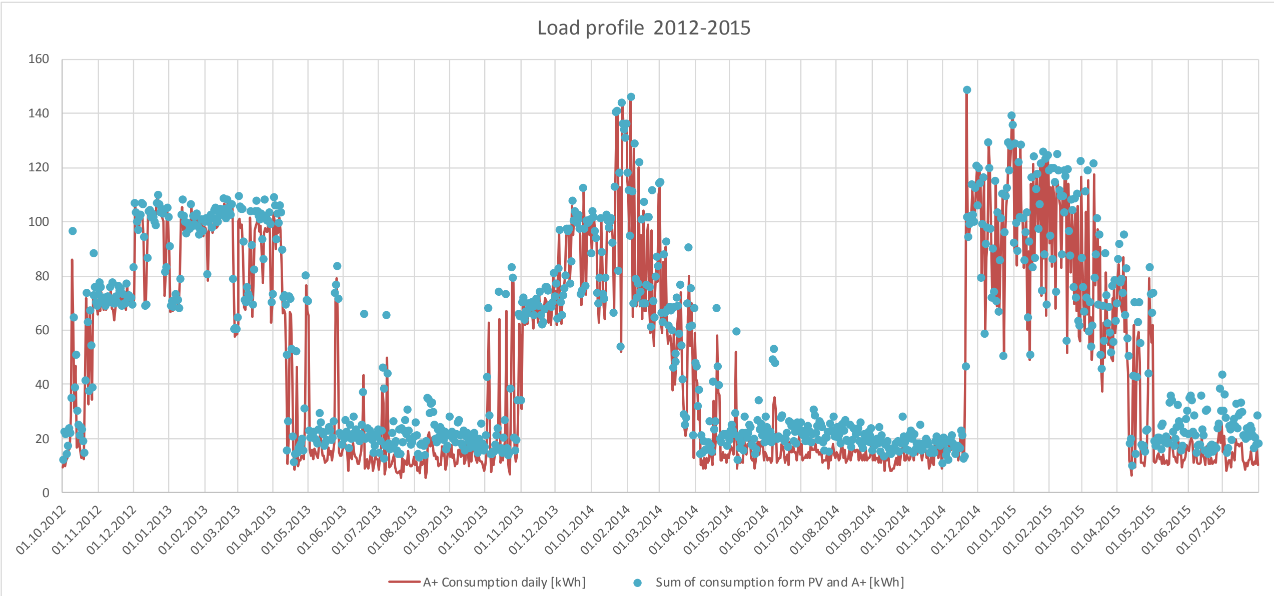


Figure *44*

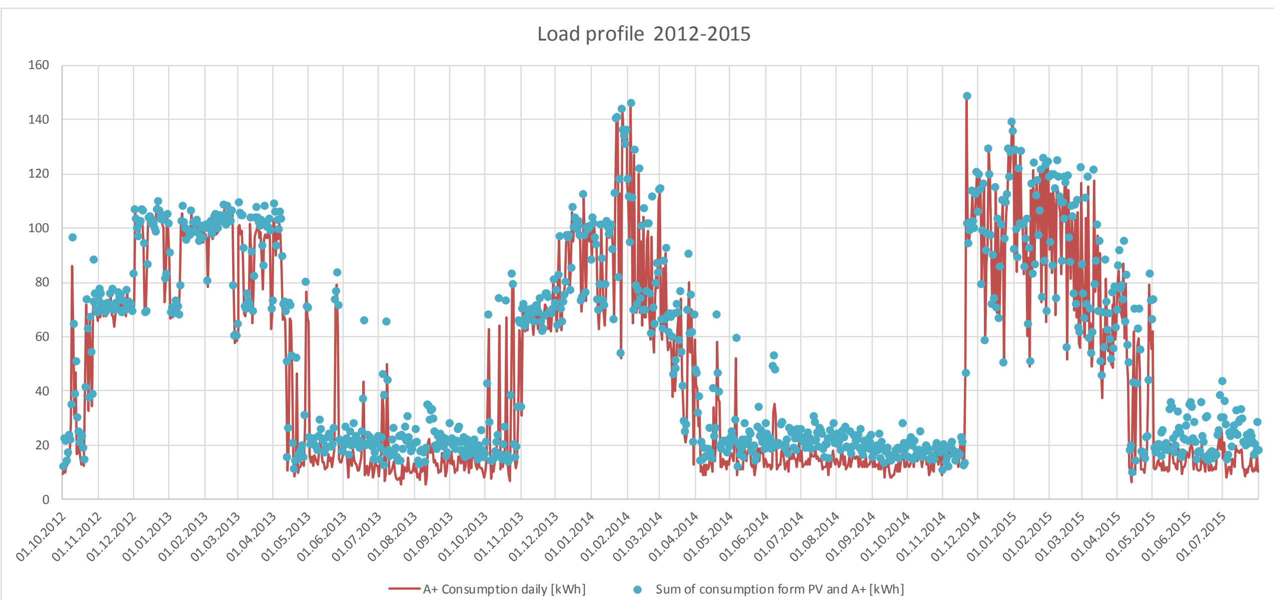


Figure 44 - Load profile of power from the grid and (A+) and PV power

The next Figure 45 depictures how much of the power produced by PV generator is used compared to the total power production. The difference is fed into the grid. The difference is a space for usage for example of batteries without installing new panels.

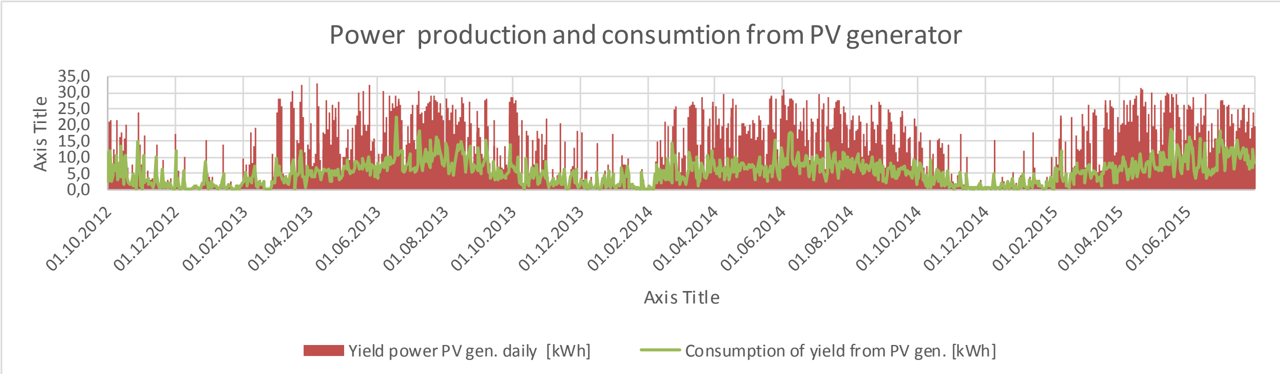


Figure 45 - Power produced by PV generator and used without storage

It is important to understand what how the data sets correlate with each other for further examination. For example if there were added any new panels (causing the rise in the Yield power from PV gen.), it is very probable that some of it would be exported (rise in A- Export) and some also some would be consumed (rise in Consumption of yield PV power), because of high positive correlation coefficient. On the other hand there will be decrease in A+ Consumption from the grid, but not as big as increases in the previous cases. Since it has smaller and negative correlation coefficient.

	A+ Consumption daily [kWh]	A- Export daily [kWh]	Yield power PV gen. daily [kWh]	Consumption of yield from PV gen. [kWh]	Sum of consumption form PV and A+ [kWh]
A+ Consumption daily [kWh]	1,00	-0,49	-0,57	-0,56	1,00
A- Export daily [kWh]	-0,49	1,00	0,95	0,63	-0,45
Yield power PV gen. daily [kWh]	-0,57	0,95	1,00	0,84	-0,51
Consumption of yield from PV gen. [kWh]	-0,56	0,63	0,84	1,00	-0,48
Sum of consumption form PV and A+ [kWh]	1,00	-0,45	-0,51	-0,48	1,00

4 Electric power supply selection for autonomous systems

In this chapter I will use the previous data analysis and weather data to make the object self-sufficient and not connected to the public grid. There might be necessary to change the source of heat from regular boiler for a heat pump to make the winter share of load lower and make the whole year-round load curve smoother. The smoother load curve would in the end bring smaller autonomous system which means lower investment cost of the autonomous system.

4.1.1 Photovoltaic generator – model 1 kWp

The PV generator model has been based on weather data from PVGIS – Photovoltaic Geographical Information System, which is widely used among specialists and also freely accessible on the internet. (3) The PVGIS is a source of data about the amount of energy which impacts onto the ground for an average day in a month, which I have used. It also may calculate the power produced by PV generator or for a stand-alone system with respect to its setting. The setting is may be done in this fields: PV technology (crystalline silicon, CIS or CdTe), installed peak PV power, estimated power losses (in %), mounting position (free standing or building integrated), slope also called inclination, azimuth, tracking options, radiation database, month of the average day, battery voltage and capacity, cut off limit (% of DOD) and daily consumption of the object.

In the model were used these variable values. Losses has been set according to data sheet of products and (27)

- Location latitude: 50.6844, longitude 13.8630
- Inclination of the roof 35 °
- Orientation 7 ° (east - 90 °, south 0 °)
- Efficiency of the panel 16 %
- Efficiency of invertor 92 % (Victron)
- Efficiency of MPP 98 % (Victron)
- Losses caused by heat in summer 5 %
- Losses in AC cables 2 %
- Losses in DC cables 2 %
- Shadow 0 %
- Too weak irradiation to generate necessary voltage 3 %
- Snow and dust 3 %

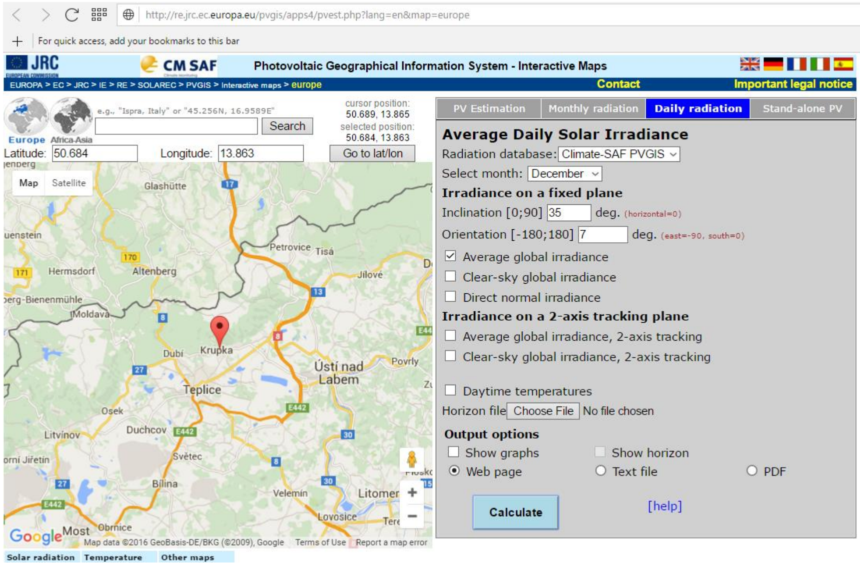


Figure 46 - PVGIS configuration for the model

The model has been created with respect to all condition described in the chapter 1.3.1 and 2.1. Since I have used a values for an average day in the month for each day I should use an average daily temperature in the model. This was not done, because of two reasons. The average temperature monitored in one hour period is not available anywhere close to the object, so I was forced to use an average day in the month. And the testing temperature was 25 °C. The monthly average temperature of a day never rises above 25 °C, so instead of the real temperature losses given by temperature coefficient I have used heat loses in percentage of total losses according to literature.

In the Figure 47 there is the outcome of the model for 1 kWp PV generator as a graph of an average day in a month. The x-axis is the hour of the day and on the y-axis is the AC power output.

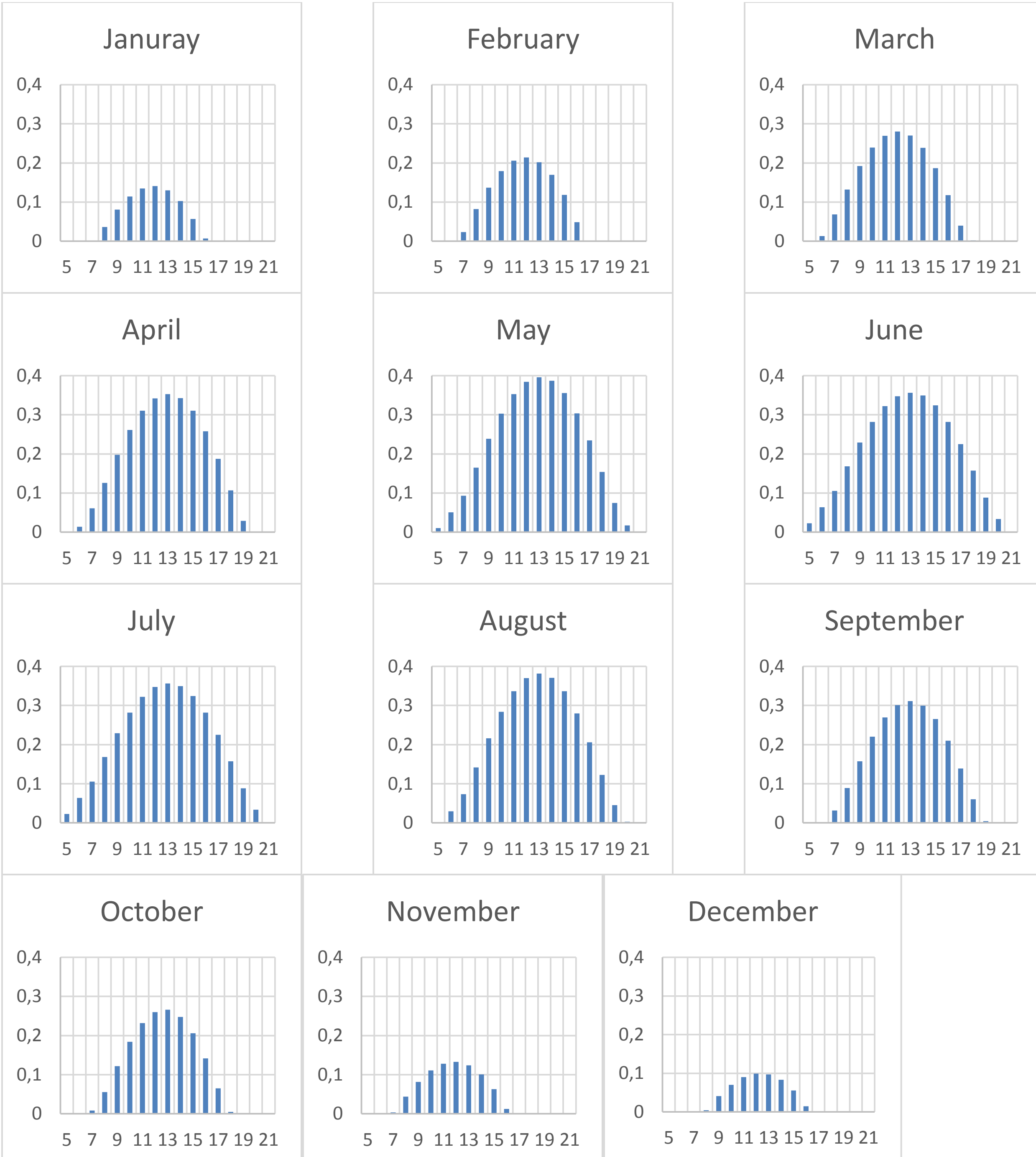


Figure 47 - The plot of an average day in a certain month as a result of the PV generator's model

4.1.2 Wind generator – model 1 kWp

Likewise in PV generator model, in the wind generator model will be calculated an average day in each month. The data needed for this are more difficult to obtain. There is three official are several amateur weather station close the object. The historical data which these weather station provide are very limited, or are not downloadable. Therefore the WECS model was calculated from the data extracted from

EOSWEB - NASA Surface meteorology (28). To make the model more reliable there was installed my own weather station right on the roof of the object in January 2016.

10m height

There was used ten year average of the wind speed at height 50 m/s, since it is thought to place the wind turbine on the roof of the object, the wind speed was reduced according to Difference between the Average Wind Speed at 10 m Above the Surface of the Earth and the Average Wind speed At 50 m above the Surface Of The Earth (% coefficient - average coefficient -46 %) also from EOSWEB - NASA Surface meteorology (28). And further reduced according to the local conditions (22) especially according to roughness classes as in Table 6 - Roughness classes descriptionTable 6. The roughness class according to description was 2,5, which means reduction of wind speed 69 % (the difference between avg. wind speed and local avg. wind speed in **Ошибка! Источник ссылки не найден.**)

The following table shows the input data:

	avg. wind speed in 50 m [m/s]	diff between 50 m and 10 m [%]	avg. wind speed in 10m [m/s]	Wind shear recalc wind speed
January	8,65	-0,48	4,50	6,128631444
February	7,91	-0,47	4,19	6,27
March	7,68	-0,44	4,30	
April	6,26	-0,43	3,57	
May	5,90	-0,43	3,36	
June	5,92	-0,42	3,43	
July	6,38	-0,42	3,70	
August	6,38	-0,46	3,45	
September	7,35	-0,49	3,75	
October	7,59	-0,51	3,72	
November	8,36	-0,51	4,10	
December	8,73	-0,50	4,37	

The last column of the **Ошибка! Источник ссылки не найден.** was used to calculate probability of all wind speeds according to chapter number 2.2.5 for each month. Energy produced monthly was than divided into an average day in the month. Since there was done measurement of wind speeds from January to April 2016 for these months were used the average hour in the month. For the rest of the months will be used the average of January – April to create the average day model.

It is apparent that there are higher wind speeds (and power production) during the day, mostly from 12 pm to 22 pm, with some exceptions. There must be longer observation if it is true to all months. As the **Ошибка! Источник ссылки не найден.** shows, there are slightly higher wind speeds in the winter season. In the Figure 48 –The plot of an average day in a month as a result of 1 kW WECS modeFigure 48 is the plot of the WECS in 10 m. At the 10 m height the yield power was too low, therefore it was used just like a referential height for the model. And was considered to use a height of 30 or 50 m. The 50 m was considered better even at higher cost, because it will bring higher yields.

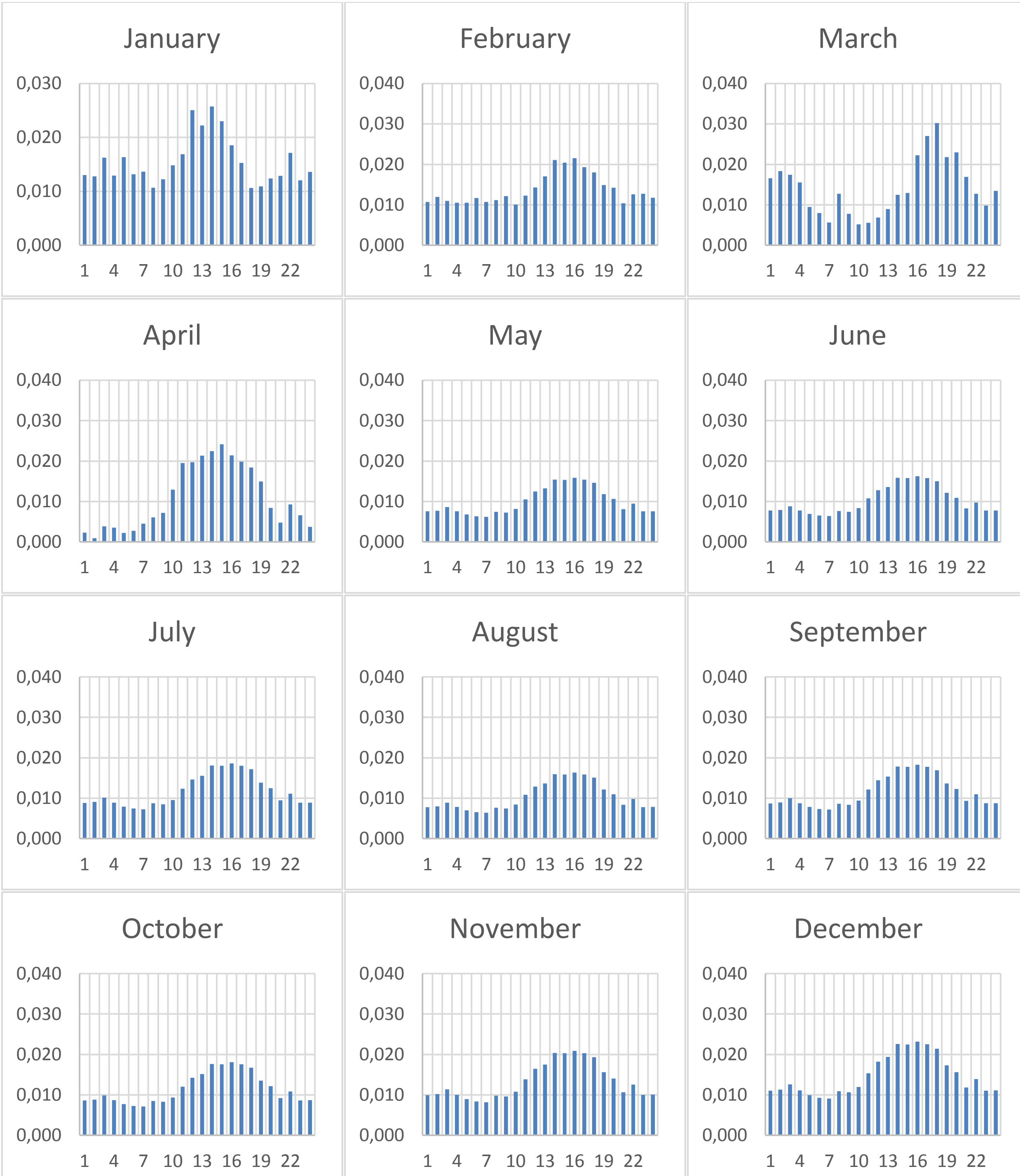
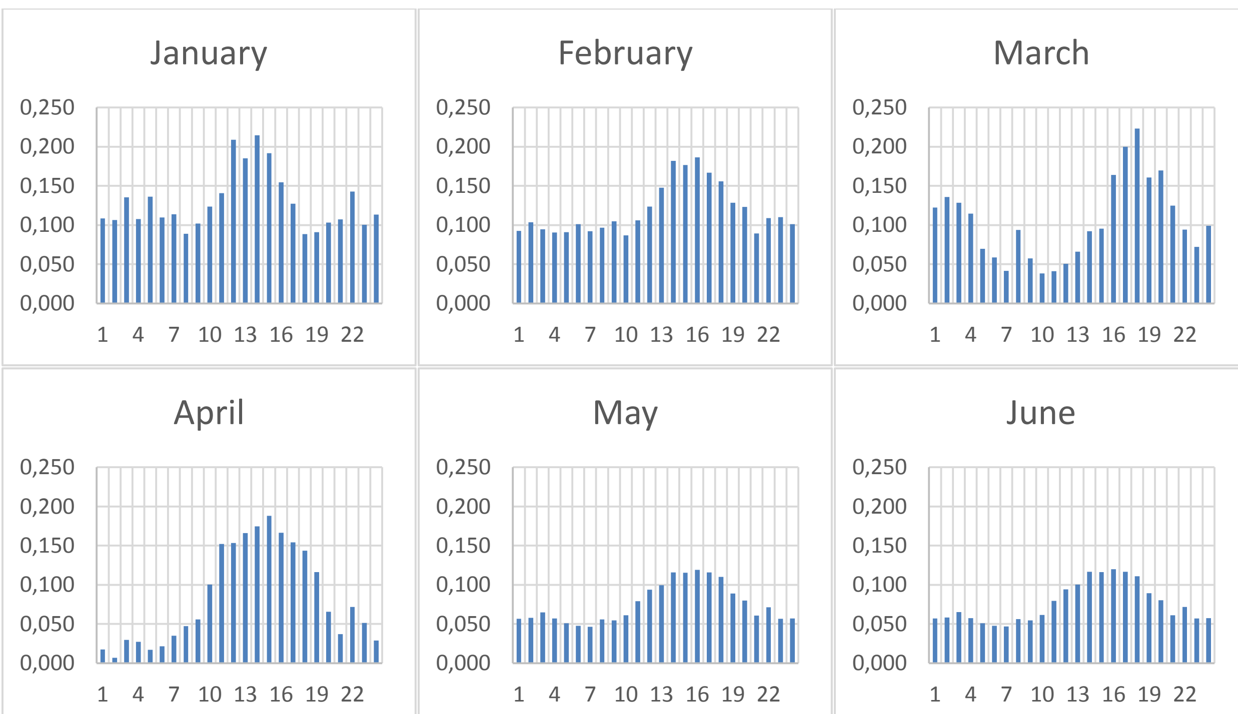


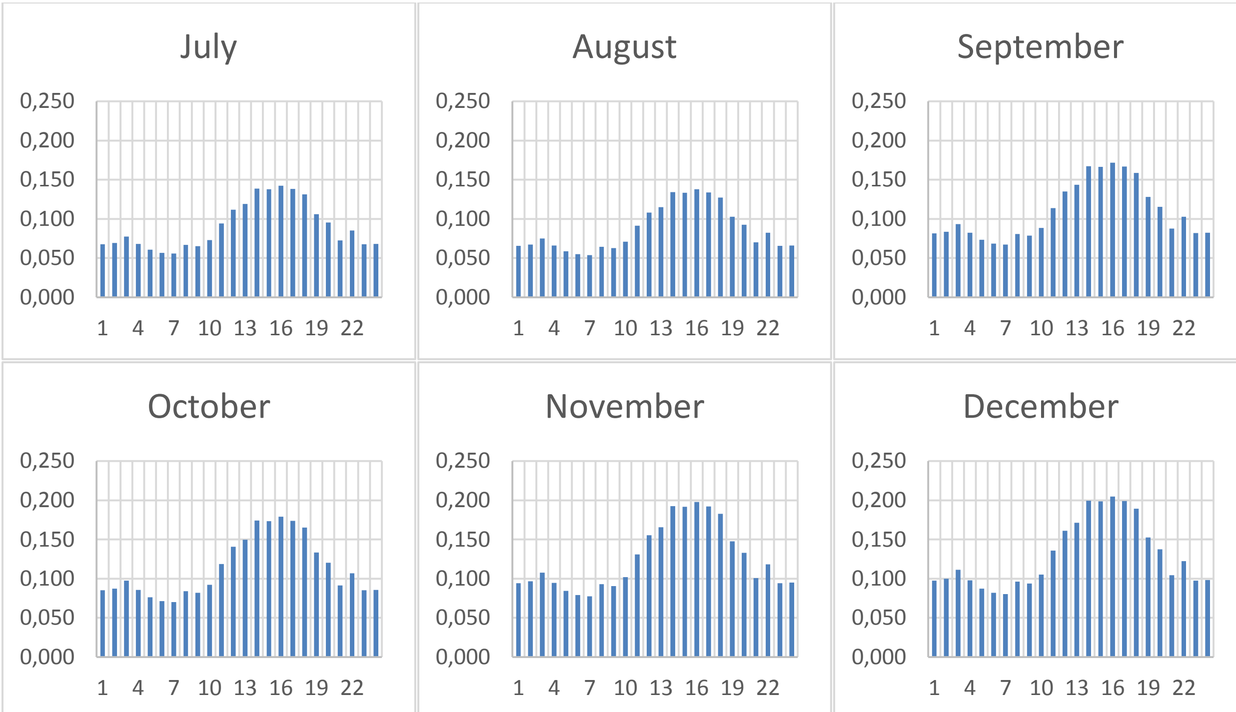
Figure 48 –The plot of an average day in a month as a result of 1 kW WECS model

30m and 50m height

Since the wind speeds in 10m height were considered too low, it was again recalculated the wind speed to 30m according to and 50m height where could be the wind generator placed.

	avg. wind speed in 50 m [m/s]	local 50 m avg. wind speed [m/s]
January	8,65	2,68
February	7,91	2,45
March	7,68	2,38
April	6,26	1,94
May	5,90	1,83
June	5,92	1,84
July	6,38	1,98
August	6,38	1,98
September	7,35	2,28
October	7,59	2,35
November	8,36	2,59
December	8,73	2,71





4.1.3 Battery model

At any hour the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during **the time from t-1 to t**. During the charging process, when the total output of PV and wind generators is greater than the load demand, the available battery bank capacity at hour t can be described by**:**

$$C_{bat}(t) = C_{bat}(t-1)(1-\sigma) + \left(E_{PV}(t) + E_{WG}(t) - \frac{E_L(t)}{\eta_{inv}}\right)\eta_{bat}$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at hour t can be expressed as:

$$C_{bat}(t) = C_{bat}(t-1)(1-\sigma) - \left(\frac{E_L(t)}{\eta_{inv}} - E_{PV}(t) + E_{WG}(t)\right)$$

Where $C_{bat}(t)$ and $C_{bat}(t-1)$ − are the available battery bank capacity (Wh) at hour t and $t-1$, respectively; ηbat is the battery efficiency (during discharging process, the battery discharging efficiency was set equal to 1 and during charging, the efficiency is 0,7 to 0,9 depending on the charging current), σ is self-discharge rate of the battery bank. The manufacturer documentation gives a self-discharge up to 5 % per month with lithium ion batteries and up to 25 % with lead acid per month. (29).

4.1.4 PV and Wind generator together

In the following figures there are average winter and summer generators characteristics together with the load characteristics of the object. The wind speed is higher in the winter season, on the other hand the sun is shining more in the summer. This complementary character is shown in the next figure. Since there is quite low wind speed potential nearby the object it was calculated that the ratio WECS and PV generator should be about the 2:1 to produce the same amount of the energy during the winter and summer.

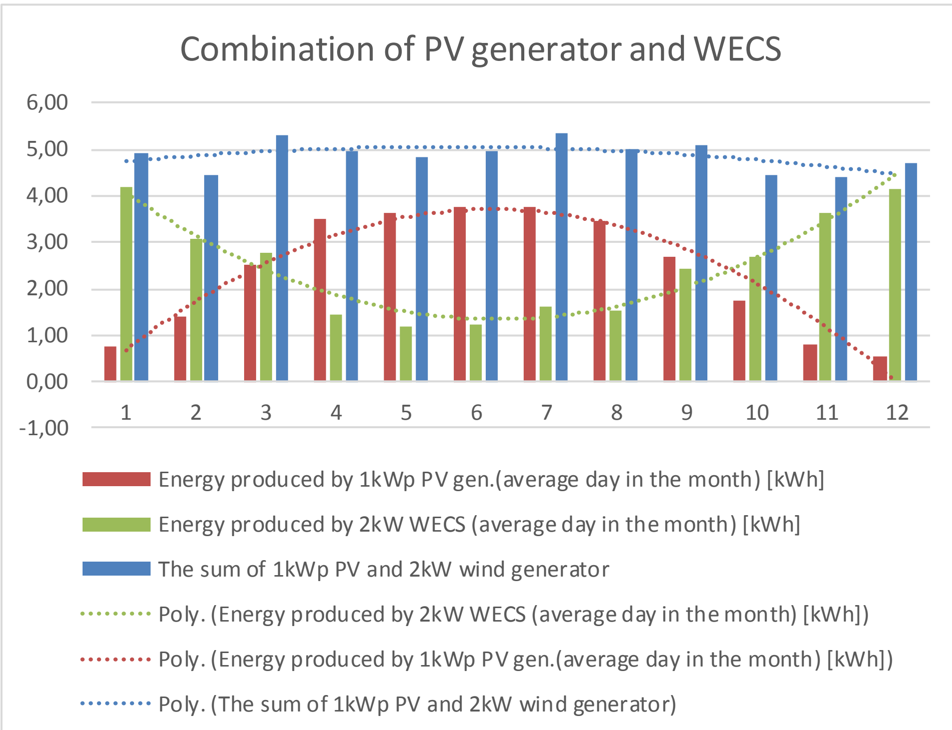


Figure 49 - Power production curves comparison

In the ratio about 2:1 of WECS to PV could be used for linear consumption throughout the year. Otherwise there will be a great excess of energy in the summer season. In the following figure there is the rated power of PV or WECS. With the available wind speed source near by the object, the average power production per 1 kW of wind generator installed throughout the year excess the production of average 1 kWp installed of PV generator.

As the Figure 49 shows with the 1kWp PV generator and 2 kW WECS could be covered an average day of each month with load about 3 kWh without any storing the energy (on average day). The limitation of wind speed in the area is considerable.

4.1.5 Diesel generator

In the basic cases the diesel generator will be used only in cases when the PV and WECS will not be sufficient. In others it will be an adequate part of the generator system.

4.1.6 Heat pump and the modification of load curve

A heat pump is a device that provides heat energy from a source of heat to a destination called a "heat sink". Heat pumps are designed to move low potential thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. Whoever owns a refrigerator owns a heat pump in a cooling mode. There are also reversible heat pumps which work in either thermal direction to provide heating or cooling to the internal space. They employ a reversing valve to reverse the flow of refrigerant from the compressor through the condenser and evaporation coils.

In heating mode, the outdoor coil is an evaporator, while the indoor is a condenser. The refrigerant flowing from the evaporator (outdoor coil) carries the thermal energy from outside air (or soil) indoors, after the vapor temperature has been augmented by compressing it. The indoor coil then transfers thermal energy (including energy from the compression) to the indoor air, which is then moved around the inside of the building by an air handler. Alternatively, thermal energy is transferred to water, which is then used to heat the building via radiators or underfloor heating. The heated water may also be used for domestic hot water consumption. The refrigerant is then allowed to expand, cool, and absorb heat to reheat to the outdoor temperature in the outside evaporator, and the cycle repeats.

The use of the heat pump will lower the electrical power consumption. The boiler uses the electrical power transferred into the thermal power with the ratio of 1:1. The COP (coefficient of performance) of the heat pump is usually from 2,5 – 5. COP is given by the ratio of input and output energy. The input energy is the power consumed by the pump. The output is the thermal power of water used for heating. The coefficient of performance or COP of a heat pump is a ratio of heating or cooling provided to work required. Higher COPs equate to lower operating costs. The COP may exceed 1, because, instead of just converting work to heat (which, if 100% efficient, would be a COP of 1), it pumps additional heat from a heat source to where the heat is required. For complete systems, COP should include energy consumption of all auxiliaries.

With the use of the heat pump there would be a change in the load profile. The intensity of the change would be caused by the COP. The change would be mostly seen in the winter season by lowering the load profile. Therefore I will calculate 3 variants. One with current load profile, one with heat pump and one without heating at all.

The modification of the load curve will influence (lower) just the days which the heat pump will be in process instead of the boiler. On the other hand will increase the load in the summer, when it will be used to cool down the house. It is supposed and further will be proved that in the summer season is enough power produced to do so. This modification is shown in the Figure 50.

5 Installed power optimization

This installed power optimization of the system will be based on models mentioned above. The power generated is decreased by all loses and is counted like all of it goes through batteries. All variants of the system have been chosen to cover the power balance at all time. The changed load profiles were estimated to never be underestimated. The power balance have been calculated to loads without any other change in the consumption behavior of the inhabitants of the house. Otherwise in all cases the inhabitant knows there is limited amount of energy in the island system they try to save it. The battery charging for gear is done during excess of power and all other activities not necessary also. This way is possible to lower the cost of the system. In the Economical evaluation will be presented also possibility of using the gen-set as an active part of the system.

5.1 Hybrid solar-wind system power according to variants and system devices selection

The combination of PV generator and WECS is reasoned by their almost complementary power production characteristics, they are usually used in hybrid system configurations. The monthly power characteristics of 1kW blocks of PV generator and WECS are shown in chapter 4.1.1 and 4.1.2. The correlation of the power produced by 1kW of WECS and 1 kWp of PV is - 0,97. To secure enough energy even if it will be stored in batteries, the calculated power will be rounded up at least more than 10 % than calculated. There will be calculated with three options of loads. The current one and two reduced ones.

In these two reduced cases the load curve is changed. In general there is always needed more energy in the winter – more heating, more hot water, shorter days and therefore more light, people watch more TV. The most power, in this object about 70 %, is used for heating and hot water. Therefore if this 70 % is reduced, it will result in flattening the load curve over the year.

This reduction may be done in two ways. Installing the heat pump or whole another source of heat i.e. non electrical boiler using wood, wooden chips, biomass, pellet fuel or so on.

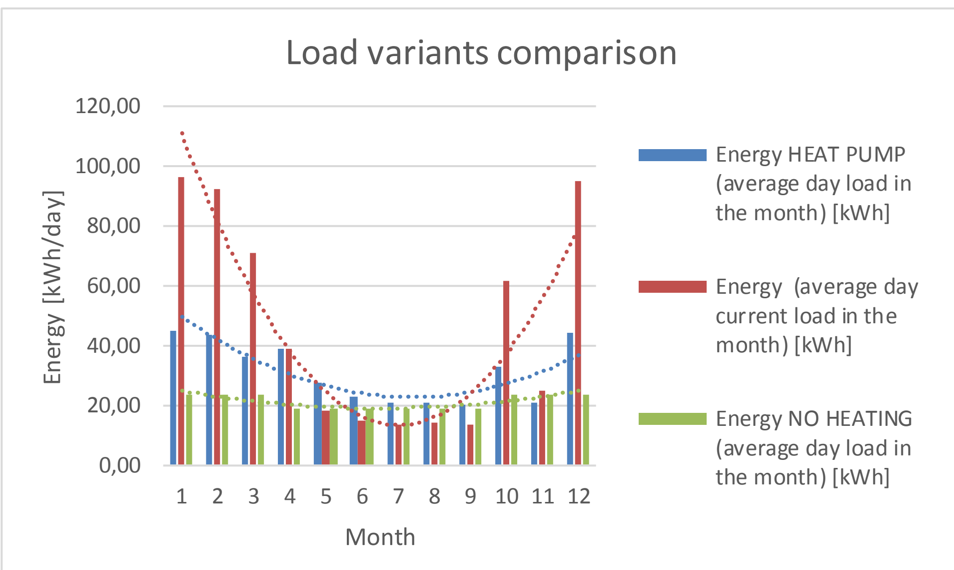
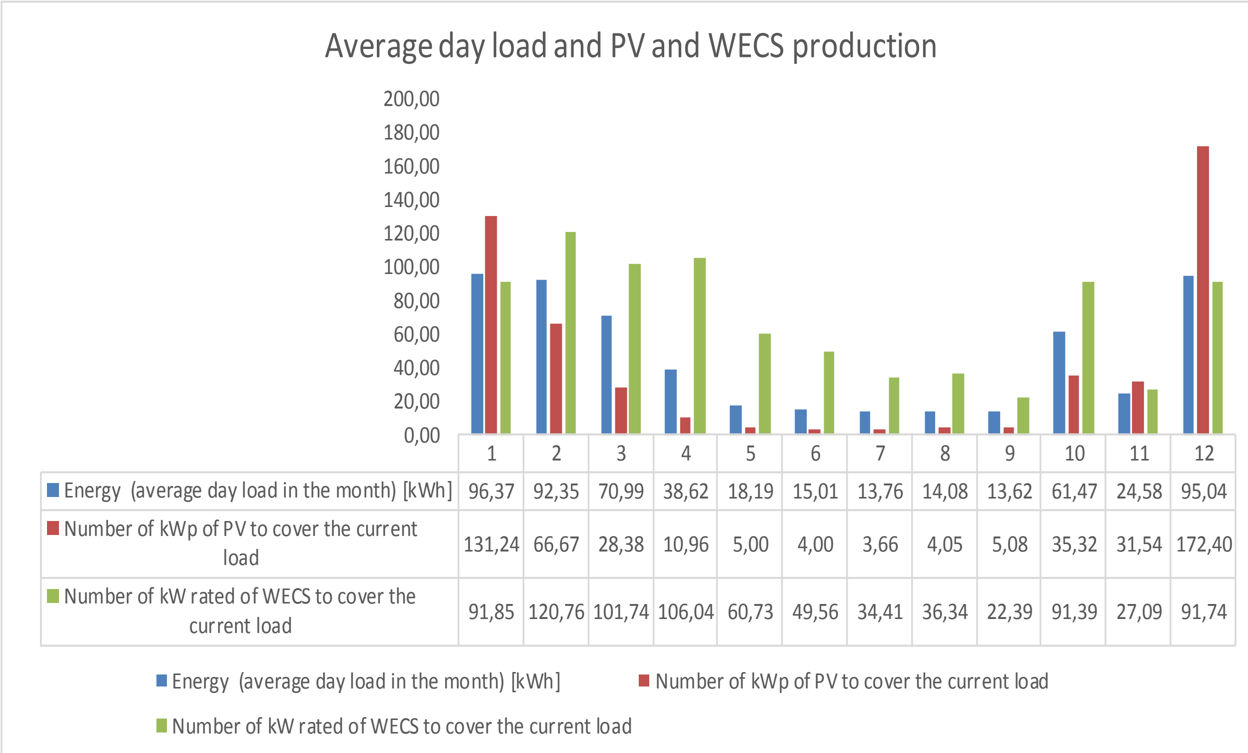


Figure 50 - Comparison of different load variants

5.1.1 Calculation of WECS and PV power according to current load profile

In the next Figure 51, there is load of an average day in the month, and the number of kW installed (separately PV generator and WECS) to cover the load. There is obvious that the WECS exceeds the PV generator only in the highest winter season – November, December and January.



	1	2	3	4	5	6	7	8	9	10	11	12
Energy (average day load in the month) [kWh]	96,37	92,35	70,99	38,62	18,19	15,01	13,76	14,08	13,62	61,47	24,58	95,04
Number of kWp of PV to cover the current load	131,24	66,67	28,38	10,96	5,00	4,00	3,66	4,05	5,08	35,32	31,54	172,40
Number of kW rated of WECS to cover the current load	91,85	120,76	101,74	106,04	60,73	49,56	34,41	36,34	22,39	91,39	27,09	91,74

Figure 51 - Average day load and kW installed of generators

As shown in the Figure 51 there was calculated, to cover the load for the whole year there is necessary 127,7 kW wind turbine or 172,4 kW. The Figure 52 shows that if there is used 127 kW wind turbine will have small excess of energy in the summer. If used the 172 kW PV generator, there is the excess of energy considerably high. It's so because the trend lines of load and wind turbine production are of the same shape. On the other hand the shape of PV generator production. To lower the investment cost, it is in place to combine both sources.

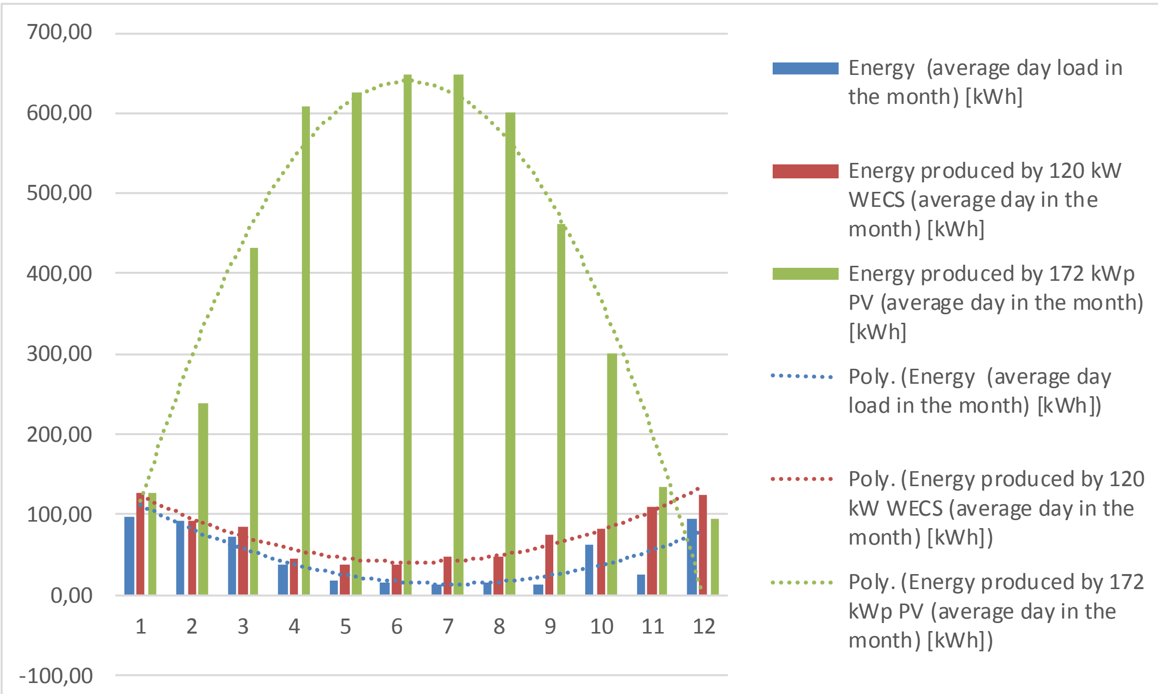


Figure 52 - Wind turbine and PV daily production compared to daily load

Both sources will be combined to produce together over the whole year approximately the same amount of the energy. To simplify the optimization I will use the combined production of WECS and PV generator will be an average day with the highest consumption 96,37 kWh. The average summer and winter yield of 1 kW WECS installed is 0,35 kWh respectively 0,81 kWh. The average summer and winter yield of 1 kWp PV generator installed is 3,47 kWh respectively 1,28 kWh per day. This leads me to a set of two equations with two variables.

$$0{,}35WECS_i + 3{,}47PV_i = 96{,}37$$

$$0{,}81WECS_i + 1{,}28PV_i = 96{,}37$$

Which results in installed power of $WECS_i$ =88,96 kW and PV_i = 18,70 kWp. These results will be rounded up to find the standardized solution – for PV up to one whole kWp, and WECS up to standardized unit, which is possible to buy. This means $WECS_i$ = 100 kW and PV_i = 19,5 kWp this solution will work during average day. With this rounding up the power is overrated by 17,52 %. With such combination the graph of PV and WECS production will look like the Figure 53.

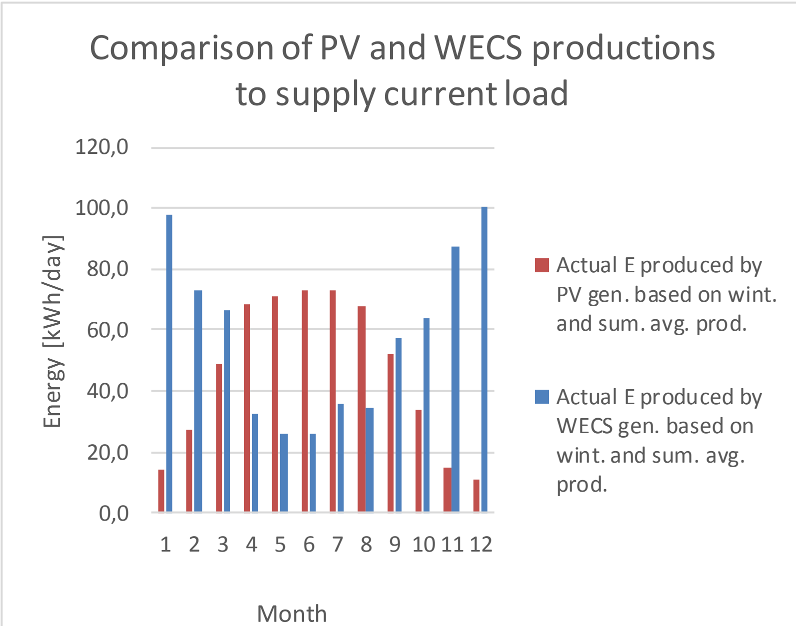


Figure 53 - Comparison of PV and WECS production

As it is showed in the next Figure 54 there are three months which will not be covered if the installed power calculated in this way. The energy missing in these months January, February and December is supposed to be energy for heating. The missing energy to the highest consumption measured (150 kWh in January) is about 30 kWh short per the day. The missing energy in similar cases would have to be fulfilled by the diesel generator or fireplace in the case of it is heat energy.

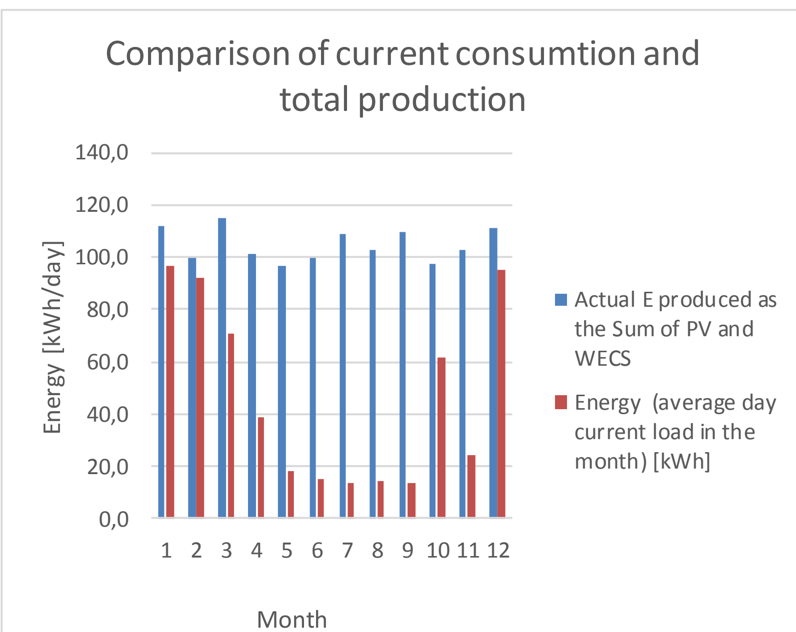


Figure 54 - Comparison of current consumption and total production

5.1.2 Calculation of WECS and PV power according to heat pump load profile

The heat pump will reduce the consumption necessary in the winter as said in the paragraph above and on the other hand it will increase the consumption in the summer. The reason of increase in the summer is, that there might be regulated the temperature of the house by cooling it. The heat pump is never installed as peak source of heat, therefore I will use the corrected average winter day's consumption to design the load curve. The correction is done so I do not calculated the reduction in regular consumption (set on the summer average day level) twice.

To simplify the optimization I will use the combined production of WECS and PV generator is an average winter day's consumption 37 kWh. The average summer and winter yield of 1 kW WECS installed is 0,35 kWh respectively 0,81 kWh. The average summer and winter yield of 1 kWp PV generator installed is 3,47 kWh respectively 1,28 kWh per day. This leads me to a set of two equations with two variables.

$$0{,}39WECS_i + 3{,}47PV_i = 37$$

$$0{,}85WECS_i + 1{,}28PV_i = 37$$

Which results in installed power of $WECS_i =$ 34,22 kW and PV_i = 7,19 kWp. This solution is rounded up to 40 kW WECS and 7,8 kWp PV. With this rounding up the power is overrated by 24,5 %. This combination will assure the production over 37 kWh each day. There must be taken in account, there will be surplus in the average summer day.

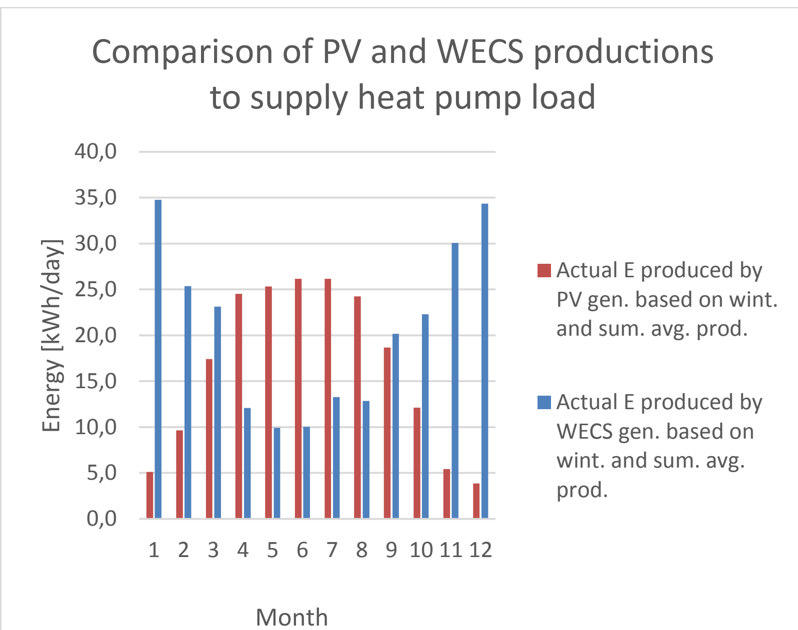


Figure 55 - Comparison of PV and WECS production to supply the variant with heat pump

In the Figure 56 there is the comparison of consumption with a heat pump and production of calculated installed power of PV and WECS. There only one month which does not have sufficient power production. These are again to be supply in the form of heat by the fireplace, or diesel generator.

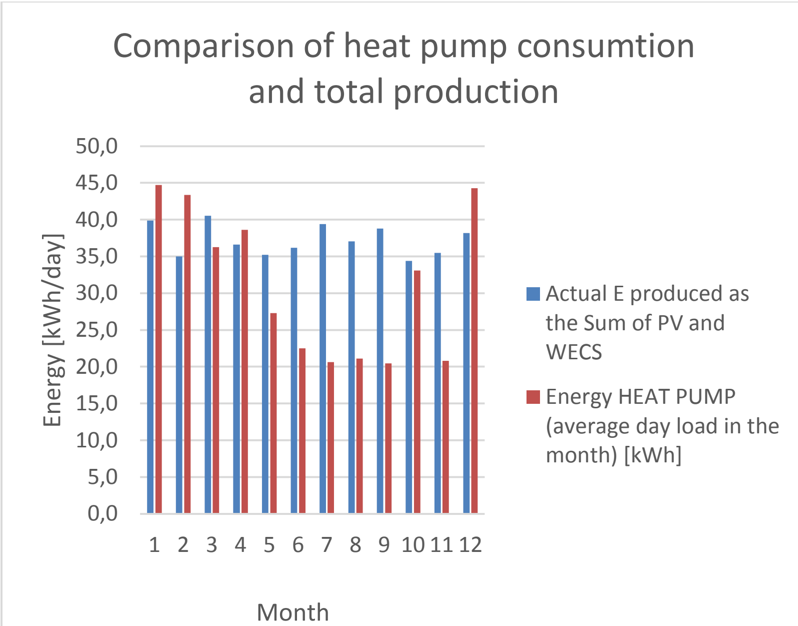


Figure 56 - Comparison of production and consumption with calculated installed power of WECS and PV generator

5.1.3 Calculation of WECS and PV power according to No electrical heating load profile

In this case will be also taken into account only two parts of load curve, the winter and summer one. The summer is the average of the current load profile and the winter is 25 % higher. It was solved as in the previous case

This variant has been calculated the same way as the variant with the heat pump with result of $WECS_i =$ 21,78 kW and PV_i = 4,58 kWp. This result was rounded this time down to 20 respectively rounded up to 7,8 kWp installed power. With this rounding up the power is overrated by 33,82 %. Which assure production as showed in the Figure 57. The missing power will be gained from the diesel generator. In the economical evaluation I will also take into account the energy necessary for heating of the building.

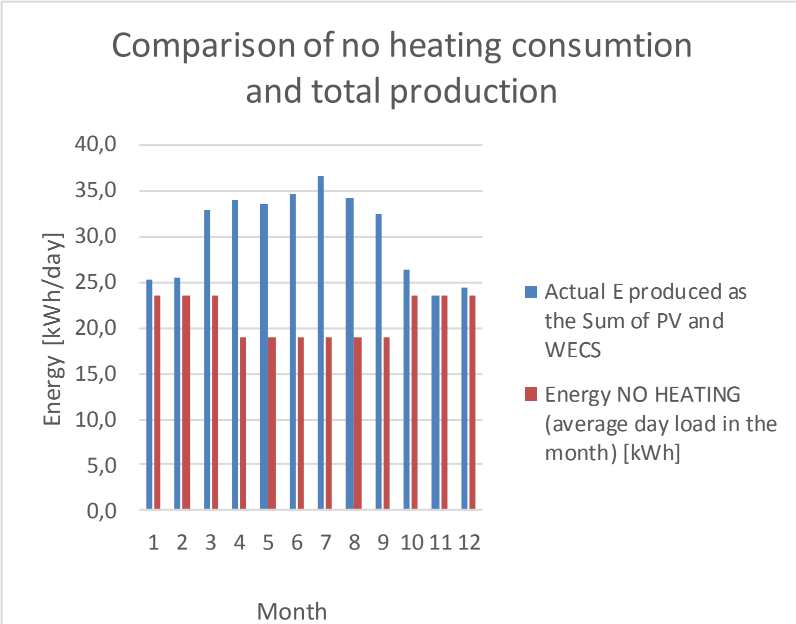


Figure 57 - Comparison of no heating consumption and total production

6 Selection of electric power system devices

6.1 Wind turbines

The sizes of searched wind turbines were:

- 100 kW for the current load profile,
- 40 kW for the heat pump profile
- 20 kW for no heating profile.

The model calculated with cut in wind speed 2,5 m/s. For such sizes as mentioned above, the cut in wind speed is usually higher. For 100 kW it usually is 3,5 or more m/s, for smaller it is 2,5 or 3 m/s and the power for 100 kW wind generator is much smaller in low wind speeds. With the respect to this fact and low wind speeds at the place of installation I have divided the 100 kW turbine into two smaller ones. Suitable ones I have been choosing from were WES 50, Aeolos H50 and Ghrepower 50. The total energy produced over the year has WES 50, second Ghrepower 50 and third Aeolos H50. The reason WES50 is first is higher efficiency at lower wind speeds. During the winter season the Ghrepower 50 has slightly higher power production, which could be useful. The most similar to the model is the WES 50 but it is an asynchronous generator with which there may be some problems in off grid application (it has to be induced before the use, the output should be transformed from AC to DC to Ac to be usable for regular usage. So I will rather use Ghrepower which is a synchronous motor with permanent magnet and comes together with its own invertor.

	Ghrepower 50 kW	**Aeolos 20 kW**
Rated power at wind speed	50 kW at 12 m/s	20 kW at 10 m/s

Rotor diameter	14,2 m	10 m
Work speed	3 – 2 m/s	3 – 25 m/s
Generator type	3 phase PMG	3 phase
Voltage	380 V AC (460 V DC)	100-380 V
Off grid rectifier and dump load	Yes	Yes
Charger/inverter	Yes	Yes

Figure 58 - The basic data technical parameters of wind turbines

In the Figure 59 there is comparison of daily production of each wind turbine and the model.

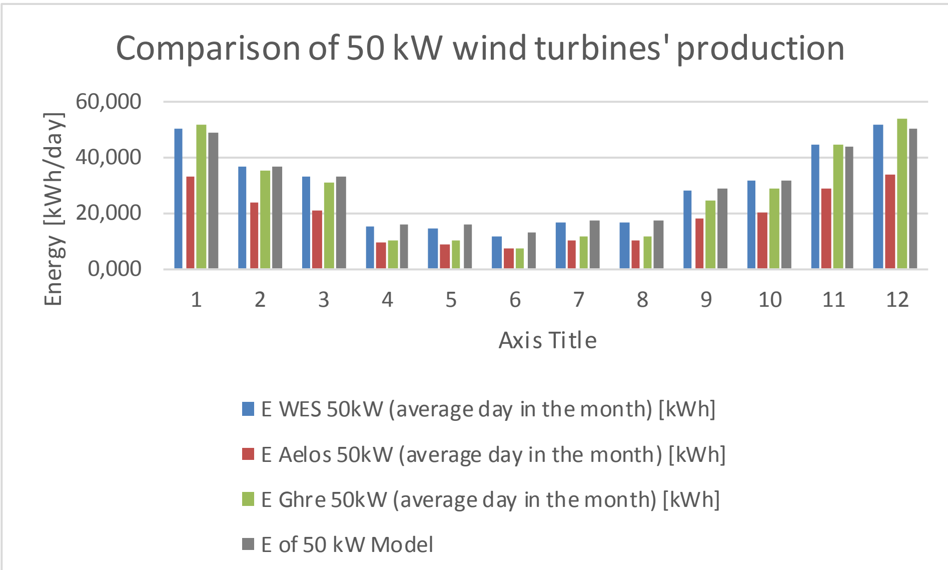


Figure 59 - Comparison of wind turbines 50 kW

For the 40 kW wind turbine I have chosen to build two 20 kW ones from Green Energy CF 20, Aeolos H20 and Polaris America 20. The best in total production over the year is Aeolos H20, second Green Energy CF 20 and third Polaris America 20. The Polaris America is lacking behind because, it was rated at higher wind speed than all other ones. The most similar to the model is Aeolos 20 kW, therefore I will use it.

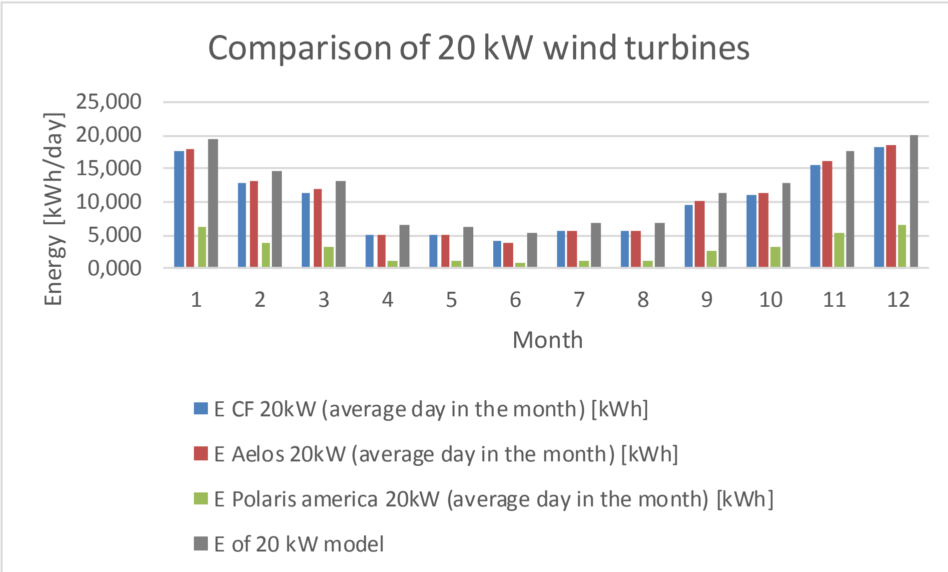


Figure 60 - Comparison of 20 kW wind turbines

To keep the power production voltage and frequency stable, there will be used a dump control from Hummer connected to proper dump load.

6.2 PV Panels

There is many brads with very similar properties and characteristics. I have good personal experience with the brand BenQ (Czech Republic) so I will use it. The exact model is called Green Triplex PM060P00, The nominal power is 260 Wp. The efficiency of the panel is 0,1 % higher than in the theoretical model (16,1 %).

	BenQ
Nominal power	260 W
Module efficiency	16,1 %
Nom. Voltage	31,2 V
Nom. Current	8,34 A
Type	Polycrystalline silicon
Wight	18,5 kg
Dimensions (LxWxH)	1639 x 983 x 40 mm

6.3 Invertor

The size of the invertor depends on the maximal power, which is necessary to transform form the DC to AC. It is also possible to use several parallel-connected smaller to add up the power. The inverter used within the off grid system must have the off grid function. There are also inverters which may be connected to the gird but as long as there is power within the off grid system, they do not use it (called HUB).

Chosen wind generators work at 230 V, the diesel generator also works at 230 V. So there are two AC inputs, PV generates DC and batteries store it. All these inputs are required. This can manage only a complex invertor. As possible solution comes Steca Xtender XTH 8000-48.

	Steca Xtender XTH 8000-48	Steca Xtender XTH 6000-48
System voltage	48 V	48 V
Continuous power	7000 VA	5000 VA
Power 30 min	8000 VA	6000 VA
Power 5 sec	21 000 VA	15 000 VA
Efficiency	96 %	96 %
Charging current	0-120 A	0-100
Battery voltage	38-68 V	38-68 V

6.3.1 For Current load profile

The highest fifteen minute load maximum power measured was 18 kW. Therefore this power should be the invertor able to withstand. The peak power must be even higher. This power can supply three parallel connected Steca Xtender XTH 8000-48 with total continuous power 21 kW at (power factor = 1).

6.3.2 For load profile with heat pump

The estimated maximal power of this load profile is up to 16 kW. The peak is expected in winter and the heat pump does not have such power as the resistance boiler. Therefore the power can provide three parallel connected Steca Xtender XTH 8000-48 with total continuous power 21kW.

6.3.3 For no heating load profile

The estimated maximal power of this load profile is up to 12 kW, which can provide three parallel Steca Xtender XTH 6000-48 with total continuous power 15kW.

6.4 Rechargeable battery

There were compared 11 different batteries of different kinds by the multiple-criteria decision analysis (MCDA). There has been compared in 6 criterions: chemical composition, usable capacity, weight, and effectivity of a cycle, price and how many time the battery must be replaced in 20 years. The desired capacity of the battery system was 30 kWh at 48V.

There were used 8 mathematical methods of MCDA. Average of orders has been done and as the best came out Tesla's Power wall, second the battery from Fronius – Energy package and third BMZ ESS 3.0.

Since the Tesla's Power wall and doesn't occur on the European Market yet, I will use the Fronius Energy Package or BMZ ESS.

Into the current load profile variant the will be installed usable capacity 60 kWh, into the heat pump load profile will be installed 40 kWh and into the no electrical heating will be installed 30 kWh of usable capacity.

	BMZ ESS 3.0	**Fronius**
Rated capacity	6,74 kWh	12 kWh
Dicharge depth	80 %	80 %
Usable capacity	5 kWh	9,6 kWh

Nominal Voltage	48 V	320-460 V
Max charge current	80 A	16 A
Max discharge power	16 kW	6400 W
Number of cycles	5000	8000
Parallel connection	Up to 12 pcs	?

6.4.1 Solar charge controller

Also as the invertor the may be used a bigger solar charger, or many small ones. I have decided to go with Victron BlueSolar MPPT 150/35-100 charge controller or Steca Tarom M. With this there will have to be PV panels connected into groups according to MPPT's voltage, together in series and via the charger connected to DC bus on the charging side of the system. Since the Victron BlueSolar MPPT is about twice cheaper it will be used. Both chargers are suitable for 48 V batteries.

6.5 Engine generator

In case of emergency (discharged battery, no wind, and no sun) the diesel generator has been selected to be able to supply the highest estimated power in the variant's load. For variant with current load profile there has been done a simulation of energy produced by the diesel generator. The simulation was based on daily real consumption (over two year period) and average daily production of PV and WECS with 30 kWh batteries. The maximal energy produced by gen-set in one day is about 48,9 kWh. Which could be easily produced in one day by 12kW three phase gen set GD4WSS-3-012kW-YD480-YHG12. Therefore I think it should be sufficient for all variants. In the case of need for some variant it should be sufficient to use two of them.

The engine together with batteries work perfectly, any time when the engine generator is necessary to turn on, it works at its optimal level, because the excessive power may be used to charge the battery. Therefore it is possible to calculate the constant fuel consumption 0,37 l per 1 kWh.

6.6 Scheme of hybrid system

In the following Figure 61 there is a Steca's scheme of the three phase off grid system. There are two solutions to connect the PV panels to the grid. Either each string has its own inverter and is connected into the grid – the AC system or each string has its own MPPT tracker and is connected to the DC bus – between batteries and inverter – the DC system. Each has its own advantages and disadvantages.

The direct use of PV's power is in both cases the same, PV produces DC which is transformed into the AC. The difference is in indirect use, when the batteries are used. In the DC system the PV produces DC which is used as DC to charge batteries, later transformed to AC – as in direct use. In the AC system the PV produces DC which is by the invertor changed into AC which comes to charger which transforms it back into DC if charging the batteries and later when the power is supplied by battery bank it is again transformed into the AC.

I will use both types, because the 5 kWp PV array is already installed on the roof and is connected like AC system, all new panels will be connected like DC system to increase the systems efficiency.

The wind turbine may be placed as in the picture or to the DC bus to charge the batteries. Since the power of the wind turbine is large, I will place the wind turbine to the system as on the picture with a rectifier/dump control and the off grid inverter to create a stable network.

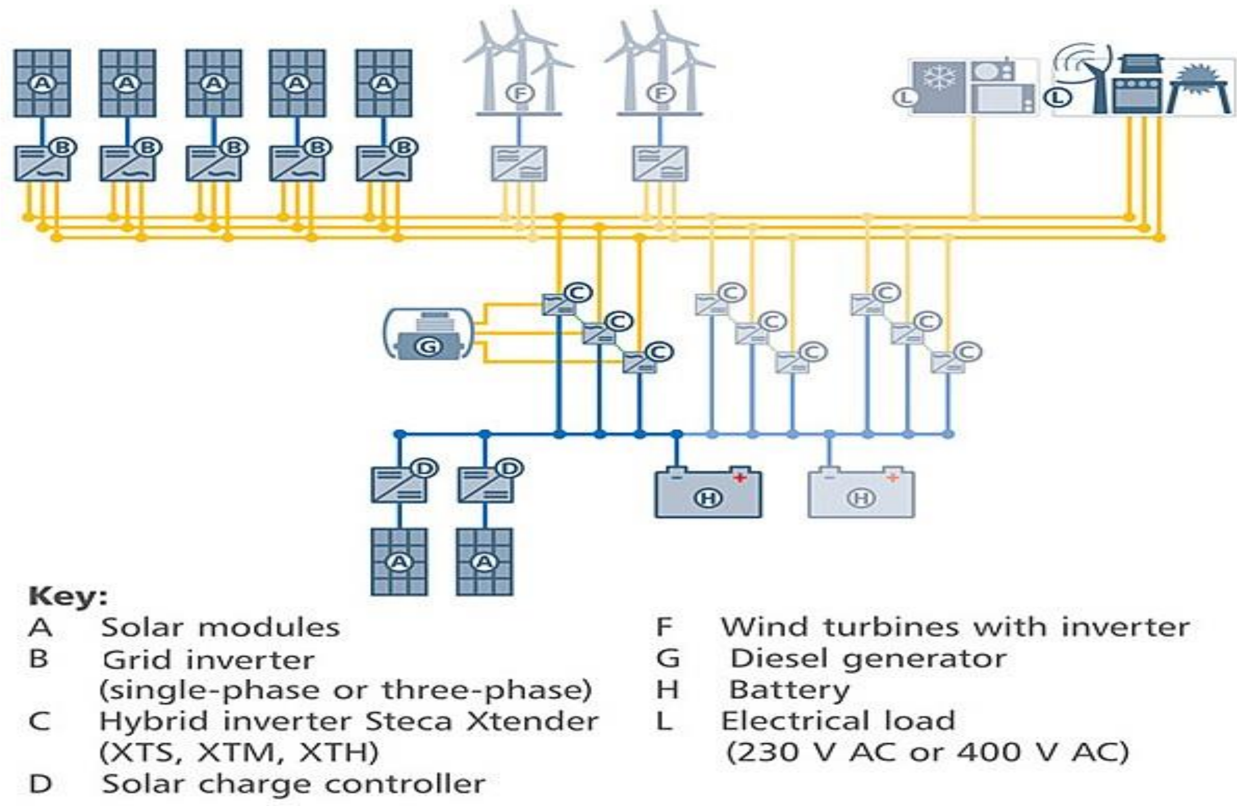


Figure 61 - Scheme of the off grid system

7 Technical-economic evaluation wind and solar power in autonomous systems

There have been constructed three variants for electrical supply of the object. It has been constructed to be supplied from renewable resources with backup of generator. Each variant is fully capable of suppling the object with heat and electricity.

After creating model of WECS and PV generator, it has been calculated size of each generator in the combination to be able to supply the object in the average winter day. The diesel generator has been sized to be in a backup mode.

7.1 Evaluation of current load profile

The variant with current load profile, is the most problematic one. The load profile is curved according to winter season as showed in the Figure 52. There has been calculated the levelized cost of electricity (LCOE) for each case of the current load profile. LCOE is sum of cost over the life time divided by the sum of produced energy (consumed energy). For the combination of PV generator WECS and gen-set.

	LCOE – Energy Produced [Kč]	**LCOE – Energy Consumed [Kč]**	**Energy produced [kWh]**	**Energy consumed [kWh]**	**NPV [Kč]**
PV,WECS, (gen-set backup only)	21,25	46,86	37 054	16807	-11 696 871
WECS only	29,97	48,39	27 134	16807	-12 076 754
PV only	5,15	46,00	150 074	16807	-11 483 501
Gen-set only	21,32	22,78	17 963	16807	-5 68 7248
PV, gen-set active	10,40	19,70	31 847	16807	-4 917 089

Table 9 – Economical evaluation of the current load profile

The column LCOE - Energy Produced means the total cost over lifetime was divided by the energy which was produced and shows the cost of energy, which could be reached if all energy was consumed. Important column LCOE – Energy Consumed is the same calculation instead of Energy produced was used as divisor the Energy which was actually consumed.

In the table Table 9 is possible to see, that the cost of energy depends very much on the load profile and the source to be able to follow it. Since WECS and PV are not able to do so it. The lowest cost (if all energy consumed) reaches the PV generator and the second bests the generator. So as the last combination has been calculated the combination of PV and generator in the point of minimal cost. Theoretically the gen-set may be thought as variable part of the cost of the system and the PV generator would be more like the fixed cost.

PV, WECS, (gen-set backup only)

In the chapter 5.1.1 there has been calculated a set of 100 kW wind turbine and 19,5 kWp PV generator, together with 12 kW backup generator. This solution provides whole year round sufficient amount of energy, which is paid by higher cost of the system. And overrated summer production. As it may be seen in the Figure 54. The gen-set is functions only as a backup and emergency system.

Since the PV and WECS were designed to provide almost all energy, the system is almost not sensitive to price of fuel – If the fuel cost changes twice, the LCOE changes by 0,08 Kč/kWh.

Among other basics what if analysis belongs the sensitivity belongs sensitivity to a discount rate and purchase prices of the most expensive parts which follow.

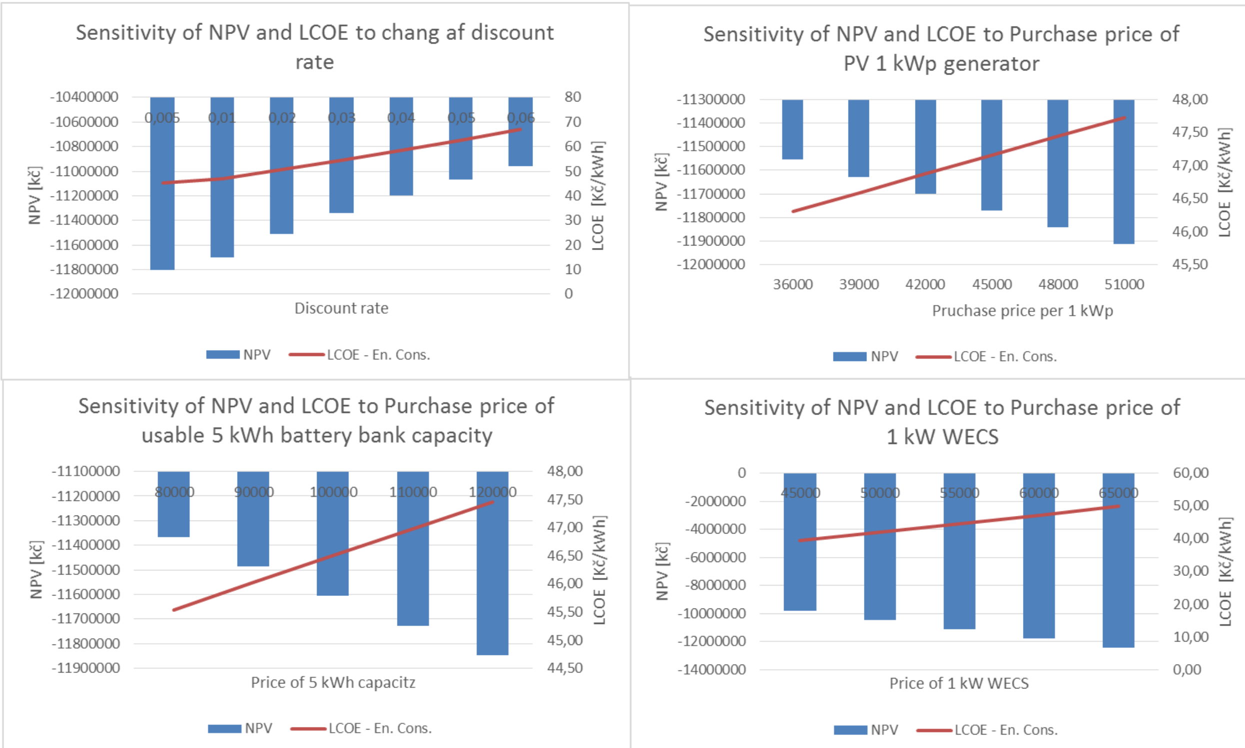


Figure 62 - Economical sensitivity analyses of Current load supplied by PV and WECS

WECS only, PV only, gen-sets only

These variants have been calculated to set the boundaries of costs, which other combinations should not exceed, if designed properly. The WECS showed up as the worst variant, because at the chosen place is not enough wind speed. Even it has. The cost of WECS is too high compared to its yields.

PV – gen-set active

The solution to minimizing of LCOE – Energy Consumed is to build 27,65 kWp - rounded up to 107 panels and 27,82 kW PV generator together with 24 kW gen-set. This combination have showed up to be the most efficient with lowest investment and fuel cost together. The advantage of this combination is that it is very reliable and produces the power when needed. Three quarter of the year are supplied by the sun and the winter peaks is the gen-set running, which is nicely shown in the Figure 63.

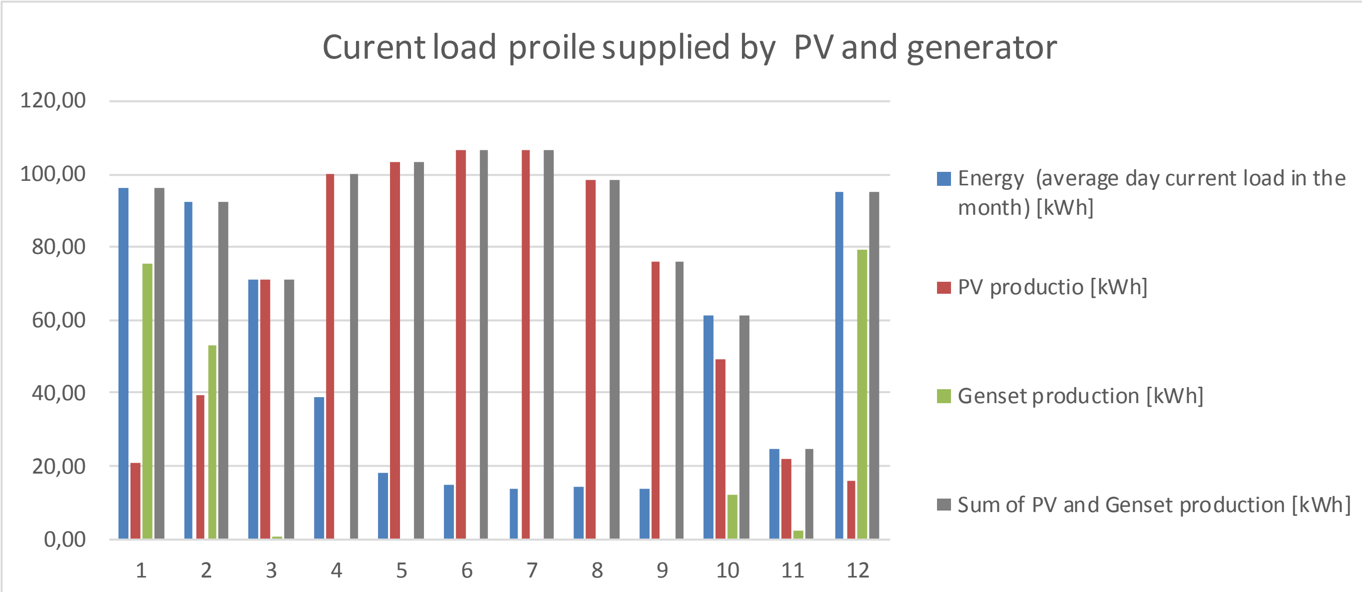


Figure 63 - Current load profile supplied by PV and generator

In this case may the system is quite dependent on fuel prices of the gen-set. In the next Figure 64, there is the sensitivity of NPV (Kč) respectively LCOE (Kč/kWh) to a fuel price.

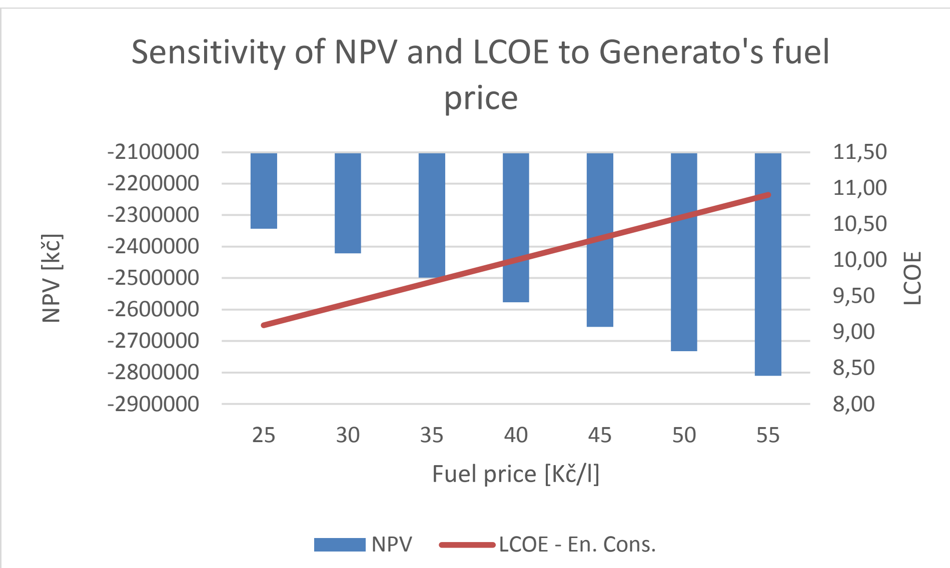


Figure 64 - PV, gen-set sensitivity of LCOE and NPV to a gen-set fuel price

7.2 Evaluation of heat pump load profile

The variant with the heat pump has been calculated to more flatten the load curve and that way to achieve cheaper production. The best economical option was again to combine PV and engine generator. The flat profile which may be seen in the Figure 56 suits the LCOE. Now it is about half of it was in the variant with current load profile.

	LCOE – Energy Produced [Kč]	LCOE – Energy Consumed [Kč]	NPV
PV,WECS, (gen-set backup only)	18,72	23,51	-5 867 667
PV only	5,12	23,4	-5 433 372
PV, gen-set. active	11,10	13,06	-3 031 696

Table 10 - Economical evaluation of Heat pump load profile

The best result has been achieved by PV and gen-set, the Sensitivity analyzes follows. The most important is, even if the price of the fuel rises by 50 %, the LCOE and NPV is still be just about half of the PV and WECS supply variant.

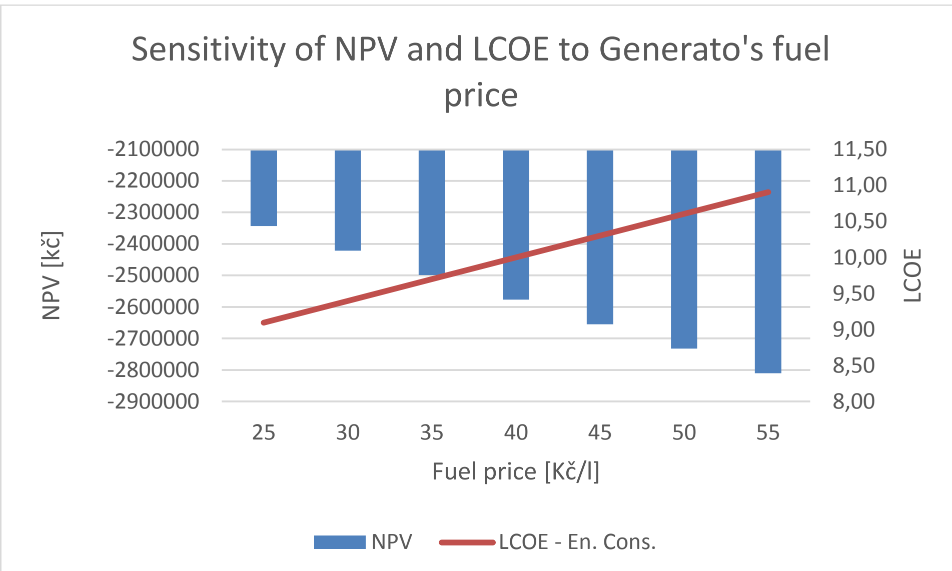


Figure 65 - Heat pump load profile supplied by PV and ge-set. sensitivity to fuel cost

7.3 Evaluation of load profile with no electrical heating

This variant differs from the other ones that the heating is not used electrical but there is installed new wood/pellet fuel boiler. The cost of this is also counted within the electrical supply. Otherwise it would not be possible to compare the three load profile variants.

	LCOE – Energy Produced [Kč]	LCOE – Energy Consumed [Kč]	NPV
PV,WECS, (gen-set backup only)	14,38	17,03	-4385236
PV only	5,05	15,00	-3855384
PV, gen-set. active	9,07	9,70	-2498894

Figure 66 - - Economical evaluation of profile with no electrical heating

As the most economical solution has been proved to not to use the electricity made as the power to heat up the object, nor cool with the heat pump. But to use the wood/wooden pellets for heating up the water and control the temperature in the house. And the electricity produced use only for the general consumption in the house. The most suitable is to use a combination of PV generator and engine generator. The PV reduces the usage of gen-set and therefore the fuel cost. The sensitivity charts follow.

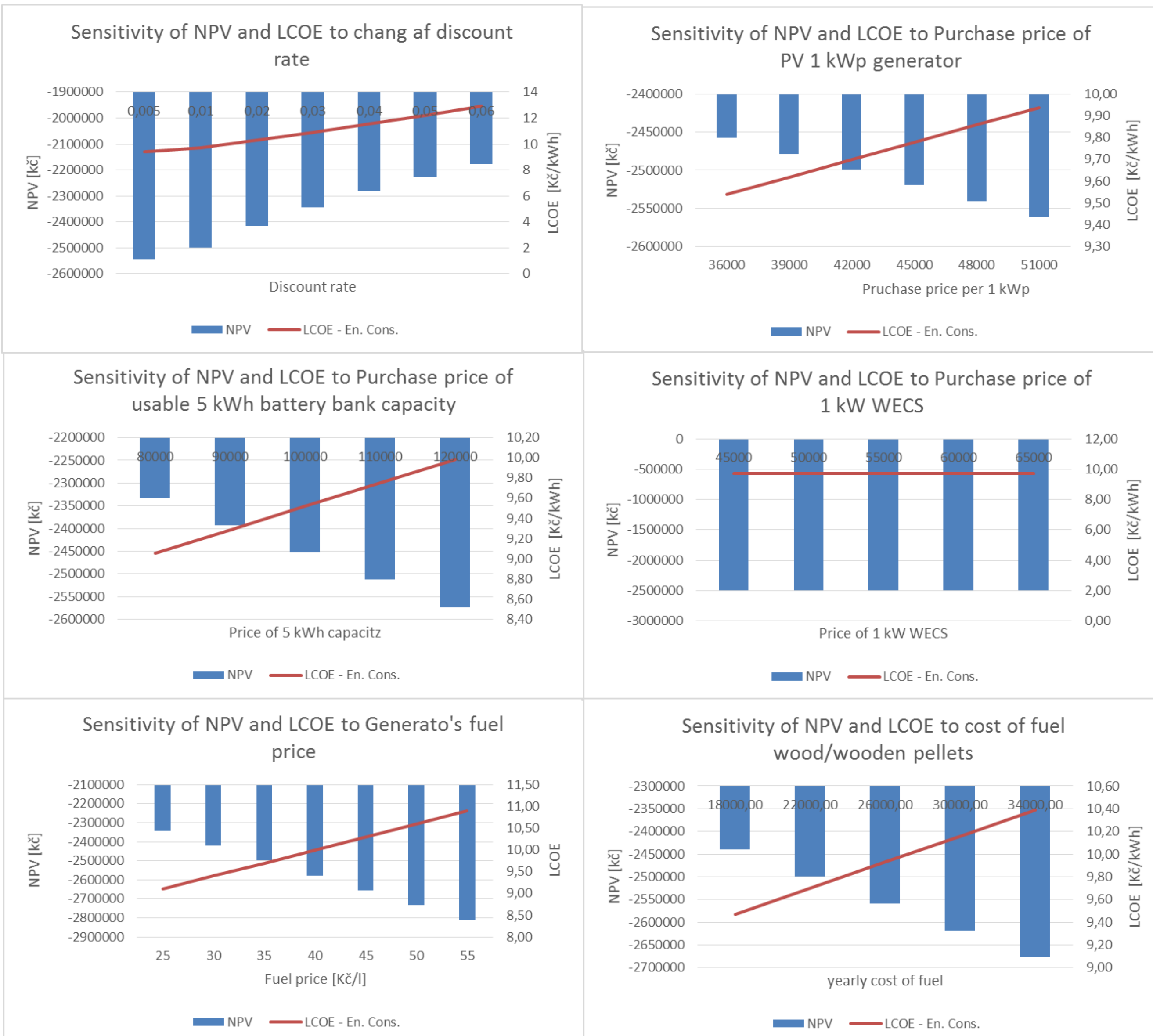


Figure 67 - Sensitivity of No electrical heating to purchase and fuel costs

This las variant is possible to compare with pricing of electricity from the grid

8 Conclusion

The aim of this theses was to evaluate the suitability of the object to be powered by the hybrid off grid system and evaluate the suitable combination of sources' power. It has been divided into six practical chapters, each set on a theme. I have introduced and shortly described the house and its surrounding area in the first chapter together with a possible variants to solution how to supply the object. There has been described how each technology work and what is the technological limitation.

In the second part I have described the behavior of natural conditions for PV and WECS. In detail has been described the solar irradiation potential and wind power potential. This description and theoretical knowledge has been used when modeling these sources. Important part is the Weibull distribution of the wind speed. The power of the wind increases with the third power of its speed.

The third part was important, there has been created the list of all appliances, which is in the house. This theses was aimed at no restriction in the use of electrical devices. In the third part was also analyzed the current load profile three different ways. As a 15 minute measured values. This access is not usually possible. There is very few houses who actually have this method of measurement. The data has been processed to gain important information as the highest load power, the average day in the month consumption and the influence of current PV generator. In the case this measurements are not accessible it must be used the alternative way. Which was presented in two variants according to tariff.

One of the most important thing in third part have been found out, in the most cases, there is not very important when the house is supplied by the electricity – it always uses the power (especially in winter season) when it is available. The heating is programmed to always use the cheap energy.

Next after load examination have been created models of PV generator and WECS. These were calculated as yields of a 1 kW installed power. The PV has been based on data form PVGIS and the wind generator on data from NASA and measured wind speed at the place of the house. The wind speed seemed low but usable according to necessary yields. Later economical evaluation showed something different.

In the fifth chapter I have created a three load profile variants: the current load profile, the load profile with heat pump instead of resistance boiler and no electrical heating. According to these variants I have calculated the combination of PV and WECS using the generator as a very high peak source, used only at the worse conditions than the average winter day of a month with highest consumption.

In the sixth part I have chosen adequate devices to be compatible with each other. There is usually listed more than one product, which has the same function.

As seventh chapter was final economical evaluation of each consumption – production variant. There has been presented in all variants the advantageous combination PV-engine generator. Even the sensitivity analyzes have showed it it's the stable variant.

As the most economical solution has been proved to not to use the electricity made as the power to heat up the object, nor cool with the heat pump. But to use the wood/wooden pellets for heating up the water and control the temperature in the house. And the electricity produced use only for the general consumption in the house. The most suitable is to use a combination of PV generator and engine generator. The PV reduces the usage of gen-set and therefore the fuel cost.

In general the wind speed in the location is decisive, whether to use WECS. In this case the wind speed even in 50 m height was inadequate dispute the town is at the edge of the area for economical profitability of wind turbines (created for WECS connected to the grid). Economically in low wind speeds is more suitable to use a gen-set. Otherwise WECS together with PV are very suitable for all year balanced load. To get the flat curve production in conditions by the object, there must be the ration of PV: WECS about 1:3. In higher wind speed locations it may be used WECS for heating.

9 Bibliography

1. **ECO trend Research centre, s.r.o.** *Souhrn Podmínek pro uplatnění malých OZE v ČR.* s.l. : Omega, 2014. ENV/CZ009649.

2. **Solar GIS.** *GeoModel Solar.* [Online] 2015. [Cited: December 10., 2015.] http://solargis.info/doc/free-solar-radiation-maps-GHI.

3. **PVgis.** [Online] Institute for Energy and Transport, 2013-2015. [Cited: Decemeber 10, 2015.] http://re.jrc.ec.europa.eu/pvgis/cmaps/eur.htm#CZ and http://www.photovoltaic-software.com/.

4. **Messenger, R. A. and Ventre, J.** *Photovoltaic Systems Engineering.* s.l. : Taylor & Francis Group, LLC, 2010. 978-1-4398-0292-2.

5. **Kusala, J. ČEZ.** Svět energie. *Solární energie.* [Online] ČEZ, 2006. [Cited: 12 11, 2015.] http://www.cez.cz/edee/content/microsites/solarni/solar.htm.

6. **Christopher, D., Wang, R. and Wang, Ch.** *Battery Systems Engineering.* Sussex : John Wiley & Sons, Ltd, 2013. ISBN 9781119979500.

7. **Henze, A. and Hillebrand, W.** *Elektrický proud ze slunce - Fotovoltaika v praxi: technika, přehled trhu, návody ke stavbě.* Ostrava : HEL, 2000. ISBN 80-86167-12-7.

8. **Fesli, U., Bayir, R. and Özer, M.** *System, Design and Implementation of a Domestic Solar-Wind Hybrid Energy.* Zonquldak, Karabük : s.n., 2009.

9. **Anonimous.** ITACA. *The application of Appropriate Technology.* [Online] 2015. [Cited: 05 28, 2015.] http://www.itacanet.org/.

10. **Pidwirny, M.** The Encyclopedia of Earth. *Solar radiation.* [Online] 05 24, 2012. [Cited: 09 02, 2015.] www.eoearth.org/view/article/156098/.

11. **Nave, C. R.** HyperPhysics. [Online] 2014. [Cited: 09 02, 2015.] http://hyperphysics.phy-astr.gsu.edu/hbase/vision/isql.html.

12. **Pidwirny, M.** Fundamentals of Physical Geography. *Atmospheric Effects on Incoming Solar Radiation.* [Online] 2006. [Cited: 06 05, 2015.] http://www.physicalgeography.net/fundamentals/7f.html.

13. **Anonimous.** Wikipedia. [Online] 08 10, 2015. [Cited: 08 20, 2015.] https://en.wikipedia.org/wiki/Sunshine_duration.

14. **Häberlin, H.** Photovoltaics System Design and Practice. *Proquest - Ebrary.* [Online] 01 2012. [Cited: 07 16, 2015.] http://80.site.ebrary.com.dialog.cvut.cz/lib/cvut/detail.action?docID=10526535. ISBN 9781119992851.

15. **Sargosis Solar and Electric.** Sargosis. [Online] 01 2014. [Cited: 09 02, 2015.] http://sargosis.com/articles/science/how-shade-affects-a-solar-array/.

16. **Siddiqui, R., Bajpai, U.** International Journal of Energy and Environmental Engineering. [Online] 2012. [Cited: 09 02, 2015.] http://www.journal-ijeee.com/content/3/1/26. doi:10.1186/2251-6832-3-26.

17. **Shaharin, A. S. et al.** Solarwash. *Effects of Dust on the Performance of PV Panels.* [Online] 2011. [Cited: 09 02, 2015.] http://www.solarwash.ca/dat/content/impact_of_dust.pdf.

18. **Queen's University Applied Sustainability Research Group.** Appropedia. [Online] 08 11, 2015. [Cited: 09 03, 2015.] http://www.appropedia.org/Effects_of_snow_on_photovoltaic_performance#Snowfall_on_PV_Panels.

19. **Skoplaki, E.** ScienceDirect - Solar Energy, Volume 83, Issue 5. *On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations.* [Online] 05 2008. [Cited: 09 02, 2015.] http://80.www.sciencedirect.com.dialog.cvut.cz/science/article/pii/S0038092X08002788. doi:10.1016/j.solener.2008.10.008.

20. **HASELHUHN, R.** *Fotovoltaika, budovy jako zdroj proudu.* Ostrava : HEL, 2010. ISBN 978-80-86167-33-6.

21. **NASA.** Global Wind Patterns. *Climate Science Investigation.* [Online] 24 08, 15. [Cited: 09 08, 2015.] http://www.ces.fau.edu/nasa/content/resources/global-wind-patterns.php.

22. **Danish Wind Industry Association.** Windpower.org. *All you need to know about wind power.* [Online] 06 2003. [Cited: 09 09, 2015.] www.windpower.org.

23. **Škopík, J.** Transformační techonologie. *Využití energie Větru.* [Online] 5 2014. [Cited: 1 16, 2016.] http://www.transformacni-technologie.cz/vyuziti-energie-vetru.html. ISSN 1804-8293.

24. **Hanslian, D.** oze.tzb-info.cz. [Online] 04 15, 2013. [Cited: 09 08, 2015.] http://oze.tzb-info.cz/vetrna-energie/9770-vetrne-podminky-v-ceske-republice-ve-vysce-10-m-nad-povrchem-i.

25. **Riley, P.** GCEP. *Global Climate and energy proect.* [Online] 10 14, 2014. [Cited: 9 22, 2015.] https://gcep.stanford.edu/pdfs/symposium2014/presentations/26%20-%20Riley%20Wind%20101.pdf.

26. **USA Today Weather - Gannett Co. Inc.** Understanding air density and its effects. *USA Today* . [Online] 05 17, 2005. [Cited: 09 22, 2015.] http://usatoday30.usatoday.com/weather/wdensity.htm.

27. **Natural Resources Canada.** *Wind Energy Project Analysis.* Ottawa : CANMET Energy Technology Centre - Varennes (CETS, NASA, UNEP, GEF), 2001-2004. ISBN: 0-662-35670-5.

28. **PHOTOVOLTAIC & SOLAR ELECTRICITY DESIGN TOOLS.** Photovoltaic software. [Online] PVGIS, 2013. [Cited: 3 28, 2016.] http://photovoltaic-software.com/pvgis.php.

29. **Stackhouse, J. M.** Atmospheric science data center. *EOSWEB.* [Online] NASA, 4 2016. [Cited: 4 17, 2016.] https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip%40larc.nasa.gov&step=2&lat=50.684&lon=13.863&num=194141&p=grid_id&p=surplus1&p=T10M&p=DLYRANGE&p=CDD18&p=HDD18&sitelev=&p=wspd50m&p=ws50_0_2&p=wnd_dir&p=wspd10arpt&p=pct10m_wnd&p=gipe_wnd&veg=5&.

30. **Diaf, S., et al.** A methodology for optimal sizing of autonomous hybrid. *HAL.* [Online] 2007. [Cited: 3 29, 2016.] https://hal.archives-ouvertes.fr/hal-00183357/document. hal-00183357.

31. **Frost & Sullivan.** Power Supplies & Batteries. [Online] 2009. [Cited: 12 16, 2015.] http://ww2.frost.com/research/industry/energy-power-systems/power-supplies-batteries/.