Faculty of Electrical Engineering
Department of Electrical Power Engineering

INTEGRATION OF SMALL PV TO THE DISTRIBUTION NETWORK

Author: Aydin Nabiyev

Supervisor: Ing. František Vybíralík, CSc

A master's thesis submitted to
The Faculty of Electrical Engineering
Czech Technical University in Prague

Master's degree study program Electrical Power Engineering

Prague June 2019

MASTER‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Nabiyev Aydin** Personal ID number: **471952**

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

Department / Institute: **Department of Electrical Power Engineering**

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

Branch of study: **Electrical Power Engineering**

II. Master’s thesis details

Master’s thesis title in English:

Integration of small PV to the distribution network

Master’s thesis title in Czech:

Integrace malých fotovoltaických elektráren do distribuční sítě

Guidelines:

1. General overview of RES
2. Description of PVPP (principle, types, installed capacity)
3. Installation of PVPP in a family house
4. Case study (Connection of small PVPP to LV network)

Bibliography / sources:

[1] Annual Energy Outlook 2019
[2] Global solar capacity grew faster then fossil fuels in 2017, report, Carbon Brief
[3] Distribution network code
[4] CSN EN 50 160
[5] eVlivy application manual

Name and workplace of master’s thesis supervisor:

Ing. František Vybíralík, CSc., Department of Electrical Power Engineering, FEE

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

Date of master’s thesis assignment: **16.02.2019** Deadline for master's thesis submission: **31.05.2019**

Assignment valid until: **20.09.2020**

Ing. František Vybíralík, CSc.
Supervisor’s signature

Head of department’s signature

prof. Ing. Pavel Ripka, CSc.
Dean’s signature

III. Assignment receipt

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

.

Date of assignment receipt

Student’s signature

Declaration

I declare that I have worked on my diploma thesis “Integration of small PV to the distribution network” by myself and I have used only the sources mentioned at the end of the thesis. As an author of diploma thesis, I declare that the thesis does not break copyrights of any source.

Prague ………………………………… ……………………………………..

Aydin Nabiyev

Acknowledgements

As the outset, I would like to thank Ing. František Vybíralík, CSc. for his guidance and proper technical support. Furthermore, I also wish to express my sincere gratitude to doc. Ing. Jan Kyncl for being supportive during my whole study.

And of course, special thanks to my parents and friends who supported me no matter what decision I choose during the whole life.

Integrace malých fotovoltaických elektráren do distribuční sítě

Abstrakt

Výzkum provedený v této diplomové práci se týká integrace malých fotovoltaických elektráren, jako jsou venkovské střešní fotovoltaické panely, do rozvodné sítě nízkého napětí 0,4 kV. Výše uvedený systém jsme zkoumali při různých provozních stavech FV panelů a různých hodnotách zatížení podle denní doby.

První část práce popisuje hlavní typy obnovitelných zdrojů energie, které jsou v současné době k dispozici. Podrobnější zkoumání bylo věnováno sluneční energii, která je hlavní částí této studie.

Praktická část práce obsahuje výběr lokality, která je předmětem studia. Tato oblast byla vybrána v obci Pátek, která se nachází v okrese Nymburk v České republice. Všechny výpočty byly provedeny na softwaru EVlivy3 a výsledky jsou založeny na simulaci modelu. Výpočty poskytly profil napětí v každém uzlu, celkové ztráty výkonu, byl diskutován vliv harmonických proudů a zkratových poměrů v síti, aby se určilo, zda parametry systému odpovídají ČSN EN, když jsou PV aktivní a neaktivní.

Klíčova slova: Solární Energie, Fotovoltaické Systémy, Distribuční soustava nízkého napětí, Distribuční sit´

Integration of small PV to the distribution network

Abstract

The research carried out in this master thesis is related to the integration of small Photovoltaic power plants, such as rural rooftop PV panel systems, into Low-voltage 0.4 kV distribution grid. We have examined abovementioned system during different operating states of PV panels and different load value with accordance to the daytime.

First part of this thesis describes the main renewable sources of energy which are available at the present time. More in-depth examination was devoted to the solar energy, which is the main part of this study.

The practical part of thesis includes selection of the housing are as the object of study. This area was chosen in Pátek village which is located in Nymburk district of the Czech Republic. All measurements were performed on EVlivy3 Software, and the results are based on the model simulation. Voltage profile at each node, Overall power losses, Influence of harmonic currents and Short-circuit conditions of network were discussed in order to determine how system corresponds when PV are active and inactive respectively.

Key words: Solar energy, Photovoltaic systems, Low-voltage distribution system, Distribution network

Table of Content

1 Introduction

5 Case Study

References

List of Figures

List of Tables

Renewable energy sources – general overview

It’s generally believed that the renewable energy sources are currently one of the auspicious ways of electricity generation. The interest has been attracted by lower consumption of fossil fuels during the process of electricity production. However, due to the insufficient development of technological aspects, the status of its viability is still remains relatively constant and hasn’t yet evolved to the most common and widespread method.

These sources of electric energy generation replenish themselves and never run out. The most common are wind, solar, hydro, biomass and geothermal. Over 80% of total energy consumed in the world obtained from fossil fuels, which has destructive effect on the environmental resources of our planet. The benefits of renewables lie in the fact that they prevent climate change because of not creating direct greenhouse gas emissions, although producing only indirect emissions, as a result from manufacturing process, installation and maintenance, but still has negligible impact with comparison to non-renewable energy sources. By decreasing pollution we are reducing threats to our health and increase the standard of living which leads to the rapid advancement of technologies and further development of electricity generation systems.

Another reason why renewables take precedence over classical method is that the prices for clean energy tend to be stable over time and continues to lower as opposed to fossil fuels. The situation in Third World is also should be taken into consideration, owing the fact that these countries doesn’t have enough natural and financial resources to maintain improved standards of living by providing cheap electricity to consumers.

However there is a possibility to implement innovative sources such as Photovoltaic Solar, Wind, Geothermal power plants.

The main specificity of Renewable energy sources is that despite being virtually infinite, they are also constrained in the amount of energy which can be obtained per unit of time.

Solar energy

The sun is the most plentiful source of energy that we have. It’s about 4.6 billion years old, with another 5 billion years of hydrogen fuel to burn in its lifetime. That gives us a renewable energy source that won’t run out any time soon.

Solar energy – is a source of renewable energy which is based on the transformation of direct solar radiation into electricity. Like all the other types of renewables, solar energy is considered to be environmentally friendly, meaning that it doesn’t produce harmful waste during the active phase of use.

Solar has the potential to become the largest source of electricity in the world by 2050 [1].

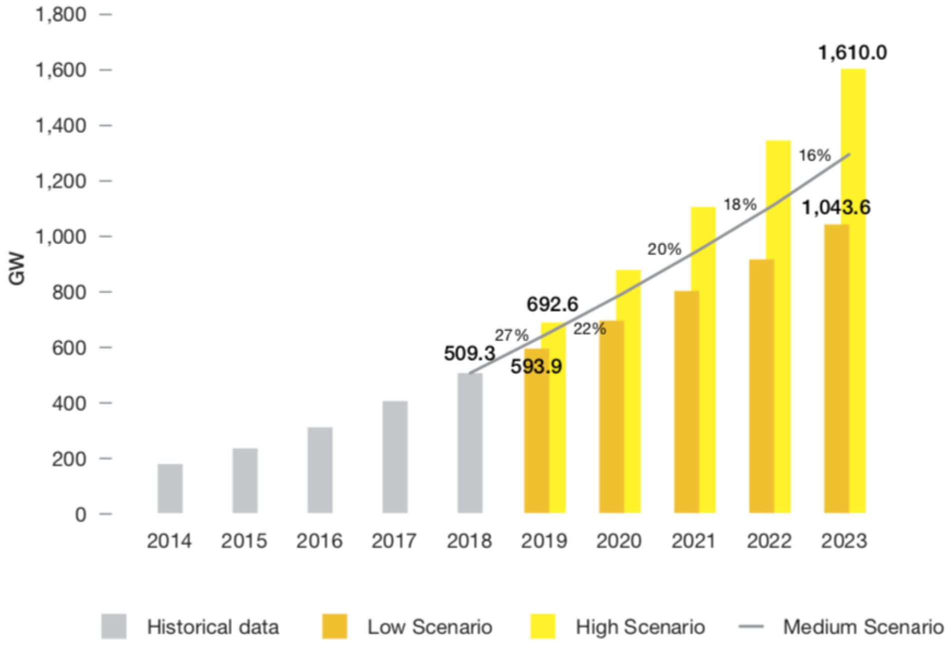


Fig.1 World total solar PV market scenarios 2019-2023 © SolarPower Europe 2019 [2]

At the same time, we should take a note of the fact that the use of sun as a source of energy originates from the XVI century. In 1767 the Swiss scientist Horace-Benedict de Saussure constructed the first solar collector. It was composed of an insulated box covered with three layers of glass in order to absorb solar energy.

However, the photovoltaic effect, which is the milestone of modern solar energy generation used in Photovoltaic solar panels, was discovered in 1839 by the French scientist Edmond Becquerel. He introduced this effect by placing two electrodes in an electrolyte and exposing it to the solar radiation [3].

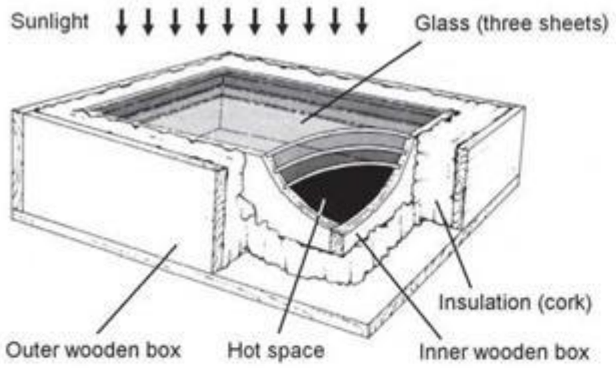


Fig. 2 The" hot box" of Horace-Benedict de Saussure

Because of high potential, the idea of using solar radiation as source of electricity, have encouraged people to continue improving technologies since the 1700s. Thus, in 1985, all installed capacity of solar panels in the world reached 0.021 GW. This value has increased up to 1.656 GW in 2005, and taking into consideration the pace of development, solar energy set a record for the growth of installed capacity in 2017 by adding 38% to the performance indicators recorded in 2016. Solar energy dominated the growth rates not only in context of renewable sources, but from the point of view of overall sources of electricity generation (Fig. 3)

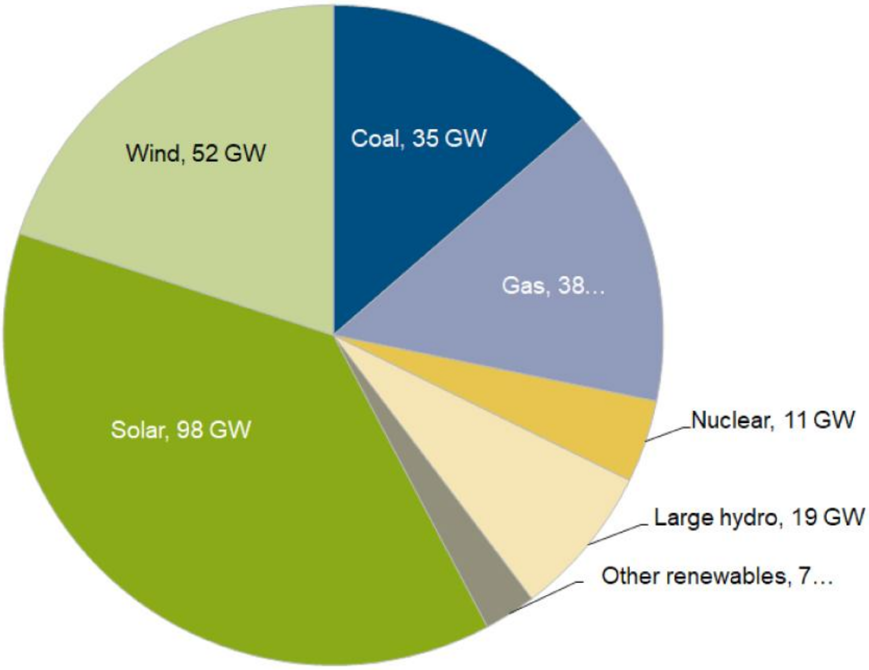


Fig.3 Global growth rates of main sources of electrical energy generation [4]

The production efficiency of solar industry continues to improve, and for over the last 5 years, electricity cost for the production of polysilicon, which is the main material of PV cells, have halved. This has reduced dramatically energy consumption and significantly increased the number of panels that can be made of a kilogram of silicon. The analysts of BNEF (Bloomberg New Energy Finance) expect that the cost of cutting silicon monolithic ingots into panels will decrease by 30% over the next 2 years.

A particular perspective is seen in the technology of manufacturing PV plates directly from a melt of silicon. According to another technology, silicon is precipitated from gaseous starting material. Both technologies eliminate several stages of production and promise to significantly reduce costs and increase yield of the same amount of raw materials.

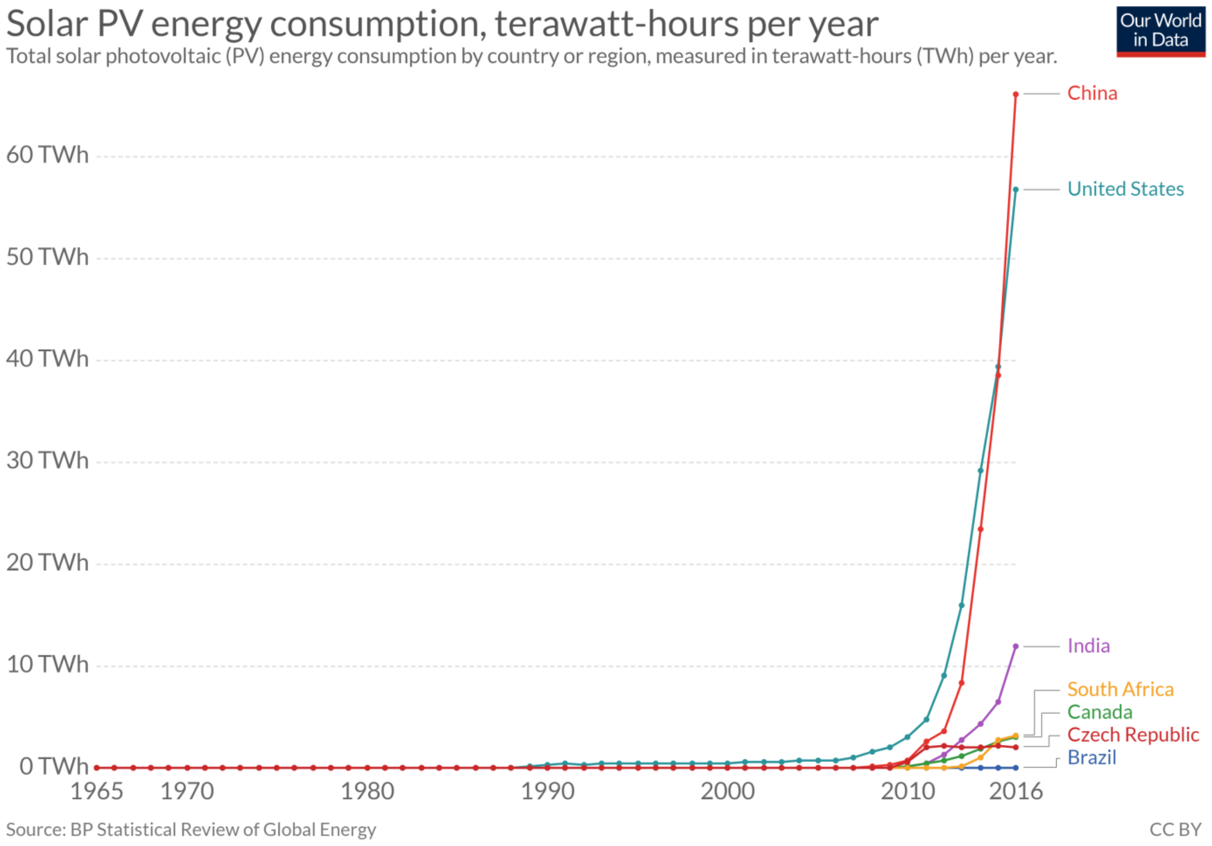


Fig.4 Solar energy consumption by country [5]

The main benefits of solar energy generation are the facts that there is no need to use water during electricity production since we don’t need to cool generators just like in traditional systems. The only time when the water might be needed is during the cleaning of panels’ surface out of dirt and dust.

Using the sun as the main source of power generation reduces toxic emissions in air and basically there is no any greenhouse gasses produced by solar panels, which helps to reduce the effects of climate change.

Another fact is to consider is that solar power plants has more secured connection to the grid with reducing the problems caused by blackouts and voltage drops. There is less chance of overloads or fires which may lead to the considerable damage in transformer substations.

Types of Solar PV systems

Solar energy system can be divided in 3 main groups:

1. Off-Grid system - is not connected to the electricity grid and requires battery storage.
2. On-Grid system – generates electricity when the utility power grid is available
3. Hybrid Solar system – combination of on-grid and off-grid systems

Off-Grid system

The main factor in such system is to choose suitable battery with appropriate capacity in order to meet the electrical energy demand of consumers. The sizing of off-grid system depends on the daily wattage usage and peak watt-per-hour value. This value can be calculated with the help of pattern monitoring and energy metering data loggers.

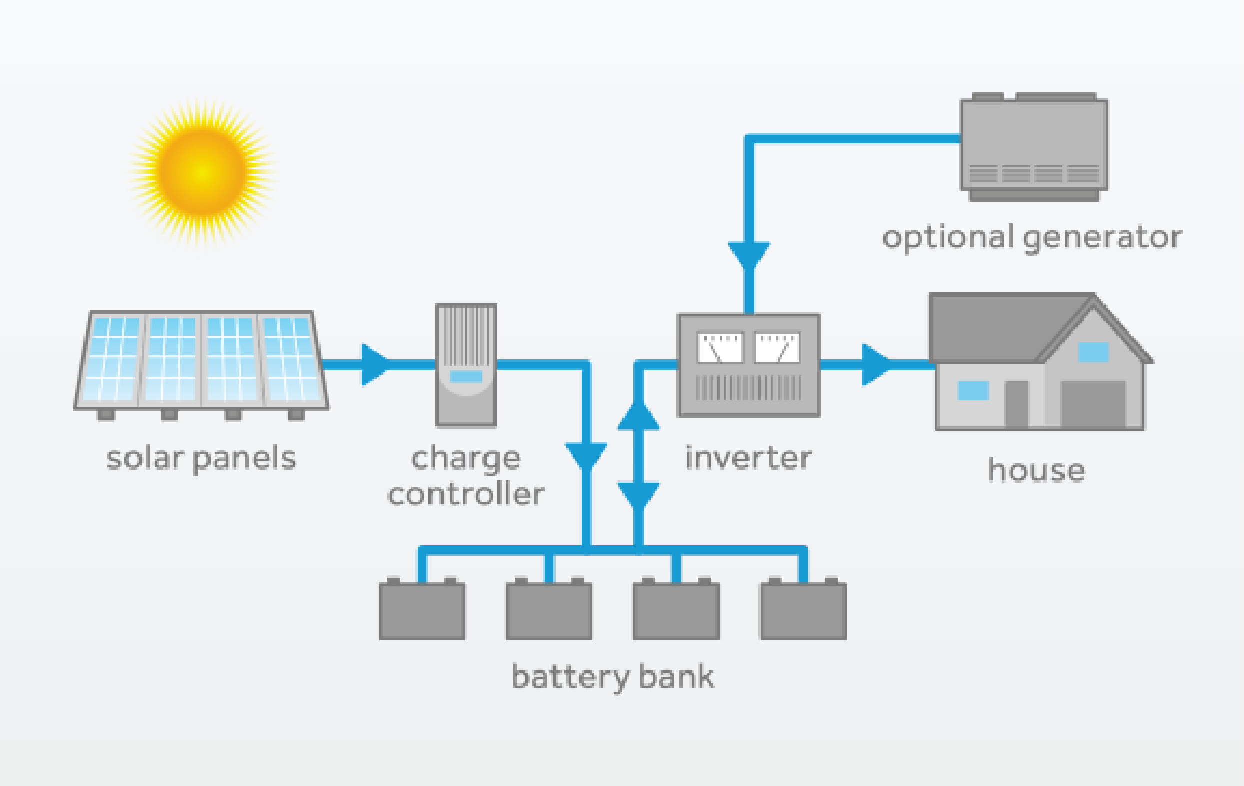


Fig. 5 Description of Off-grid solar system [6]

On-grid system

On-grid solar system, as distinct from off-grid, doesn't have any batteries, which means that the surplus power that is generated during a day can be transferred back to the grid. Therefore, such systems are rewarded by feed-in tariffs.

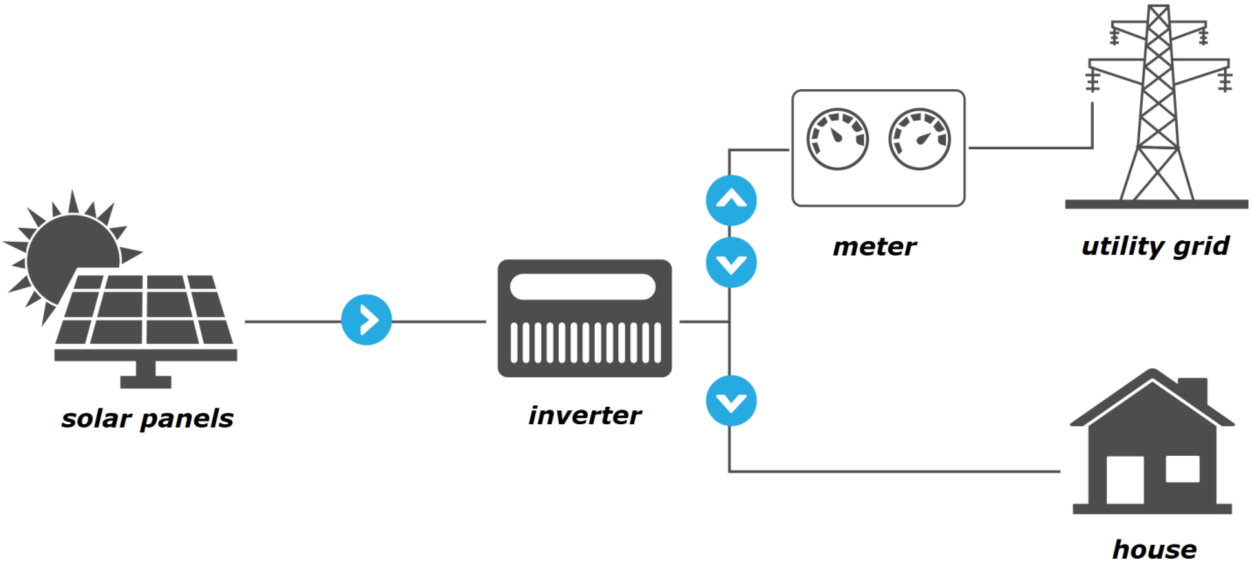


Fig.6 On-grid solar system [7]

Such system allows consumers to use mainly solar energy during a daytime and considered to be more suitable for residential areas and for locations where grid is continuously available and reliable.

However, during night time, when solar panels are disconnected from the grid, consumers have to use electricity supplied by the distribution system.

The inverters are considered to be the main part of such system. The common inverter converts DC, which coming from solar panel to the grid level AC. If there is any power shortage in the grid, it disconnects solar system in order to protect equipment and line from damage.

Hybrid type system

As it was mentioned above, this system consisted by batteries and on-grid energy supply. Hybrid system is suitable for locations with high consumption and relatively less generated energy such as residential areas, office spaces, schools and colleges, hotels and etc.

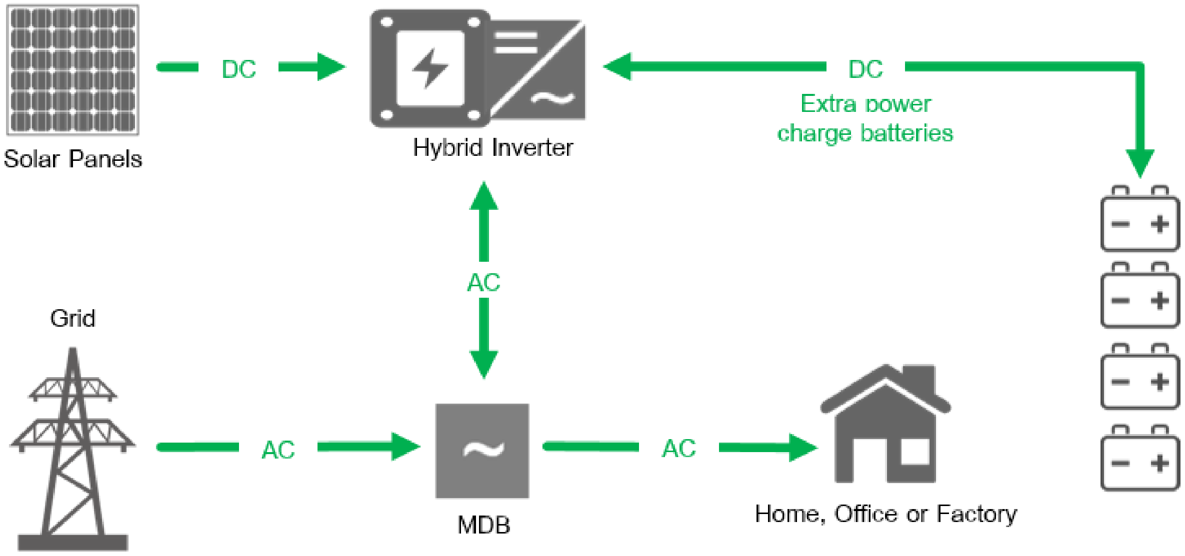


Fig. 7 Hybrid solar system [8]

As distinct from on-grid system, the excess power is sent to the batteries instead of returning it to the grid. Only when batteries are charged, then the solar energy will be exported to the grid. During the time when the solar system is not in its operating state and if batteries are drained, then the power from distribution network will be consumed.

The batteries are also able to be charged from grid electricity during off-peak period (starting from midnight until 6am) [9]

Wind Power energy

Electricity generated by transformation of kinetic energy of atmosphere's air masses by wind turbines has the potential to become one of the most popular technologies in the world. According to the Global renewable energy consumption measured in terawatt-hours, starting from the beginning of 2000 and till the year of 2016 wind energy consumption has increased from 31.7 up to 960 Twh[10].

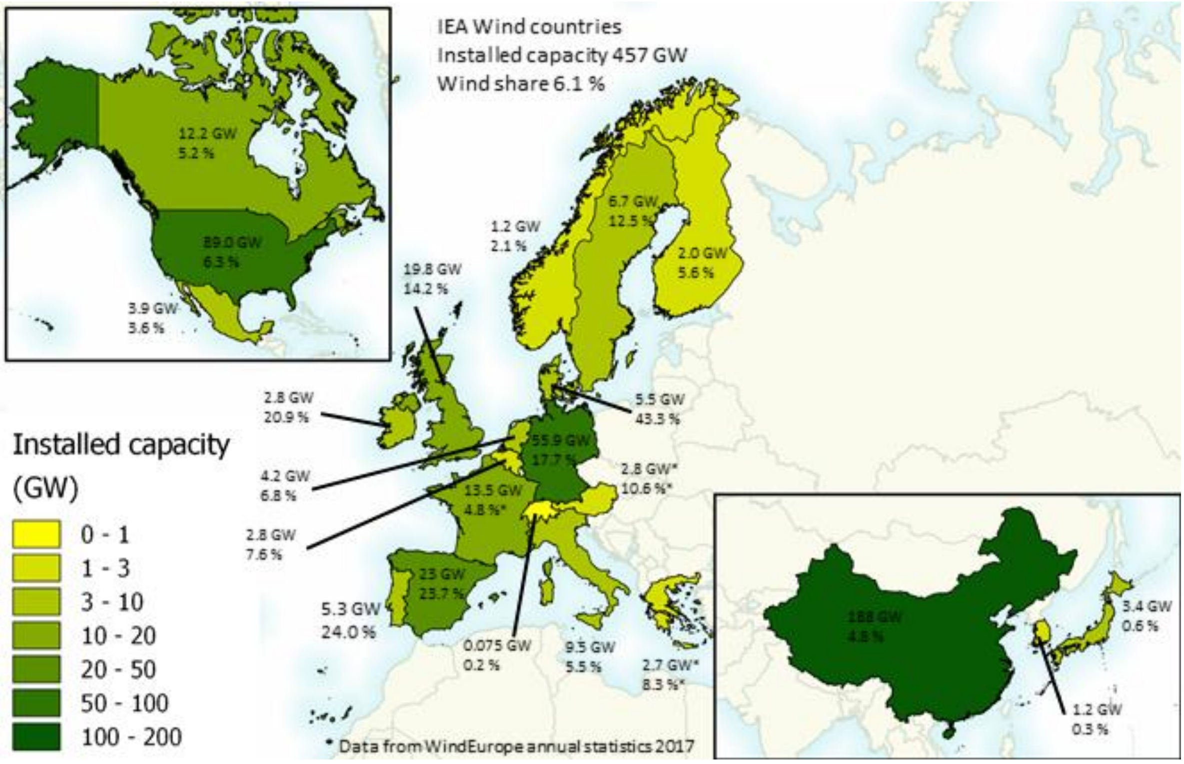


Fig. 8 Data from Wind Europe Annual statistics 2017 [11]

It goes without saying that the main advantage of wind lies in the fact that there is no need to mine or extract in comparison with any other types of fossil fuels such as coal, oil and etc. Taking into account that total reserve of potential wind energy is considered to equal 170 000 TWh, which means that theoretically there is a possibility to supply whole world with electricity obtained from wind. However each coin has two different sides, and wind energy is not an exception.

Usage of wind as energy source has its roots from the beginning of 20th century when the first electricity-generating wind turbine was installed in July 1887 by Scottish academic James Blyth in Marykirk, Scotland[12].

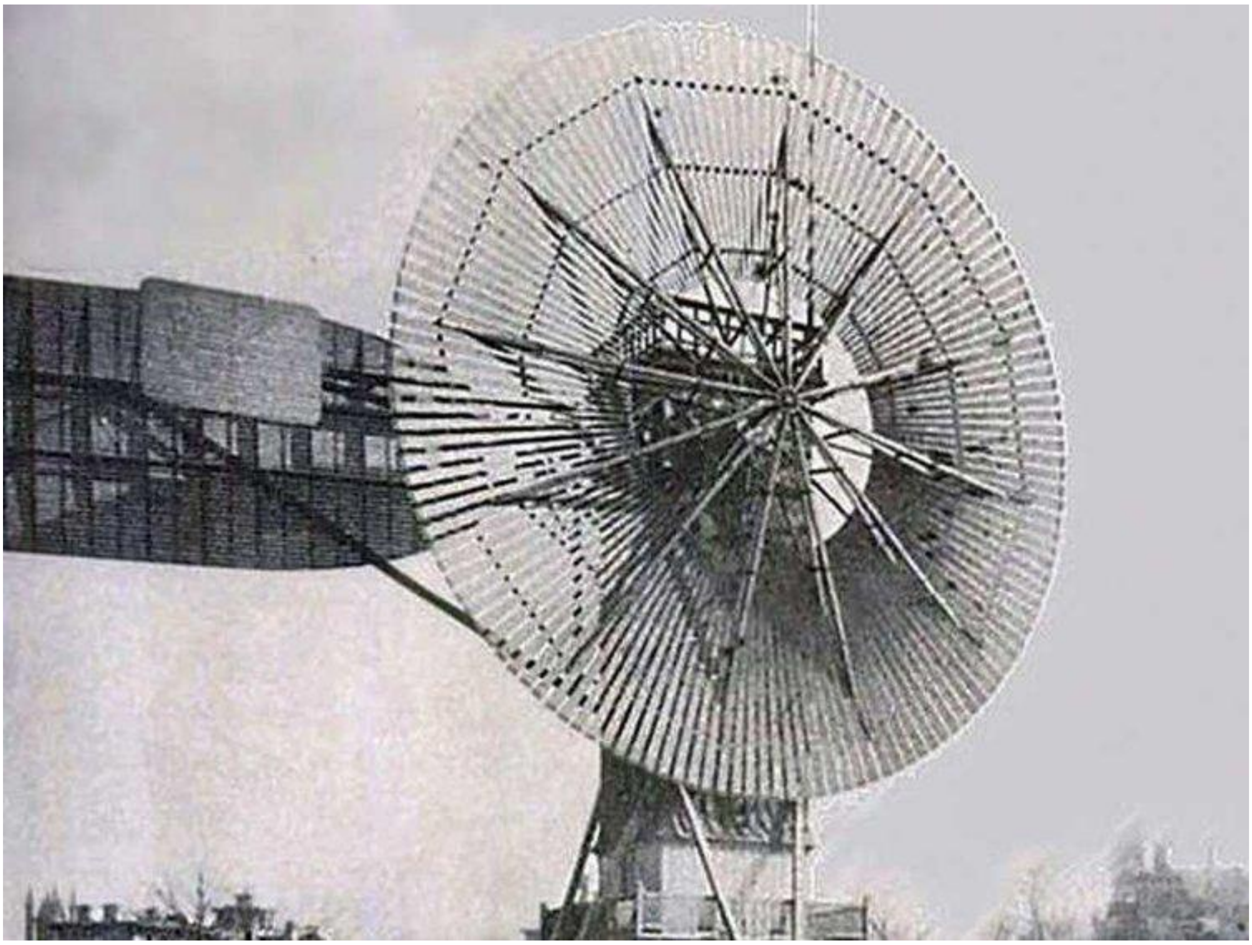


Fig. 9 World’s first wind turbine

And just only five decades later the first megawatt-class wind turbine was synchronized to a power grid. This turbine has been introduced by Smith-Putnam and utilized for 1100 hours before suffering a critical failure.

There was no opportunity for repair due to a shortage of materials during the II World War. Despite the setback of previous attempt to integrate wind turbine to a utility grid, it has been eventually possible to connect it to a grid in UK, Orkney Islands in 1951. In comparison to previous one this wind generator had more developed construction and was built by John Brown & Company [13]

At the present time we may observe considerable increase in cumulative installed wind energy capacity. It is especially can be noticed starting from the period since 1997 right up to the year of 2016, that the amount of generated energy by wind turbines has increased almost 80 times.

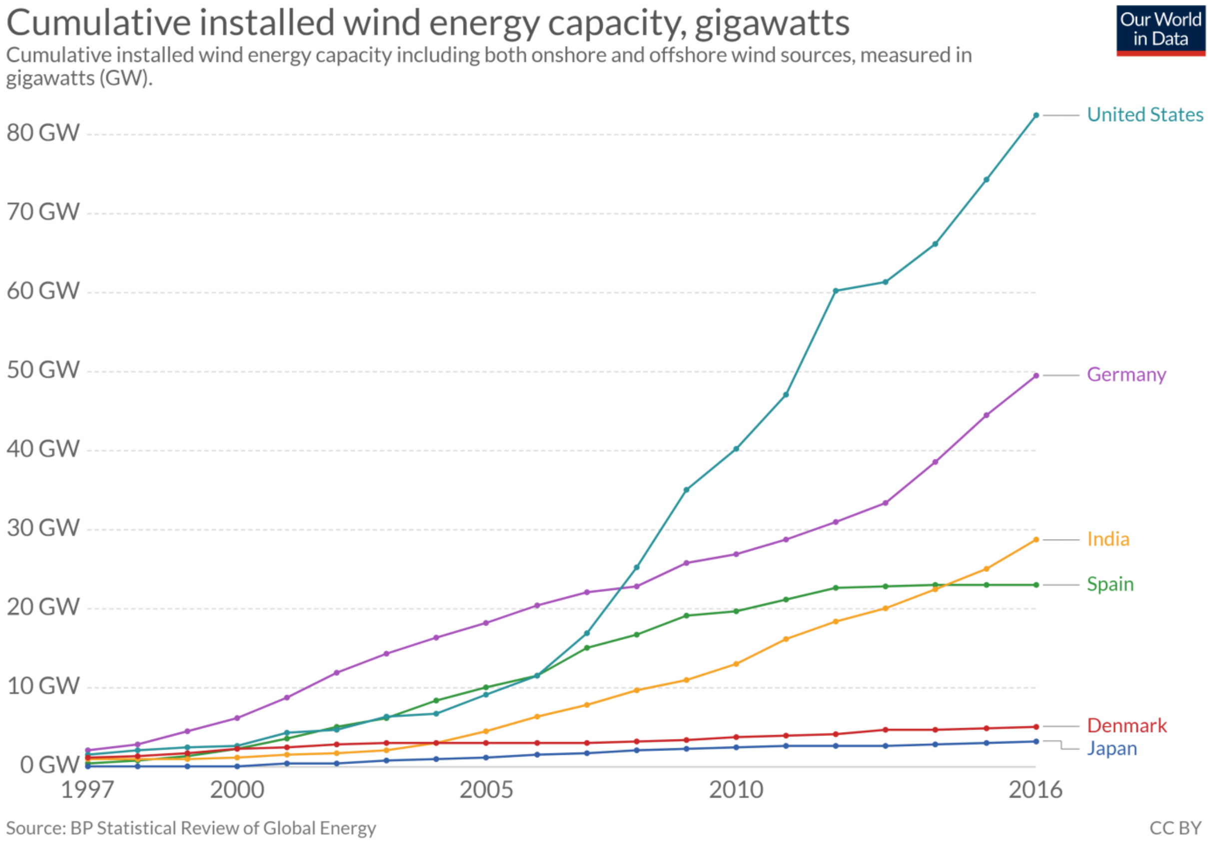


Fig. 10 Cumulative installed wind energy by country

Nevertheless, the disadvantages of such electrical energy generation system should also been taken into account, since there is huge expenditure on non-renewable materials (metals in particular) which are mined by non-ecologically friendly methods.

Ecologist claim against wind power due to the fact that the noise, infrasound fluctuations and vibrations, which are produced by the rotation of wind turbine blades, have adverse effects on human, animals and other equipment. Wind power plants not just spoil natural landscapes and also decreases animal population in such territories due to noise and huge construction. Another concern is to recycle blades which have already been utilized.

Therefore, the main options are either to reuse the blade and the composite material elements as they are found in the blade or to transform the composite material into a new source of material.

There are two main types of blade utilization which are mostly consist of fiberglass: mechanical and thermal. *Mechanical method* involves shredding of fiber and granules, in order for subsequent manufacturing of lower-grade production. In most cases, however, turbines are being recycled by *thermal method*, which implies combustion. It goes without saying, that burning has adverse effects on ecology and is contrary to the main principle of renewable energy sources, which supposed to be clean energy.

Taking into consideration all pros and cons of wind turbine technologies, it is undeniable fact, that continuous transformation of power system increases the significance of integrating such power production methods. Based by the recently released IEA Wind TCP Report, which analyzes the development of the European power system until 2030 and explores the effects of different wind turbine designs on the value of wind energy, and leads to the conclusion that technology design that takes into account both cost and value is important. Furthermore, failing to consider both cost and value in the technological development of land-based wind power and when analyzing the development of power systems could result in an underestimation of the competitiveness of wind power and its potential contribution to a cost-effective system development. [14]

Main operating principles and efficiency of Wind turbines

The Betz' law, which has been discovered back in 1920 by German physicist named Albert Betz found out that the maximum amount of wind flowing through turbines can be converted by 59-60% of efficiency rate. And it is undeniable fact that there will never be machine that will extract 100% efficiency from wind energy, taking all available kinetic energy out of the wind. Basically, it is possible to determine the power of the wind going into the wind turbine using following formula:

$$Power = \frac{1}{2}\dot{m}v^2$$

As is known, Power is considered to be the rate of energy transfer. And if we imagine, that the wind flowing through a turbine can be taken as a cylinder of air

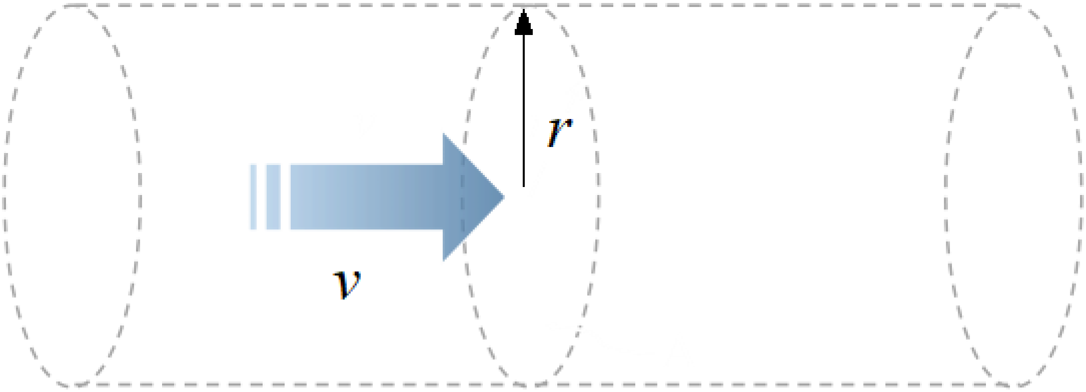


Fig.11 Cylinder of air flowing through turbine.

It should be taken into account that the wind power, which is going through a specific wind turbine depends on several variables, such as: air density, the diameter of wind turbine blades squared and the velocity of the wind.
The other variables are more or less just efficiency measurements, since there is always going to be some heat loss in the different components starting from the wind and coming to the electrical power plant.

$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot r^2 \cdot C_p \cdot C_f \cdot V^3 \cdot N_g \cdot N_b$$

, where

P – Power in the wind [W]

ρ – density of the air [kg/m^3]

r – blade length [m]

V – velocity of wind [m/s]

C_p – power coefficient

C_f – capacity factor

N_g – generator efficiency

N_b – gearbox efficiency

It is also possible to combine all constants into one, in order to make formula look simpler:

$$P = C \cdot V^3 \cdot r^2$$

The main idea of planning wind power plant consists of providing and adequate access to high-velocity air flow for each wind turbine, to acquire maximal available efficiency and generate more electricity.

Considering the fact that the speed of wind is much higher at the area which is higher than construction itself, in comparison to the air flowing through the blades of wind turbine, the best way to improve performance construction is mixing these flows.

For the time being, the vast majority of wind power is produced by *horizontal-axis* wind turbines, which are generally have three airplane propeller type rotor blades. The electrical generator is located at the top of tower and the main goal is to point it to the wind direction. For these purposes, simple wind vane is used in small turbines, whereas large turbines mainly use a wind sensor coupled with a yaw system. Three-bladed turbines are usually constructed from the blades with length range 20-80 meters.

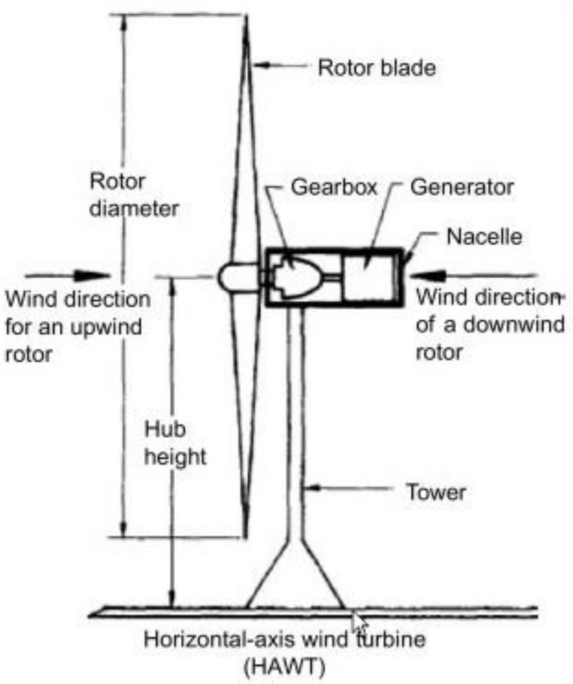


Fig.12 Horizontal-axis wind turbine[15]

There are also two mechanisms used to adjust turbine to the wind speed and direction – gyro mechanism and pitch control. To get the maximum efficiency, propeller should face wind direction all the time, so depending on this the tail of propeller turns the mechanism in order to get most suitable position.

In its turn pitch control mechanism is used to get a uniform output despite the changes of wind speed and direction. Pitch control mechanism consists of velocity measuring tool on top of the turbine which assists to adjust pitch angle automatically with relation to wind speed, in other words it is reducing propeller rotation speed during the strong wind and opposite.

However, as it was mentioned above, the stochastic nature of wind resulted in demand to explore different types of wind turbines. *Vertical-axis turbines* are more suitable for this situation considering that wind has intermittent speed and direction. The main advantage of vertical turbine arrangement is that there is no need for reorientation as wind shifts, which excludes application of additional mechanisms such as in horizontal-axis wind turbines.

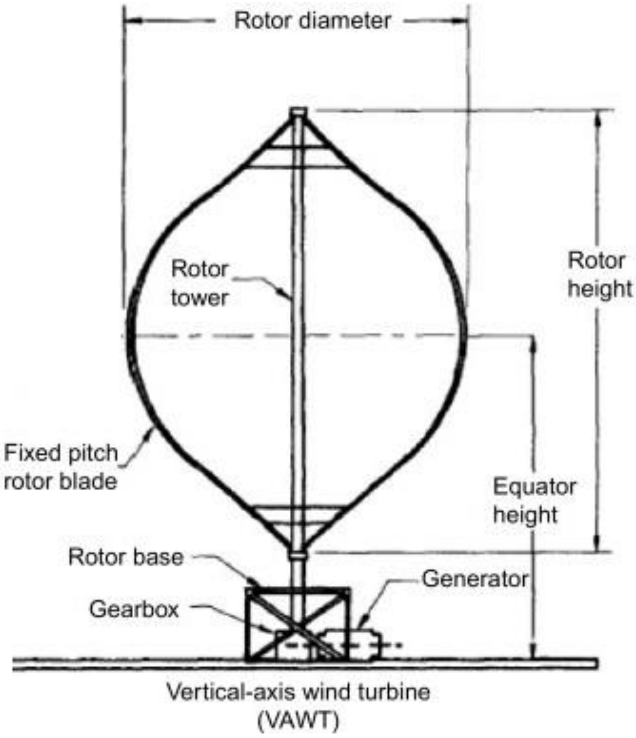


Fig. 13 Vertical-axis wind turbine [15]

Vertical-axis wind turbines (VAWT) are providing much more strong vortexes, especially if turbines of neighboring plant are rotating in the opposite direction. As a consequence, wind power plants composed of vertical-axis wind turbines requires less installation area in comparison to horizontal-axis wind turbines, for the reason that they can be grouped together and operate in turbulent and gusty wind.

Nevertheless VAWTS's tend to be less reliable and less suited for large scale energy production. Nowadays, VAWT's also can be used with combination of solar power cells. Such "hybrid" wind turbine generates energy by two methods: highly effective PV panels are producing electricity during sunny weather and at the same time horizontal blades of rotor are rotating regardless of wind direction [16].

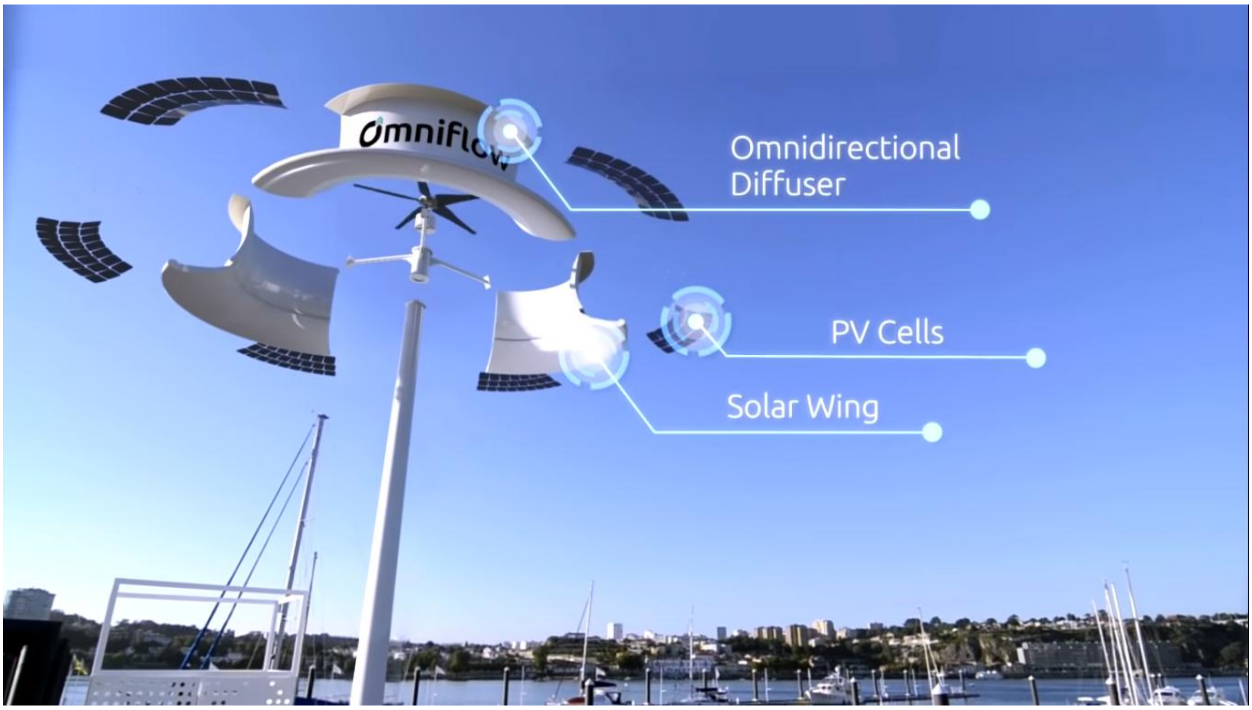


Fig. 14 Vertical-axis wind turbine with combination of solar PV cells, Omniflow.

Hydropower plants

The energy of moving water which is usually originating from rain or melted snow, creating streams and rivers can be transformed into electrical energy. Harnessing the power of water generally takes place on hydropower plants.

Hydroelectricity is considered to be a renewable energy source because the water cycle is constantly renewed by the Sun. One of the first uses of hydro energy was for mechanical milling, irrigation and water supply. The earliest application of hydro power plants, including water wheel, have been recorded over 2000 years ago. With the emergence of electrical generator by the late 19th century, it has become possible to construct more efficient power plants coupled with hydraulics.

The first prototype of modern hydroelectric power schemes was introduced in 1878 by William Armstrong at Cragside in Northumberland, England [17]

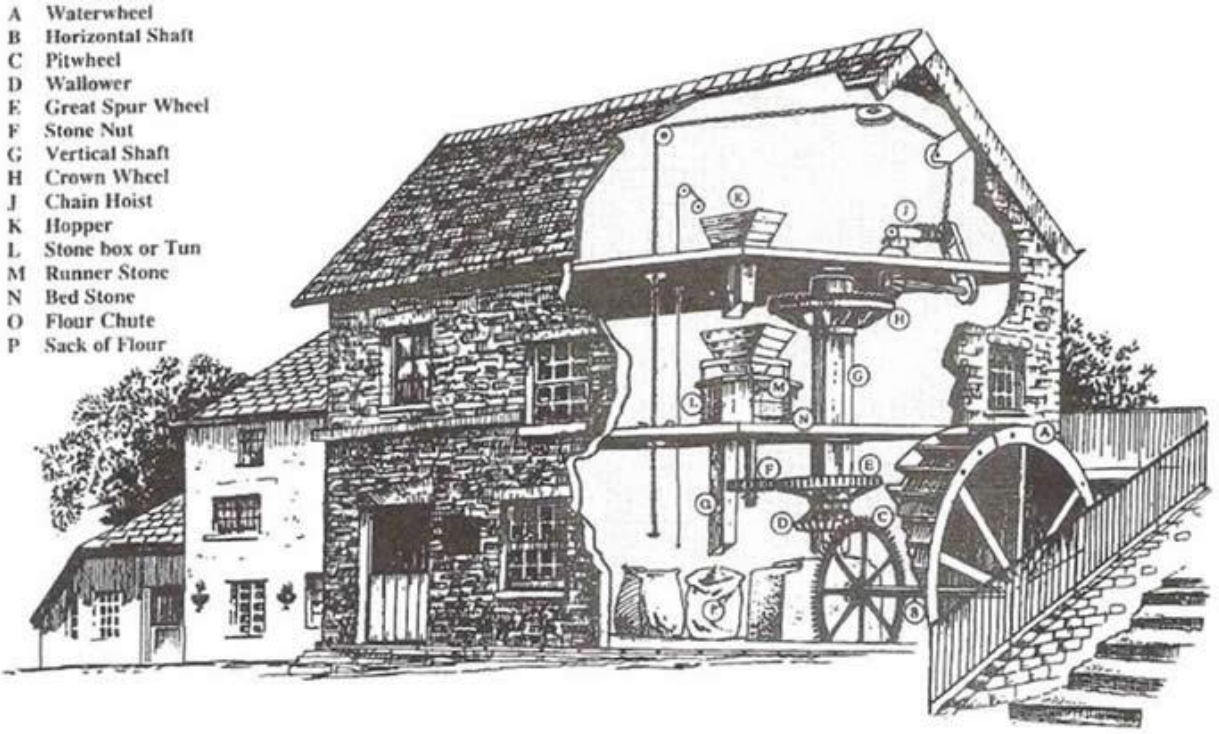


Fig. 15 Traditional Water Wheel [18]

An output of the first hydroelectric power station was 12,5 KW, however this values kept growing throughout the 20th century, reaching 1,345 MW in 1936.

Over the past decades, there has been a considerable increase in global hydroelectric power consumption conversely creating an urgent demand to implement more efficient ways of water usage.

Significant difference has been recorded between years 1950 and 1960. During this decade consumption has grown almost two times, from 333 TWh up to 689 TWh per year. The graph (Fig. 16) illustrates annual hydropower consumption for particular country, measured in terawatt-hours per year.

And the most influential period is considered to be the year of 2004, when Chine has become the biggest hydropower consuming country in the world with 353 TWh annual consumption. Besides the fact that other countries were trying to control their hydropower usage, China has reached 1162 TWh in 2016 while the second most consuming country in the world, Canada stopped at 388 TWh.

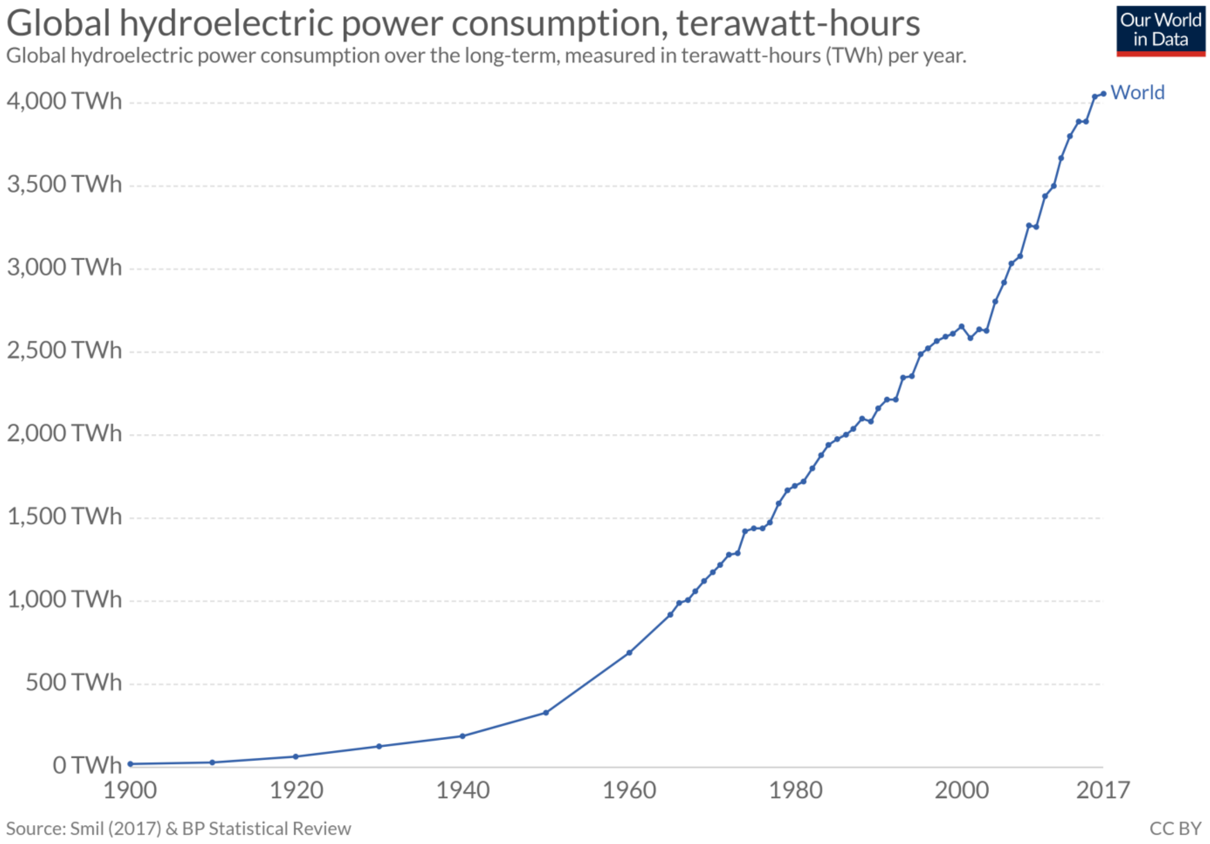


Fig. 16 Global hydroelectric power consumption

Conversely, Czech Republic has the lowest rank among the other countries shown in this graph. Which, for its part is not bad for the reason that there is a less need to utilize natural sources in order to supply consumers with electrical power.

Considering all measured data, since 1965, it can be concluded that the highest annual usage of hydroelectricity in Czech Republic was recorded in 2013 – 2.87 TWh per year.

Fluctuations in hydropower consumption can be clearly seen in *Fig. 18*, where the minimum has been recorded in year 1973 – 1.08 TWh, however because of increasing need in power, apparently this value will continue to rise.

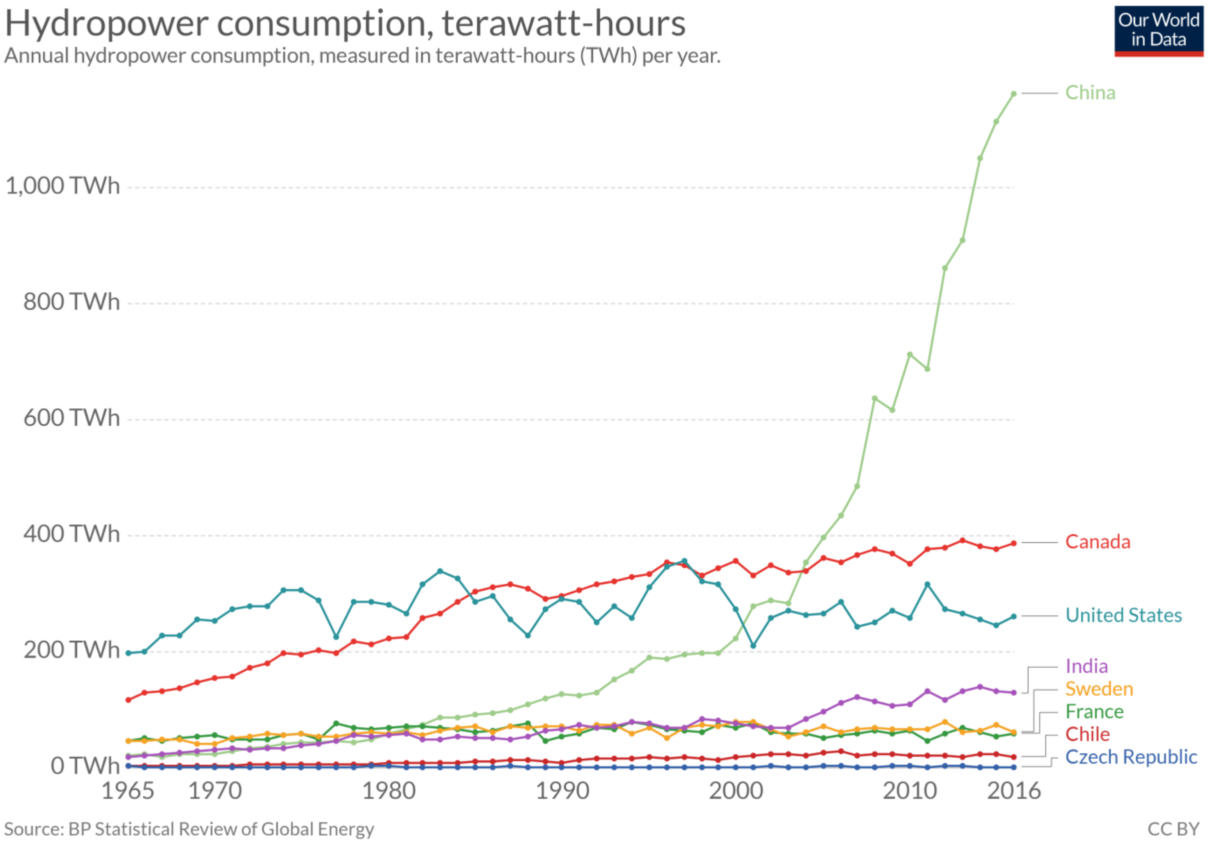


Fig. 17 Annual hydropower consumption by country

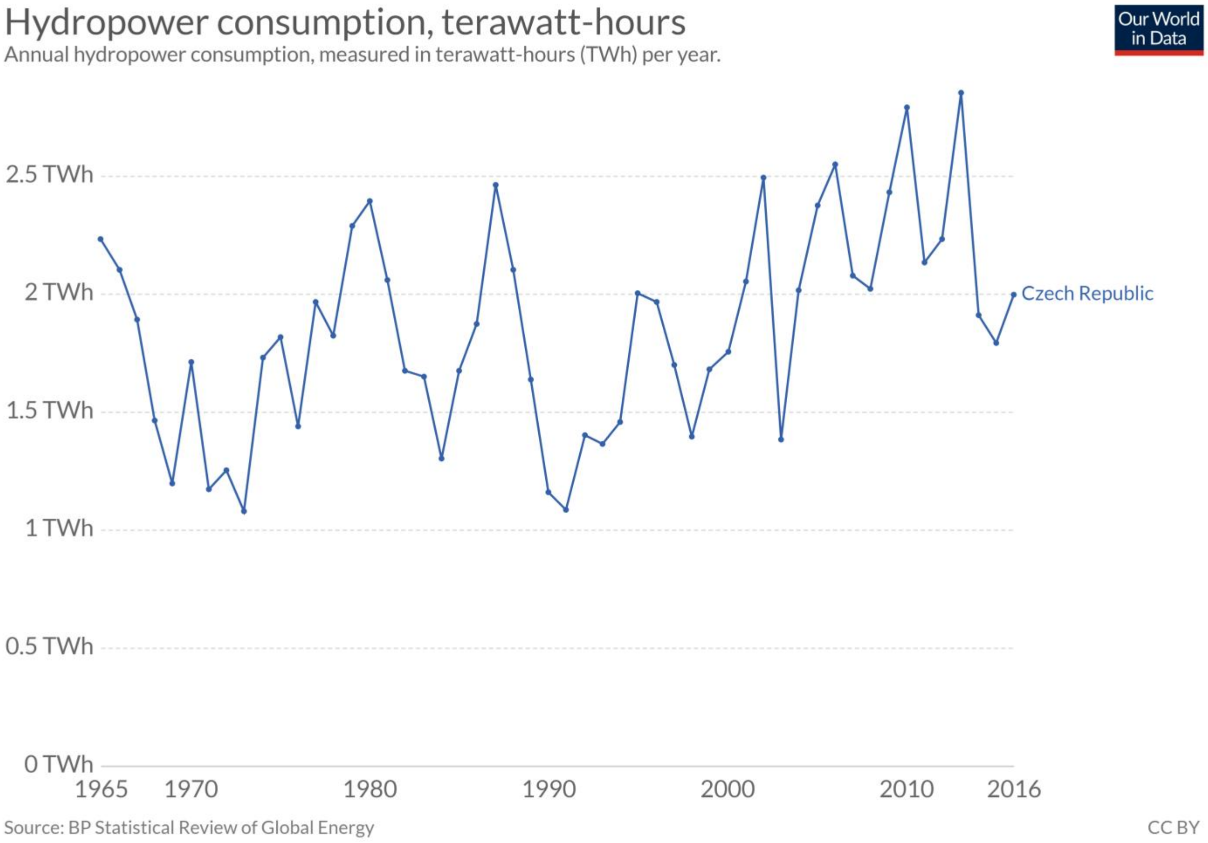


Fig. 18 Annual hydroelectricity consumption in the Czech Republic

One of the key factors determining the efficiency of hydroelectricity source is considered to be local energy potential of water flow. In order to measure output power of Hydropower plant, the main calculation parameter to take into account are Falling height (H [m]) and Flow rate of water (Q [m^3/s]):

$$P = g\rho Qh\eta$$

, where

P – power [kW]

g – acceleration because of gravity = 9.81 [m/s^2]

ρ – density of water [kg/m^3]

η – turbine efficiency = 50-75%

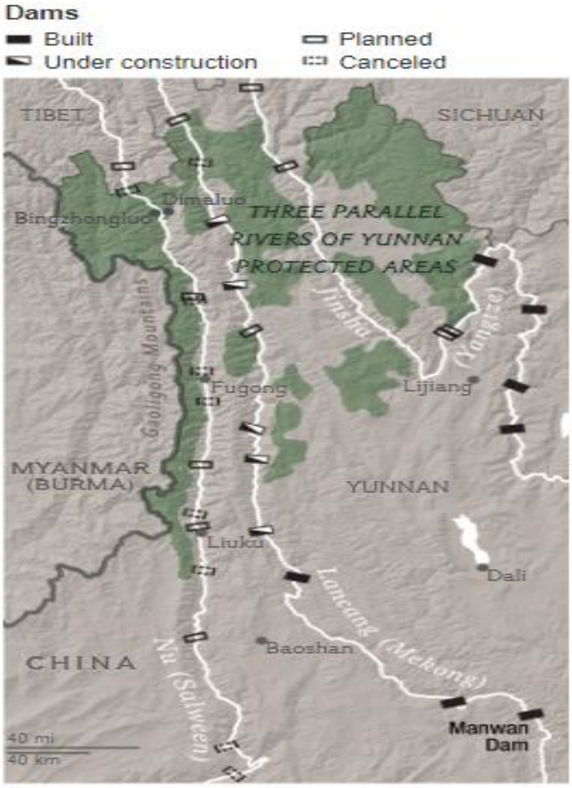
Q – water flow rate [m^3/s]

h – falling height of water [m]

In the light of the fact that hydropower resources of EU are near depletion, government is focusing on other renewable energy sources. Additionally, the regional ecosystem is also affected by hydropower plants as a result of damming rivers.[19]

In spite of the fact that hydro plants are believed to be ecofriendly, nevertheless there are carbon emissions which are produced during construction due to considerable quantity of cement used. In addition to everything else, the reservoirs created by dams may emit methane into the atmosphere as a result of vegetation loss in stagnant pools of water.

To cite just one example of dam’s negative effect, during the last 60 years there has been constructed more than
80 000 dams with the total power of 300 GW, which caused to relocation of 1.3 million villagers in order to implement the project of the Three Gorges Dam, China’s biggest hydropower project. [20]



NG MAPS
SOURCES: STUART LEAVENWORTH; INTERNATIONAL RIVERS; WORLD DATABASE OF PROTECTED AREAS

Fig. 19 Three Gorges Dam hydropower project [20]

Biomass energy

At the present time Biomass is considered to be the sixth largest source of energy after oil shale, uranium, coal, oil and natural gas. Total biological mass of the Earth is estimated at $2.4 \cdot 10^{12}$ tons.

Taking into account all renewable sources it is positioned as the fifth most productive source of energy after solar, wind, hydro and geothermal energy. The main part of biomass fuel (80%) is wood and it is mainly used for heating the houses and generation of electricity, biofuels or biogas (methane, hydrogen)

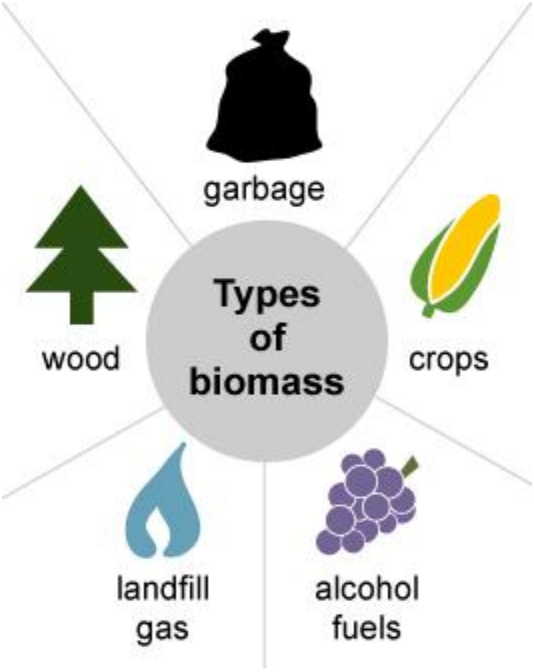


Fig. 20 Main types of biomass [21]

There are different methods of biomass energy generation such as: direct firing, pyrolysis, gasification and anaerobic digestion [22].

Direct Firing

This is probably the easiest way to get energy from biomass. Industrial facilities can burn many types of biomass-based fuels, including firewood, agricultural waste, wood pulp, and municipal solid waste. When burned in boilers, steam is produced which rotates the turbine. The latter causes the rotation of the rotor of the generator that produces electricity. Due to the potential accumulation of ash, which litters the boiler, reducing its efficiency and increasing costs, only certain types of biomass materials are used for direct combustion.

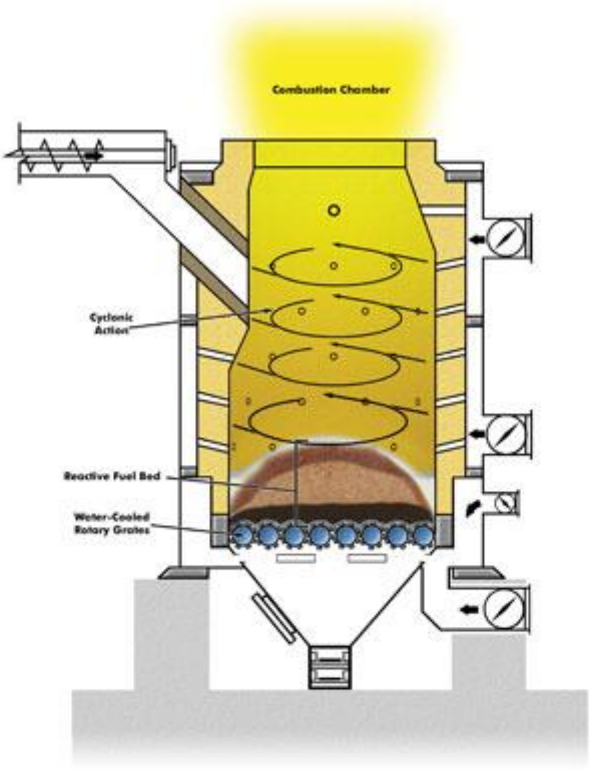


Fig. 21 Combustion chamber (direct firing method) [23]

Gasification

Gasification is the process of exposing high temperature solid fuel with limited access of oxygen to produce gaseous fuel. In this way, a mixture of gases such as carbon monoxide, carbon dioxide, nitrogen, hydrogen and methane is obtained thereafter gas is used to drive a gas turbine. Gasification has several advantages over the combustion of solid fuels. An important plus technology - one of the gases produced - methane. It can be processed in the same way as natural gas and used for the same purpose.

The advantage is that gasification produces fuel without impurities. Consequently, burning it causes less pollution problems. Under certain conditions, it is possible to produce synthesis gas - a mixture of carbon monoxide and hydrogen, which can be a raw material for the production of hydrocarbons (for example, methane and methanol) to replace fossil fuels. Hydrogen itself is also a potential clean fuel that can supposedly replace petroleum and petroleum products in the foreseeable future.

Fig. 22 Gasification plant in Maui, Hawaii [24]

Pyrolysis

In its simplest form, pyrolysis is the heating of biomass with the removal of volatile substances, as a result of which charcoal is formed. This process converts the source material into a more energy-consuming, as the charcoal weighs half the original biomass, but contains the same amount of energy, which makes the fuel more transportable. Coal also burns at a significantly higher temperature than the original biomass. This makes it more useful for production processes. More complex pyrolysis methods have been developed recently to collect volatile substances that are otherwise lost in the system. The collected volatile substances produce a gas that is rich in hydrogen and carbon monoxide. These compounds are synthesized in methane, methanol and other hydrocarbons.

Fast pyrolysis is used to produce bio-oil - combustible fuel. Heat is used to chemically convert biomass into synthetic oil, which is easier to store and transport than solid biomass materials. It is then burned to produce electricity. Pyrolysis can also convert biomass into phenolic oil - a chemical used to make wood glues, molded plastics and insulating foam.

Anaerobic digestion

Anaerobic digestion of biomass is carried out by anaerobic bacteria. These microorganisms usually live at the bottom of swamps or in other places where there is no air, consuming dead organic matter to form methane and hydrogen. We can use these bacteria to work for us. By feeding organic matter, such as animal dung or wastewater, into tanks called cooking, and adding bacteria there, we can collect the evolved gas to use it as an energy source. This process is a very effective means of extracting useful electricity from biomass. As a rule, up to two thirds of the energy of fuel from animal manure can be recovered.

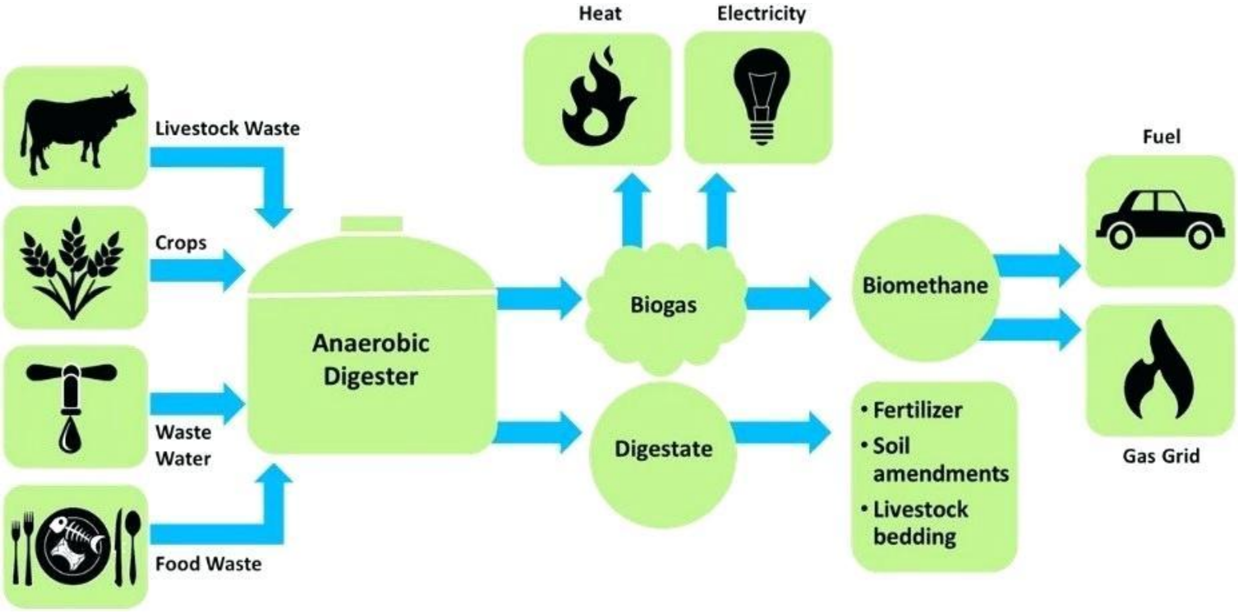


Fig. 23 Anaerobic digestion process

Another method involves collecting methane from landfills. Most of the biomass household waste, such as food waste or grass cuttings, is collected at local landfills. For several decades, anaerobic bacteria in the lower layers of such landfills decompose organic matter, releasing methane. The gas can be removed and used by installing the top stop from an impermeable layer of clay and installing perforated pipes that will collect the gas and bring it to the surface.

Fermentation

For centuries, people have used yeast and other microorganisms to ferment the sugar of various plants into ethyl alcohol. The production of biomass fuels by fermentation is only a continuation of this process. At the same time, it is possible to use a wider range of plant material from sugar cane to wood fiber. For example, wastes from wheat milling in New South Wales mills are used to produce ethanol by fermentation. Ethanol is then mixed with diesel fuel to produce fuel used to refuel trucks and buses in Australia.

Technical progress will inevitably improve this method. For example, scientists in Australia and the United States replaced the yeast with genetically engineered bacteria during the fermentation process.

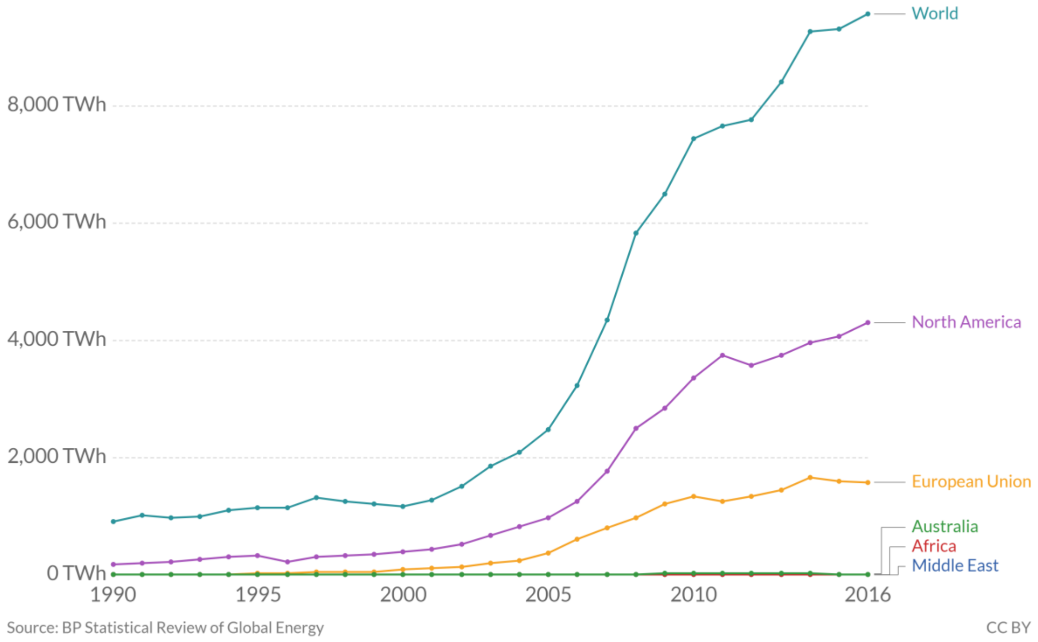


Fig. 24 Biofuel production in the world [25]

Geothermal energy

Geothermal energy is the energy of heat that has been released from the inner zones of the Earth for hundreds of millions of years. According to geological and geophysical studies, the temperature in the core of the Earth reaches 3,000–6,000 ° C, gradually decreasing in the direction from the center of the planet to its surface.

The main sources of heating of the planet’s interior are uranium, thorium and radioactive potassium. The processes of radioactive decay on the continents occur mainly in the granite layer of the earth's crust at a depth of 20-30 km or more, and in the oceans in the upper mantle. It is assumed that in the base of the earth’s crust at a depth of 10–15 km, the probable temperature on the continents is 600–800 ° C, and in the oceans - 150–200 ° C

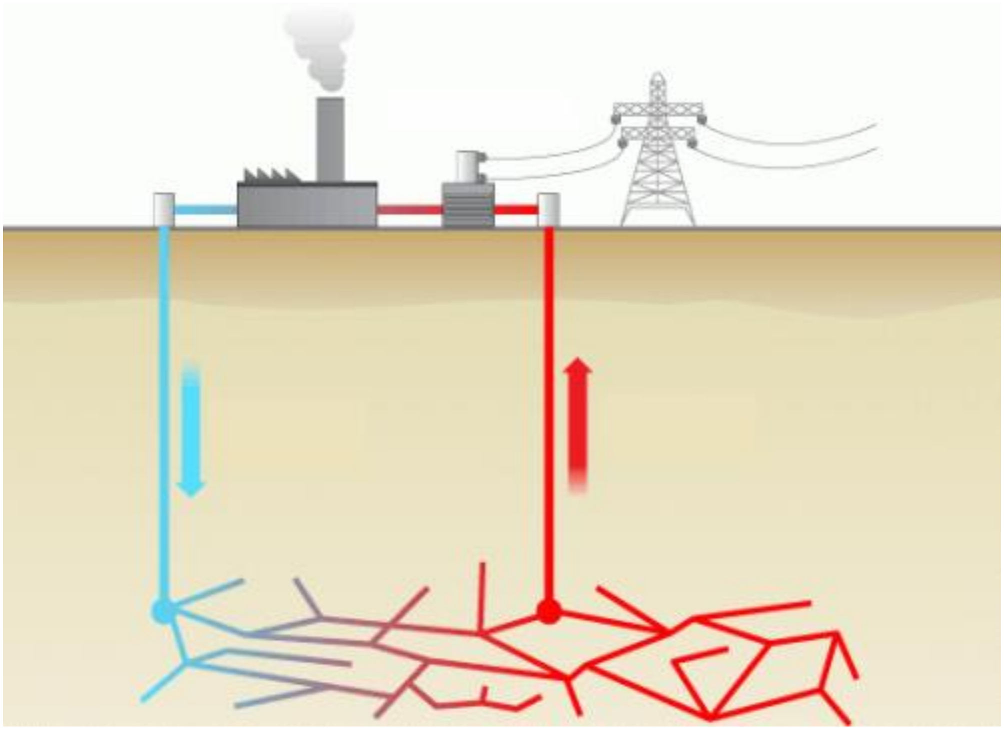


Fig. 25 Operation principle of geothermal power station [26]

Geothermal energy sources are divided into dry hot steam, wet hot steam and hot water. The well, which is an important source of energy for the electric railway in Italy (near Larderello), has been feeding dry hot steam since 1904. Two other hot spots in the world are the Matsukawa field in Japan and the geyser field near San Francisco, where geothermal energy has also been used effectively for a long time. Most of the world's humid hot steam is found in New Zealand (Wairakei), geothermal fields of slightly lower power - in Mexico, Japan, El Salvador, Nicaragua, Russia.

Fig. 26 Geothermal power plant in New Zealand [26]

Thus, four main types of geothermal energy resources can be distinguished:

- Surface heat of the earth used by heat pumps;
- Energy resources of steam, hot and warm water at the surface of the earth, which are now used in the production of electrical energy;
- Heat concentrated deep beneath the surface of the earth (possibly in the absence of water);
- Magma energy and heat that accumulates under volcanoes

Application of small Rooftop PV power stations

Over the past 10 years, houses with solar panels on the roofs have gone from curiosity to the usual phenomenon.

This technology has been available for decades — astronauts have been using solar-powered satellites since 1960, and passive solar heating systems (which convert solar energy into heat instead of electricity) have been used in US and developed European countries.

The advantages of solar panels installed on rooftop are obvious:

- The sun’s energy is infinite (for at least the next 5 billion years)
- Provides clean energy
- Without greenhouse gas emissions and this can save people money on their electric bills

Fig. 27 Example of rooftop PV installation [27]

Rooftop installations of PV panels

Being small compared to the ground-mounted PV power plants, rooftop power plants are usually mounted on residential houses and their capacity starts from 5 up to 20 kW. In order to install such PV panels, there should be made estimations of several parameters such as: Roof slope and aspect; shading effect caused by higher objects creating an obstacle for sun rays.

The way where the roof is faced plays a significant role in efficiency of installed solar panels.

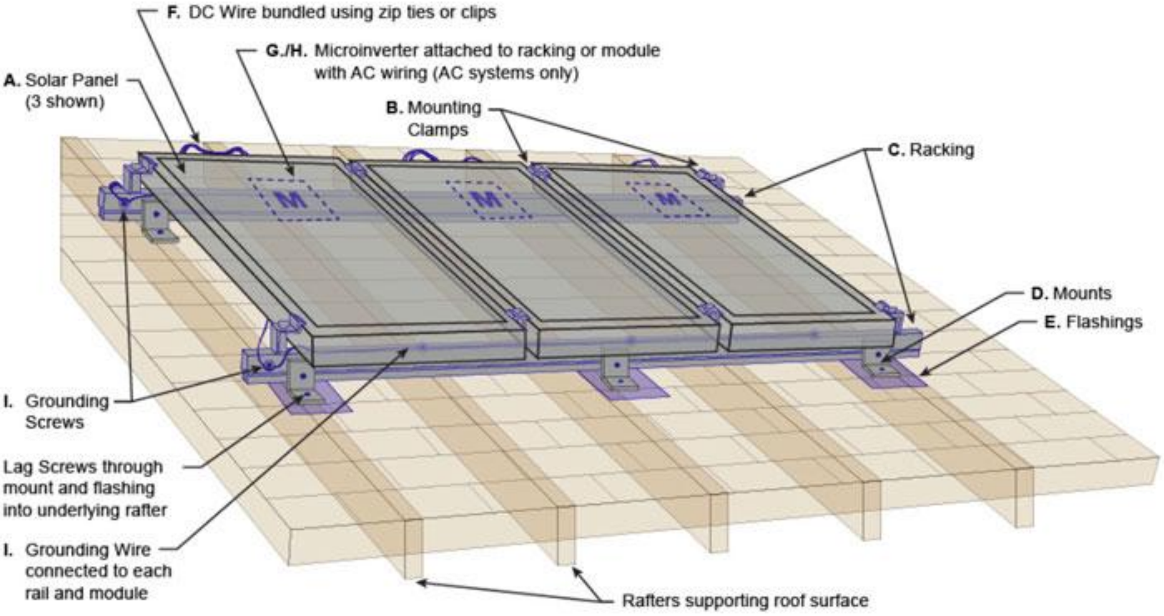


Fig. 28 Mounting solar panel on the roof [28]

The main parts of rooftop PV system:

- Solar panels that convert solar radiation into a constant voltage current.
- Controller that regulates the charge of the battery.
- Batteries
- Inverter

Solar panels are designed in such a way to allow the equipment to operate in different weather conditions, at temperatures from -35^o C to + 80^o C.

It turns out that properly installed solar panels will work with the same performance both in winter and in summer, but under one condition - in clear weather, when the sun gives the maximum amount of heat. The overcast performance is dramatically reduced.

The main requirements are: optimal slope (somewhere about 45^{o} in relation to ground), provide perpendicular incidence of sunlight. In most cases there is also installed a solar tracker which tracks the sun and adjusts the position of panels.

Controller performs several functions such as automatic adjustment of battery charge, regulation of supplied energy from solar panels, thereby protecting batteries from full discharge. When the batteries are fully charged, controller automatically disconnects them from the system. Modern devices are equipped with a control panel with a display showing the voltage level of batteries.

The main task of inverters is to convert DC coming from battery to the AC on the output where the PV system is connecting to the grid.

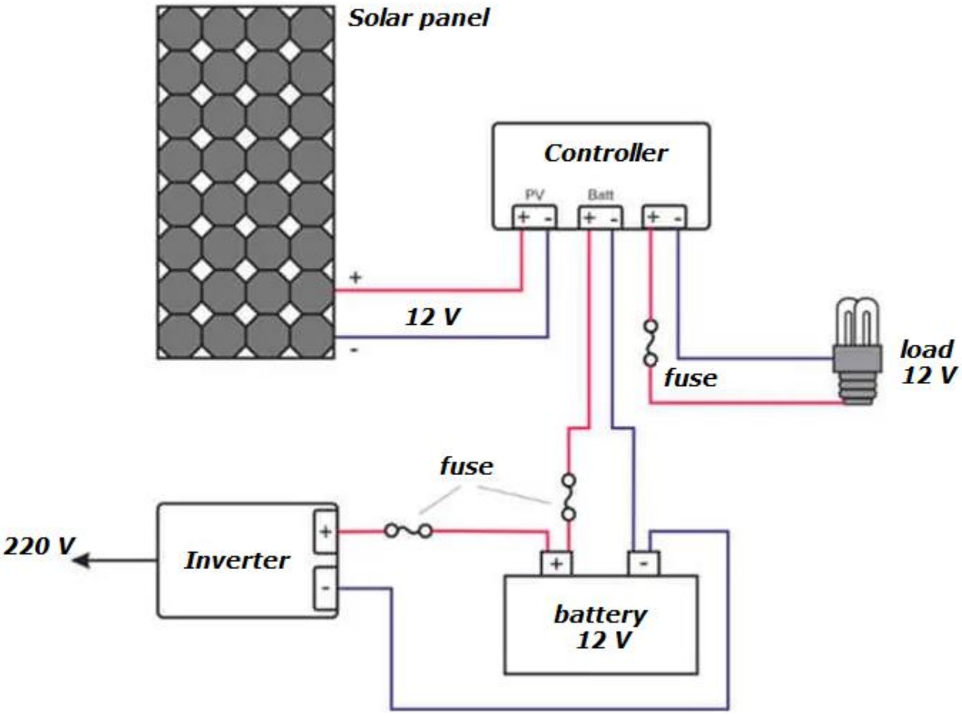


Fig. 29 Connection scheme of solar panels to the grid [29]

The scheme is connected in following order:
First of all, a battery pack is connected to the controller. This is done intentionally to check how the device detects the rated voltage of the network (standard values - 12 V, 24 V). Next, solar panels and controller are connected. The controller and battery are constantly interacting with each other, this is necessary to ensure protection of controller from failure during peak loads.

The array mounts on a frame that allows the panels to be secure with minimal interference with the waterproofing and structure of the roof. Most importantly it provides the correct aspect and elevation for the array and makes possible to receive the maximum amount of sunlight and convert it to the electricity.

The array is connected to the inverter by cable. A second cable connects the inverter to house's switchboard, which conversely connects to the main power grid. This creates a continuous and dynamic system for the contribution of solar energy in the house. The inverter also serves to log the data of total energy production, instantaneous power and etc. These values will fluctuate depending on the time of year, the cloud cover, and temperature, allowing to keep a data of system's performance.

One of the main factors to consider is availability for service. Solar panels generally don't require special care, but since they are used during warm season, therefore a layer of dirt and dust forms on the panels in summer, and there is also snow creating an obstacle for sunlight in winter. These factors may decrease productivity of PV system, which means that preventive actions should be done in order to keep equipment clean and maintain the maximum level of efficiency [30].

Solar tracking system

As previously noted, it is known that the optimum efficiency of solar panels is in the case that they are perpendicularly located in relation to the rays of the Sun falling on them. When the solar tracker is present in the design, its turning mechanism allows the batteries to track the luminary, without losing the level of efficiency. The solar tracker provides regular tracking of the Sun, allowing the panels to “catch” its rays and absorb the maximum amount of light.

The following scheme is an example of solar tracker prototype applied to the PV system (Fig. 30)

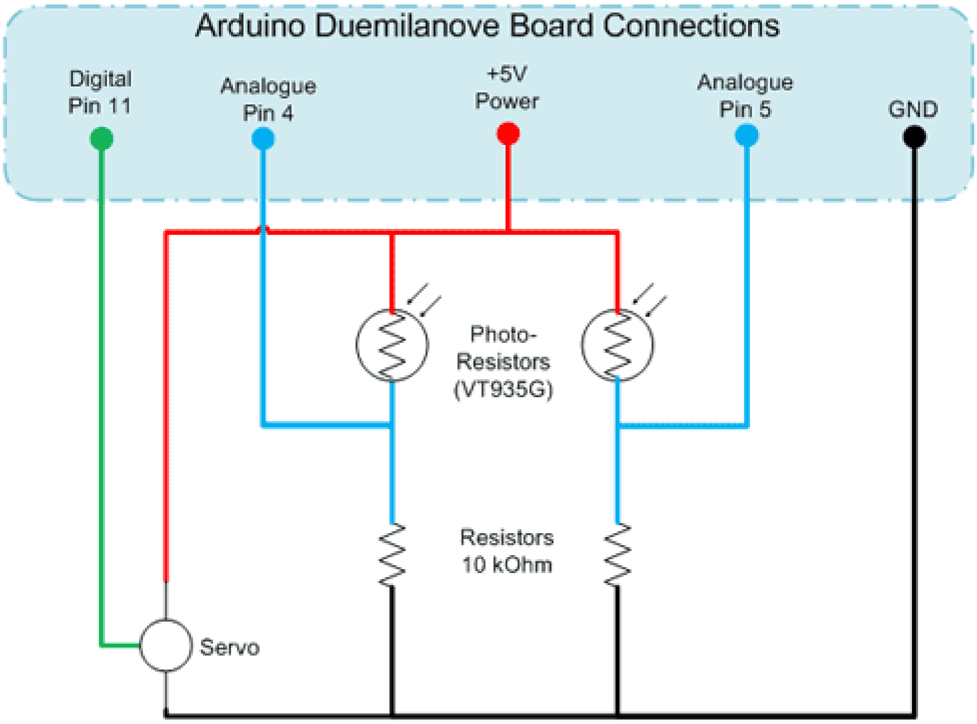


Fig. 30 Solar tracker administered by Arduino controller [31]

Abovementioned scheme contains Arduino controller, which periodically reads the values from the two sensors and compares them. If the values from the sensors are the same, then the panel is pointing at the sun. If the value of one of the sensors differs from the other, the controller gives a command to the servomotor to rotate the platform. The servo command works as long as the values from the sensors are equal.

Based on the axes of rotation, solar panels are classified into:

- With the axis rotating in a horizontal direction relative to the earth's surface;
- The axis rotates vertically relative to the earth's surface;
- The axis is rotated "on an inclined" (the middle variant between the first two);
- With the axis oriented to the North Star;
- Biaxial trackers, with greater amplitude of movement and ample opportunities (have the highest degree of freedom).

Maximum efficiency of fixed solar panels is limited for the reason that the sun rays are falling on the surface of the panels at the optimum angle for only a short time - for two hours a day. Solar panels of a fixed installation show extremely low efficiency during the period of the cloudy weather. These fixed panels should be adjusted for operation in summer and winter. However this factor is commonly neglected, resulting in reducing the effectiveness of the PV system. All of these drawbacks can be avoided by using motorized two-axis solar trackers that increase the efficiency of solar panels by up to 60%. [32]

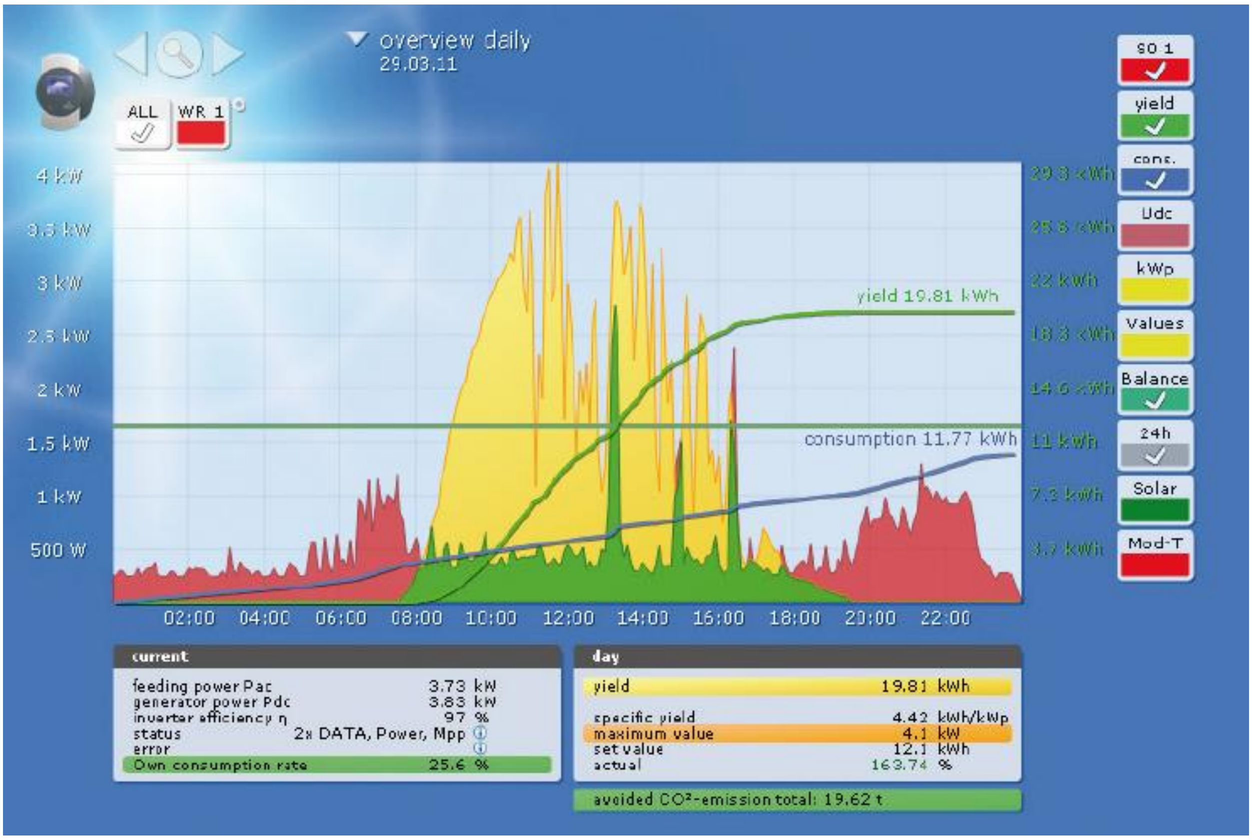
The limiting switch hampers movement to 180 ° both along the X and Y axes, and highly sensitive LEDs following the direction of sunlight. Despite the fact that a tracker for solar panels is an expensive and fragile device, there is a great opportunity to do without serious financial costs. Motors, improved by hand (with the help of limit switches), is a more economical and reliable option that will allow the panels to turn towards the Sun in any weather and at any time of the year. [33]

Monitoring of PV solar system

Nowadays, different types of PV monitoring systems are integrated into the network to collect data from inverters, sunlight sensors and etc. They can also provide charging level or temperature of batteries. There is also a large number of programmable logic controllers (PLCs) designed to control electrical system.

Such monitoring platforms provide better PV performance due to immediate fault detection at the module and system level. Some of them don't require wires to transmit data to inverter for the reason that the monitoring sensors are built into the power optimizer and the date is transmitted by typical distribution lines.

A real-time monitoring can display the balance of produced and consumed electricity: consumed from the grid (red line); supplied to the network (yellow); generated and consumed by solar panels (green) (Fig. 31)



current		
feeding power Pac	3.73	kW
generator power Pdc	3.83	kW
inverter efficiency η	97	%
status	2x DATA, Power, Mpp	
error		
Own consumption rate	25.6	%

day		
yield	19.81	kWh
specific yield	4.42	kWh/kWp
maximum value	4.1	kW
set value	12.1	kWh
actual	163.74	%

avoided CO²-emission total: 19.62 t

Fig. 31 Example of real-time monitoring system SolarLog – Sinergo [34]

Net Metering

In accordance with the "Net metering system", the owner of renewable power plant receives a retail loan of equal or more generated electricity. Most electric meters allow you to perform measurements, both in the forward and in the opposite direction, thereby allowing the consumer to take into account the electricity supplied to the network in settlements with the electricity supplying organization. Of course, the rules for the subsequent use of a consumer loan of electricity differ not only from country to country, but also by regions within the country.

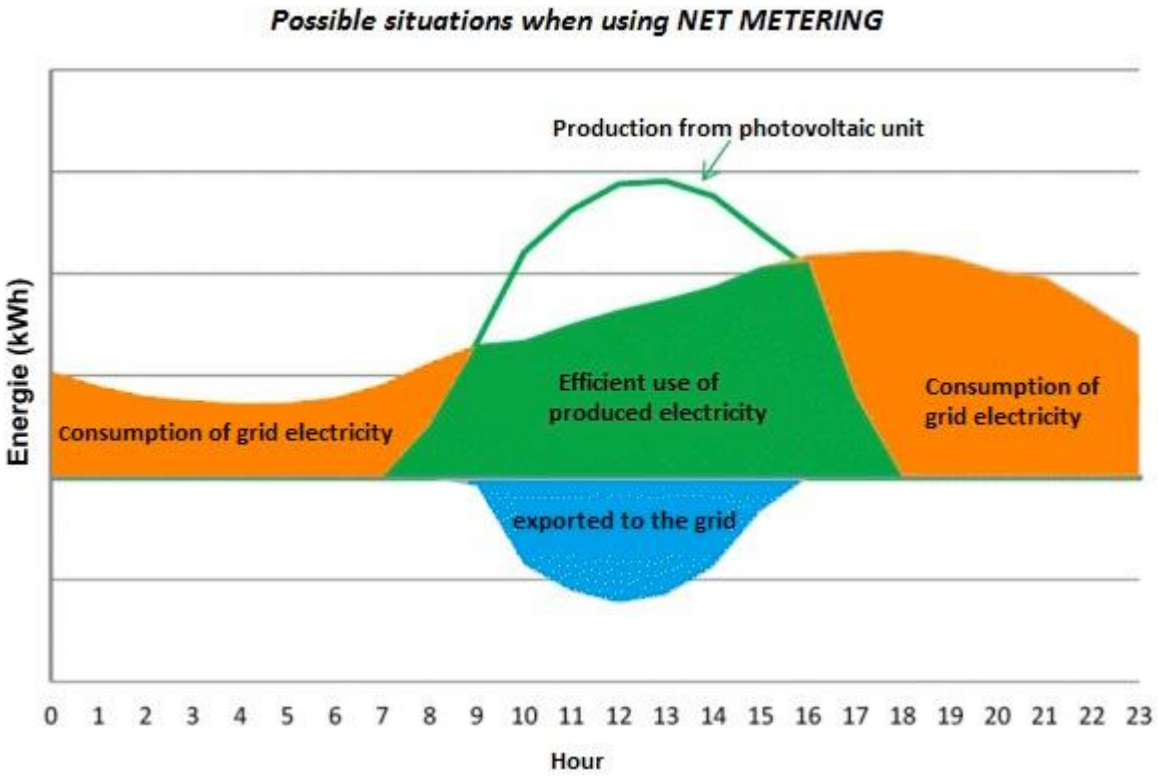


Fig. 32 Net Metering graph [35]

In this case, these rules indicate:

- whether or not there is a net measurement system;

- if so, for how long the consumer has the right to use the accumulated credit of his electricity;

- at what price this surplus is calculated (retail, wholesale price).

In accordance with applicable laws on net metering, the following basic terms are used:

- monthly extension of the loan of electricity;

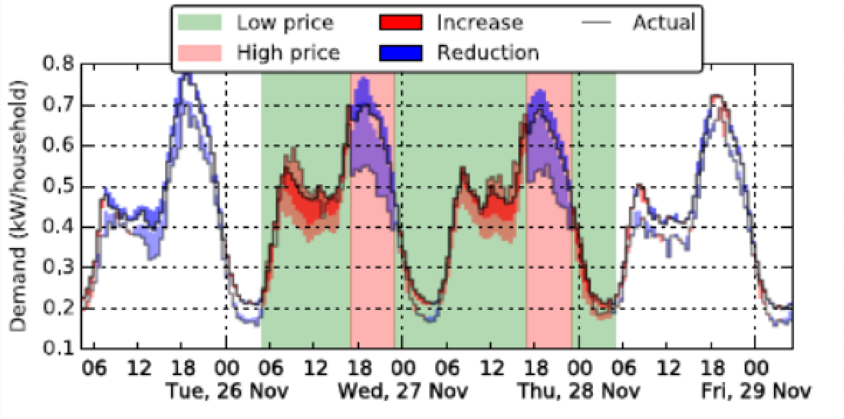
- monthly connection fee;

- monthly payment of consumed electricity (meaning the usual bill for used electricity);

- the annual amount of the calculation of the existing surplus of the consumer's electricity in mutual settlements with the electricity supplying organization.

Demand Side Management

Demand Side Management is the change in end-user electricity consumption is related to their normal load profile in response to changes in electricity prices over time or and based on incentive payments provided to reduce consumption during periods of high electricity prices on wholesale market or when system reliability is at risk [36]. Demand management can reduce electricity prices on the wholesale market, which, in turn, leads to lower prices on the retail market [37]. It is widely recognized as a means of ensuring the reliability of energy supply, the integration of renewable energy sources, increasing competition in the electricity market and empowering consumers [38].



Zdroj: Konference CIRED 2015

Fig. 33 Demand Side Management of active load

The main purpose of demand management for electricity is to reduce the peak load in the power system, which is necessary both to reduce prices in the electricity market and to prevent excessive capital-intensive construction of peak power plants and electrical networks, emergency control of the power system and the integration of renewable energy sources.

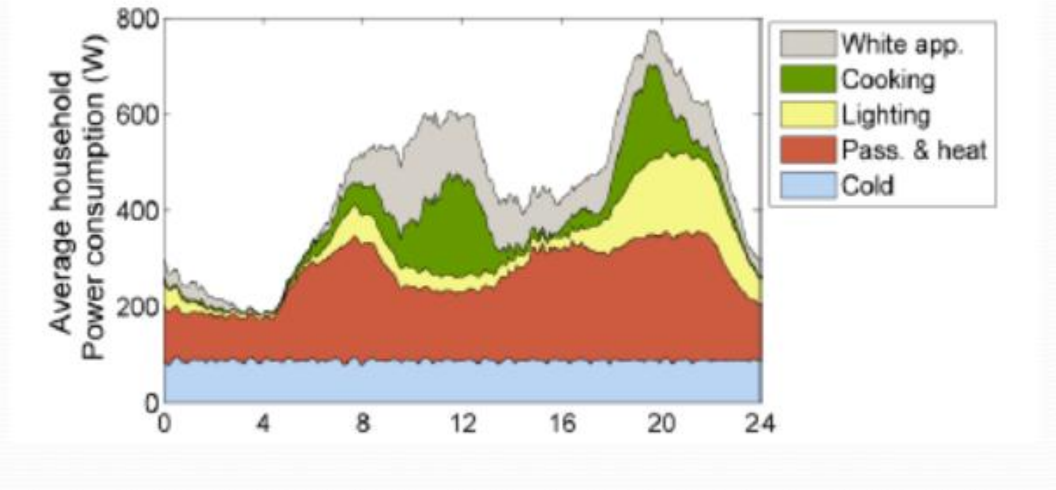


Fig. 34 Daily load with accordance to the type of electrical appliances

Eligibility for Feed-in tariff

The experience gained in the world allows us to speak of fixed feed-in tariffs as the most successful measures to stimulate the development of renewable energy sources. These measures are based on three main factors:

- Guarantee of network connection;
- Long-term contract for the RES producers;
- Purchase guarantee of generated electricity at a fixed price

Fixed tariffs for renewable energy may differ not only for different sources of renewable energy, but also depending on the installed capacity of power plant. One of the options for a support system based on fixed tariffs is integration of a fixed premium to the market price of renewable energy.

As a rule, the surcharge to the price of electricity produced or a fixed tariff is paid for a sufficiently long period (10-20 years), thereby ensuring the return of investments invested in the project and profit.

Solar energy power plants installed in Czech Republic are eligible for feed-in tariff support according to the following requirements:

- Only installations on rooftops or façades are eligible and the maximum capacity must not exceed 30 kW (§ 4 par. 5 Letter d Act No. 165/2012).
- The installation must have been put into operation until 31 December 2013 (§ 4 par. 10 Act No. 165/2012).
- Only one installation per rooftop or facade is eligible (§ 4 par. 5 Letter d Act No. 165/2012). [39]

Connection of small Photovoltaic power system to the low-voltage 0.4 kV distribution network

Since the area which has been used for our research is neither considered to be power-hungry nor industrial and large business center, therefore it is supplied by simple one-phase overhead power line provided by nearest electrical power substation.

As mentioned above, our scheme is considered to be low voltage network and fed by 0.4 kV power line. Pátek village has been selected as the location of housing area, which is in Nymburk District in the Central Bohemian Region of the Czech Republic.

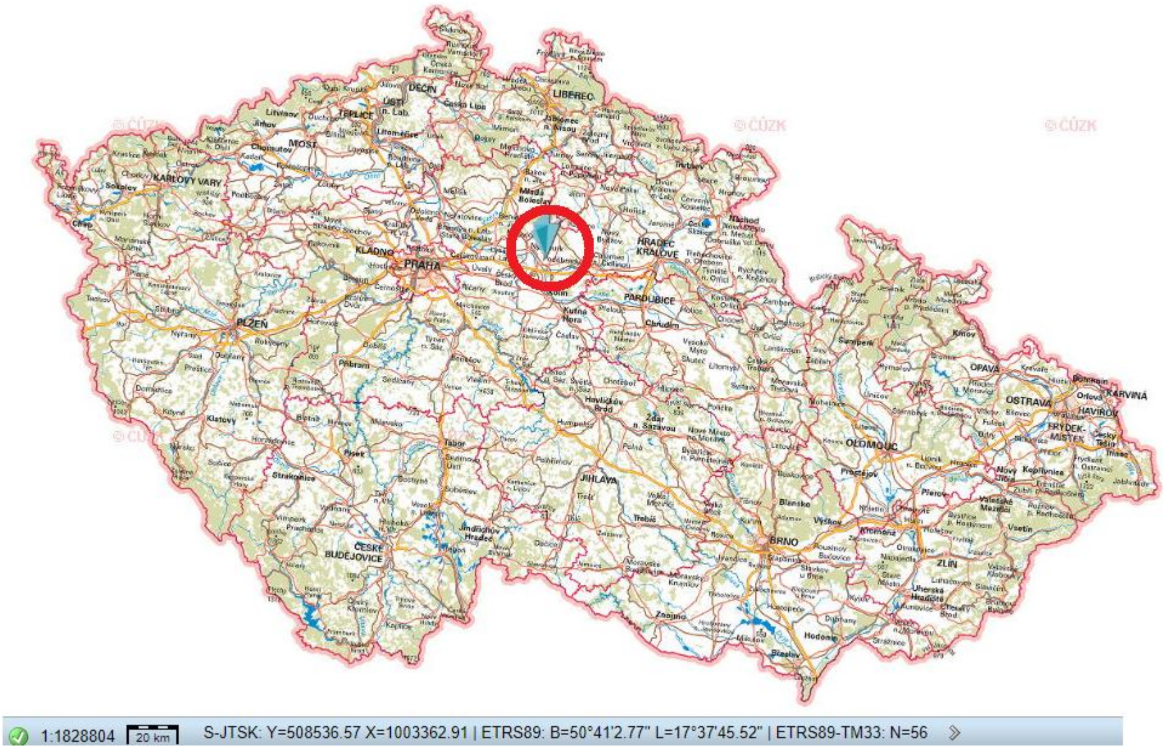


Fig.35 Pátek village on general map of The Czech Republic. Copyright © 2010 ČÚZK [40]

This village has 724 residents and the cadastral area is 690 hectares.

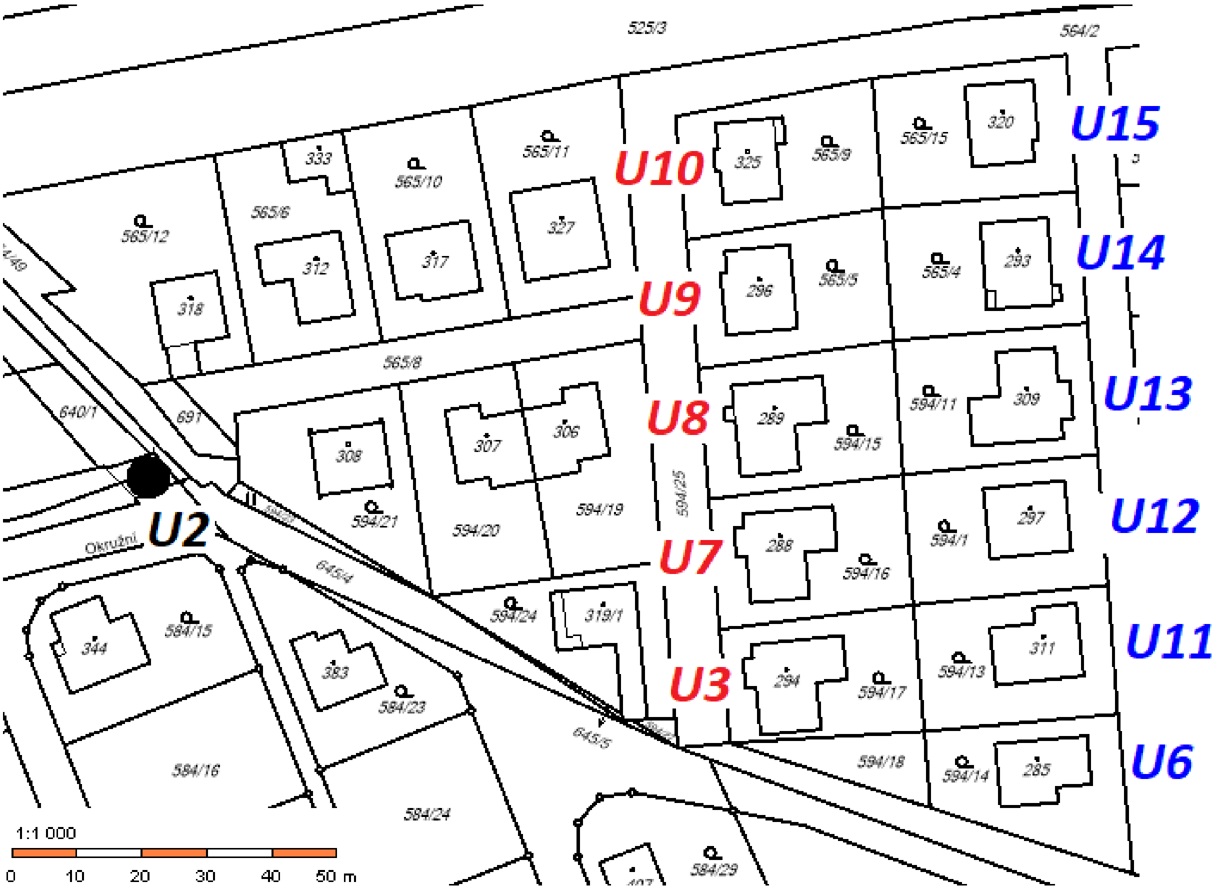


Fig.36 Cadastral map of Pátek village [41]

As shown in figure 36, the distribution system consists of nodes and branches, such as *U2-U15*.

U2 stands for output line coming from transformer (Tr1) and in its turn supplies consumers:

U3; U7; U8; U9; U10 – Line 1;

U6, U11, U12, U13, U14, U15 – Line 2;

Z11 – additional load which is not displayed on scheme for the reason that it represents all supplementary objects, such as small shops, schools and etc. which are generally operating during day time by creating extra load on power network.

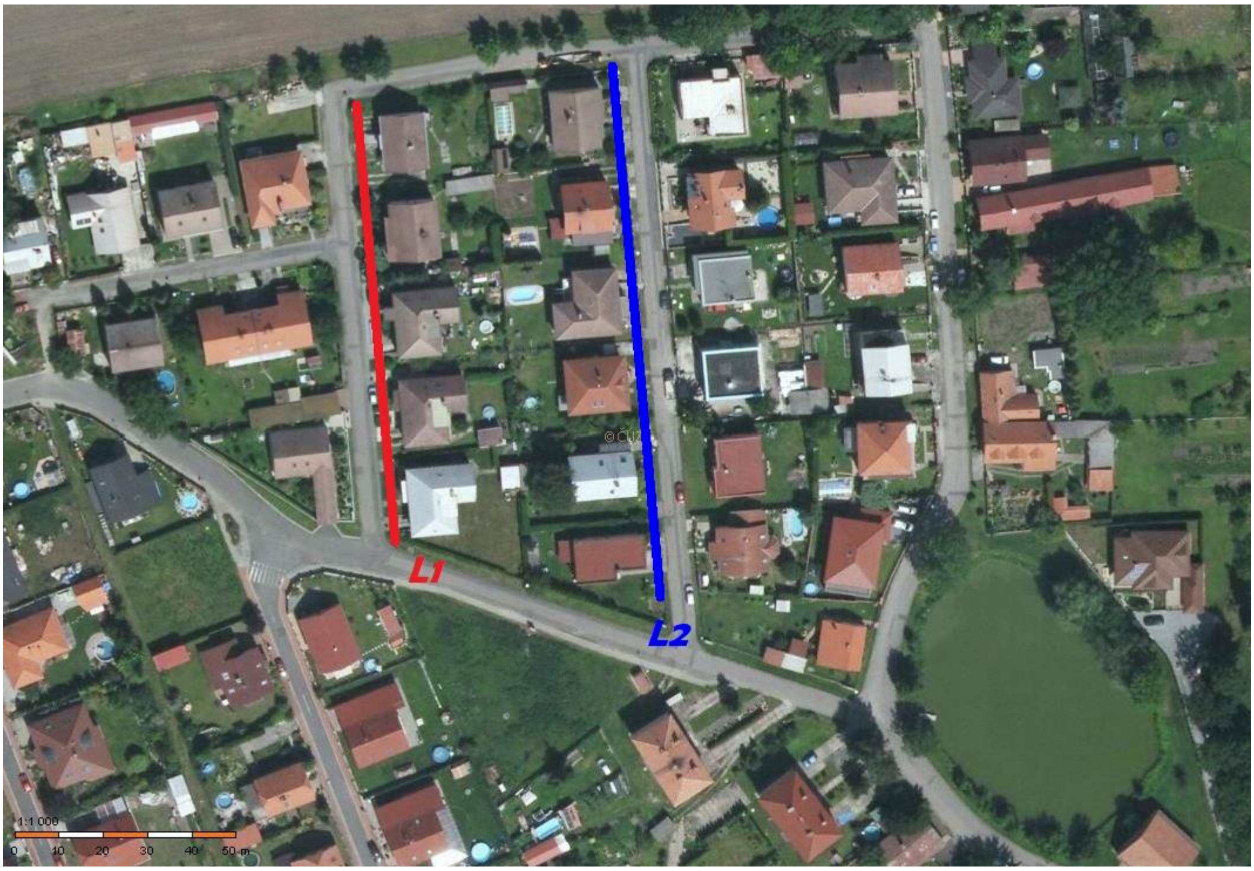


Fig.37 Satellite view on Pátek [41]

Since the consumers are located near the transformer, therefore underground cabling system is more preferable to distribute electrical energy to customers.

Table 1. Cabling of 0.4 kV power line

Name	***Type***	***Designation***	***Cross-section [mm^2]***	***Length [km]***
V1	Cable	120AYKY70	120	0.109
V4	Cable	120AYKY70	120	0.147
V5	Cable	70AYKY50	70	0.022
V6	Cable	70AYKY50	70	0.02
V7	Cable	70AYKY50	70	0.021
V8	Cable	70AYKY50	70	0.02
V9	Cable	70AYKY50	70	0.019
V10	Cable	70AYKY50	70	0.019
V11	Cable	70AYKY50	70	0.018
V12	Cable	70AYKY50	70	0.021
V13	Cable	70AYKY50	70	0.02

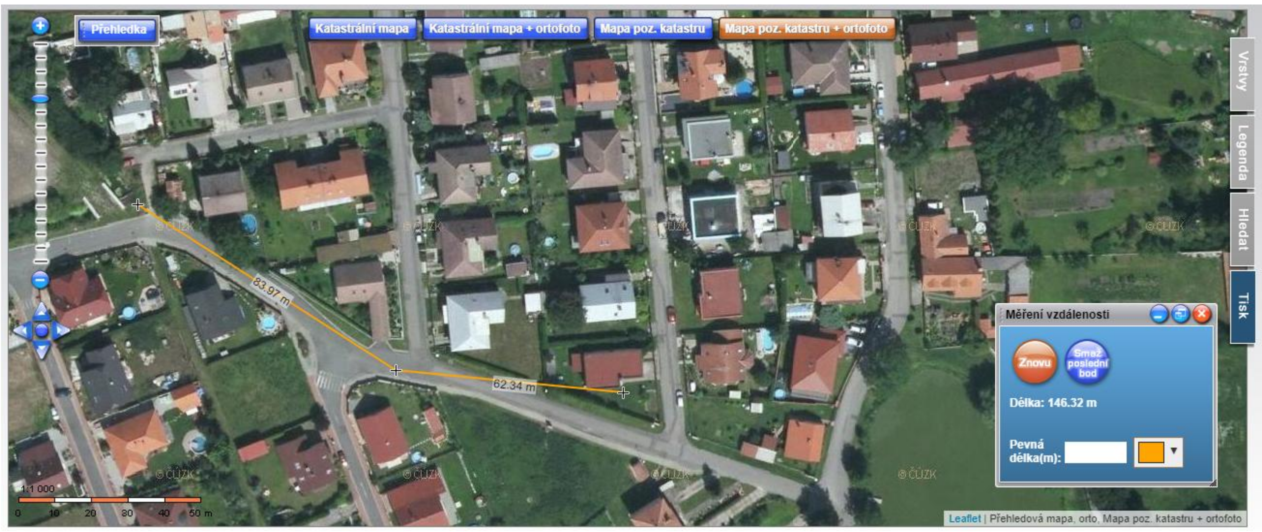
Following illustrations display the measurement of cable length:

Délka: 104.7 m

Pevná délka(m):

Fig.38 Length of V1 line [41]

All measurements has been taken based on the map database of ČÚZK (Český úřad zeměměřický a katastrální) in order to obtain more accurate data.

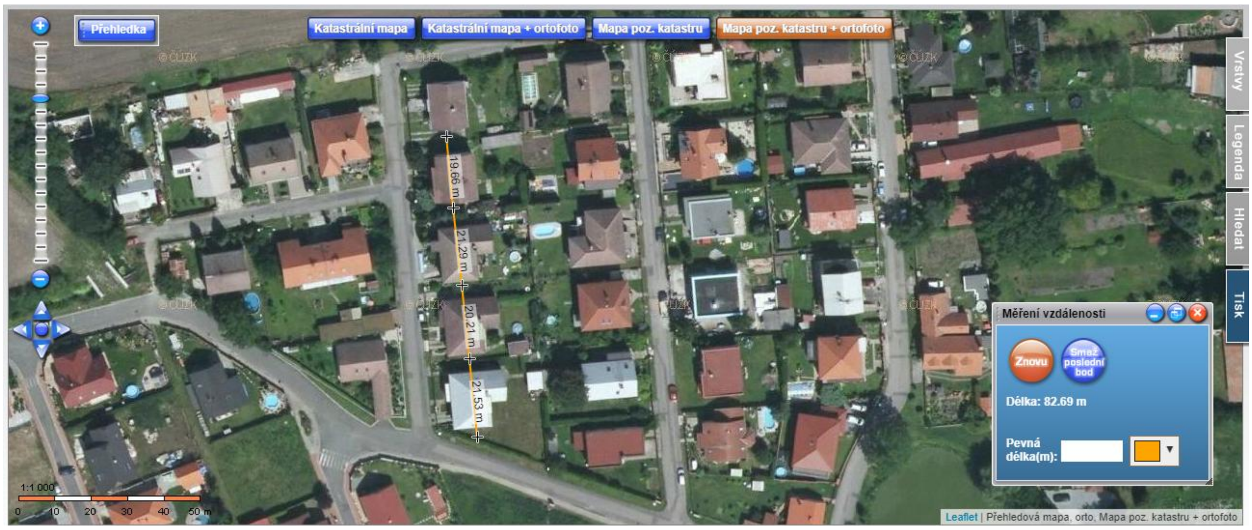


Délka: 146.32 m

Pevná délka(m):

Fig.39 Length of V4 line [41]

The aforementioned pictures display the length of V1 and V4 which are equal to 104.7 and 146.32 meters respectively.



Délka: 82.69 m

Fig.40 Length of Line1 [41]

Délka: 95.57 m

Fig.41 Length of Line2 [41]

It can be seen that the overall distance from the first house of Line1 to the last is 83 m. And for Line2 it can rounded to 97 meters.

Parameters of system components

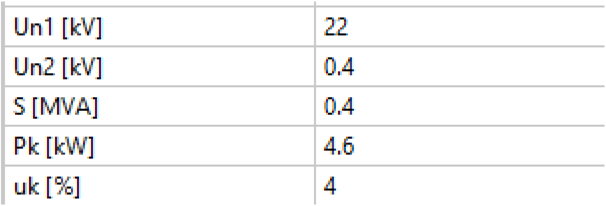
Supply system

The main supply node of our medium voltage power system is marked as EGC_22 and the parameters are U_n = 22 kV and U_{op} = 23 kV, where

U_n – nominal voltage of distribution
U_{op} – value of operational voltage

Transformer

Table 2 . Nominal parameters of chosen transformer



Un1 [kV]	22
Un2 [kV]	0.4
S [MVA]	0.4
Pk [kW]	4.6
uk [%]	4

According to the distributed voltage, transformer 22/0.4 kV with the relative short-circuit voltage U_k = 4% has been chosen.

Cables of distribution system

The distribution point of our system is taken as node U_2 which supplies nodes U_3 and U_6 with *120AYKY70* cable type and following nominal parameters:

Cross-section = 120 mm^2;
Resistance *R = 0.258 [Ω/km];*
Reactance *X = 0.069 [Ω/km]*

However, the cabling between houses has been realized by *70AYKY50* cables with parameters:

Cross-section = 70 mm^2;
Resistance *R = 0.442 [Ω/km];*
Reactance *X = 0.073 [Ω/km]*

Calculation scheme of distribution system

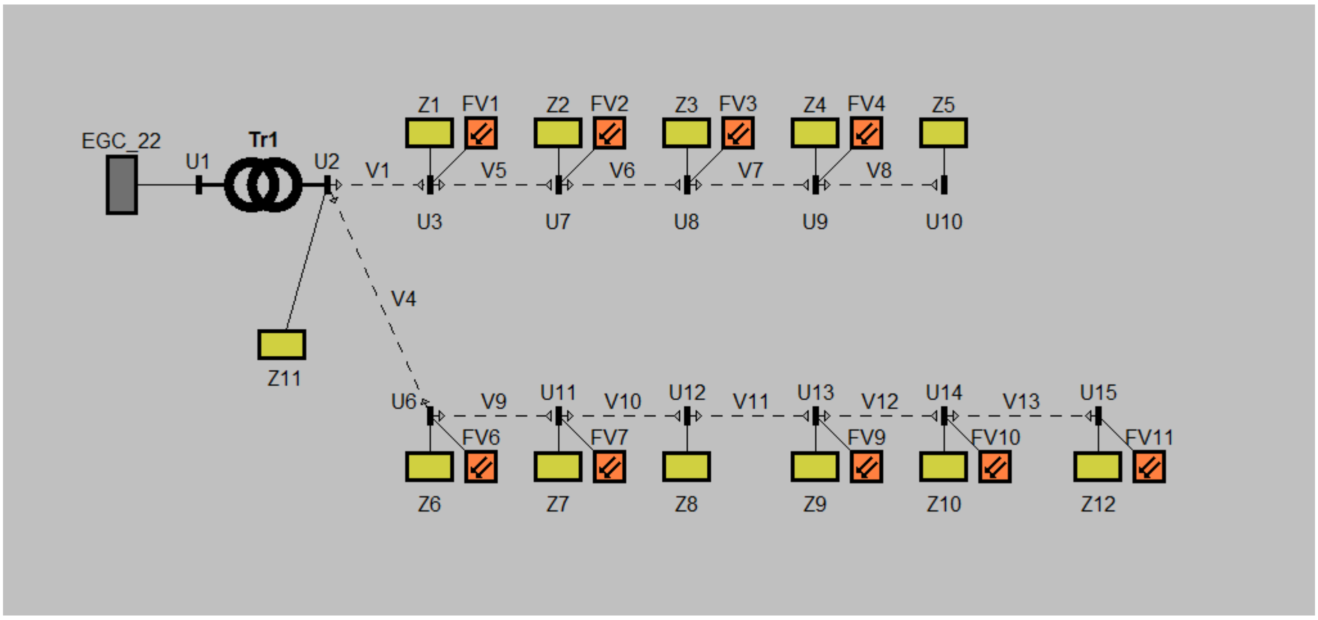
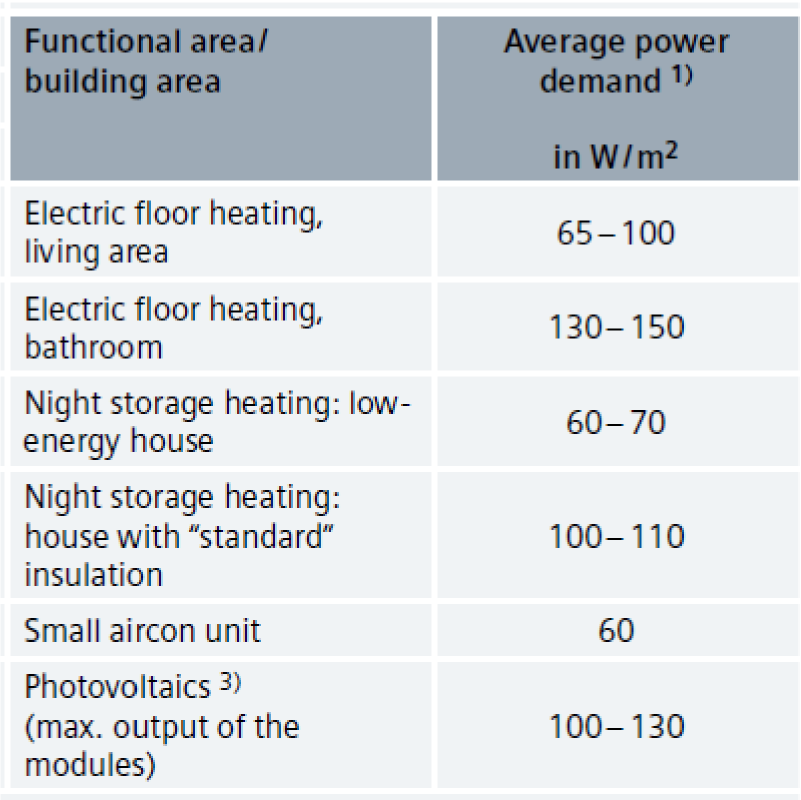


Fig.42 Main scheme of distribution system with installed PV panels

Parameters of consumption

The abovementioned scheme consists of following parameters which are taken as the main part upon which the equipment selection of power system depends. These parameters are: Values of consumed electrical power by each particular family house and the capacity of installed photovoltaic solar panels on the roofs of houses.

Bearing in mind that constructed power system has been applied for area with relatively lower energy consumption, for the reason that most houses are considered to be as summer home, therefore the range of consumed power per house was assumed as $S = 4 \div 8\ kVA$, consequently the power factor equals to $\cos\phi = 0.95$



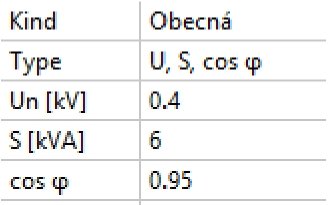
Functional area/ building area	Average power demand [1] in W/m²
Electric floor heating, living area	65 – 100
Electric floor heating, bathroom	130 – 150
Night storage heating: low-energy house	60 – 70
Night storage heating: house with "standard" insulation	100 – 110
Small aircon unit	60
Photovoltaics [3] (max. output of the modules)	100 – 130

Fig. 43 Overage Power demand in typical family house [42]

Taking for example, first house (Z1) from our scheme, which has the average value of *S = 6 KVA* consumed electricity per day.

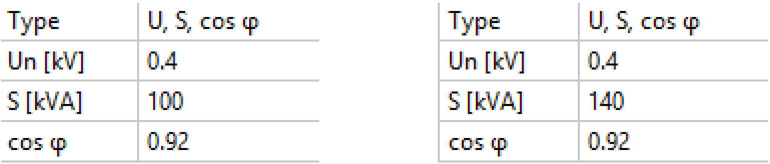
The examined power system also includes additional consumers such as small shops, schools and offices, which are located nearby our housing area and supplied by the same grid. All these objects are labeled as the load element *Z11* with the following parameters:

Table 3. Parameters of family house Z1



Kind	Obecná
Type	U, S, cos φ
Un [kV]	0.4
S [kVA]	6
cos φ	0.95

Table 4. Parameters of Z11 load element during: 1) Night time; 2) Daytime



Type	U, S, cos φ
Un [kV]	0.4
S [kVA]	100
cos φ	0.92

Type	U, S, cos φ
Un [kV]	0.4
S [kVA]	140
cos φ	0.92

If we consider all loads which are included in our scheme, there is also a small difference between houses and the amount of electricity that is consumed by them

Table 5. Load parameters of 0.4 kV system

Name	***Voltage [kV]***	***Power Factor cosφ***	***Active Power [kW]***	***Apparent Power [kVA]***	***Reactive Power [KVAr]***	***Current [A]***
Z1	0.4	0.95	5.7	6	1.87	8.66
Z2	0.4	0.95	5.7	6	1.87	8.66
Z3	0.4	0.95	3.8	4	1.25	5.77
Z4	0.4	0.95	3.8	4	1.25	5.77
Z5	0.4	0.95	4.75	5	1.56	7.22
Z6	0.4	0.95	7.6	8	2.5	11.55
Z7	0.4	0.95	7.6	8	2.5	11.55
Z8	0.4	0.95	5.7	6	1.87	866
Z9	0.4	0.95	4.75	5	1.56	7.22
Z10	0.4	0.95	6.65	7	2.19	10.1
Z12	0.4	0.95	7.6	8	2.5	11.55

Solar panel installation

Basically, each solar panel installation has maximum capacity of *P = 4 kW* in order to meet the requirements for electricity utilization of each consumer.

Solar system with *4 kW* is a viable option for an average family house. However this system might consist of overall 16 small photovoltaic panels, which means that there should be at least 30 m^2 free roof space, for the reason that the size of standard panel is 1.6 x 1 m.

Fig.44 Ordinary rooftop Solar system [43]

Based on the required supply power, following solar panels might be installed on roofs and integrated to the grid:

Photovoltaic panel with 280 Wp produced by GWL/POWER [43] seems to be suitable for utilization in our power system.

As it was mentioned above, the size of solar panels is standardized and the same also applies to the chosen PV. Its dimensions are 1650 x 992 x 40 mm. Nevertheless, considering the fact that not all houses have enough free space on their roofs and generally not designed for any additional installations, thus our scheme also includes houses without PV panels. This fact is also reflected on constructed scheme.

Fig.45 GWL/POWER CanadianSolar Poly 280Wp [43]

Therefore, the houses Z5 and Z8 doesn't have any additional renewable energy generating installments and keep consuming only grid-supplied power, without ability to feed distribution system with power generated by solar panel systems.

The additional reason for that can also be taken the fact that consumed value of electricity in these houses is relatively low, in comparison to the others.

Photovoltaic system indicated as *FV1 – FV11* on our scheme and taking into account the fact that all houses has practically the same installed capacity of PV panels, thereby their nominal and operational parameters will be equal to each other

Table 6. Technical characteristics of installed PV panels

Nominal parameters	
Name	*FV#*
P_n [kW]	*4*
S_n [kVA]	*4*
$Cos\varphi_n$	*1*
Operational parameters	
P_{op} [kW]	*4*
Q_{op} [kVAr]	*0*
$Cos\varphi_{op}$	*1*

Evaluation of results

The analysis of our 0.4 kV low-voltage distribution system includes calculation of Voltage profile in nodes and branches with load and no-load conditions; Network losses, taking into consideration PV panels' operating time (day and night time); Short-circuit conditions and calculation of sub-transient I_{sc} , P_{sc} , I_{sc} ; Analysis of voltage harmonics in nodes *U2, U6, U15.* All measurements have been performed on EVlivy3 software

The main purpose is to compare the main parameters of distribution system during the time when PV system is in its operating state and when there is no direct sunshine, which is usually observed after sunset.

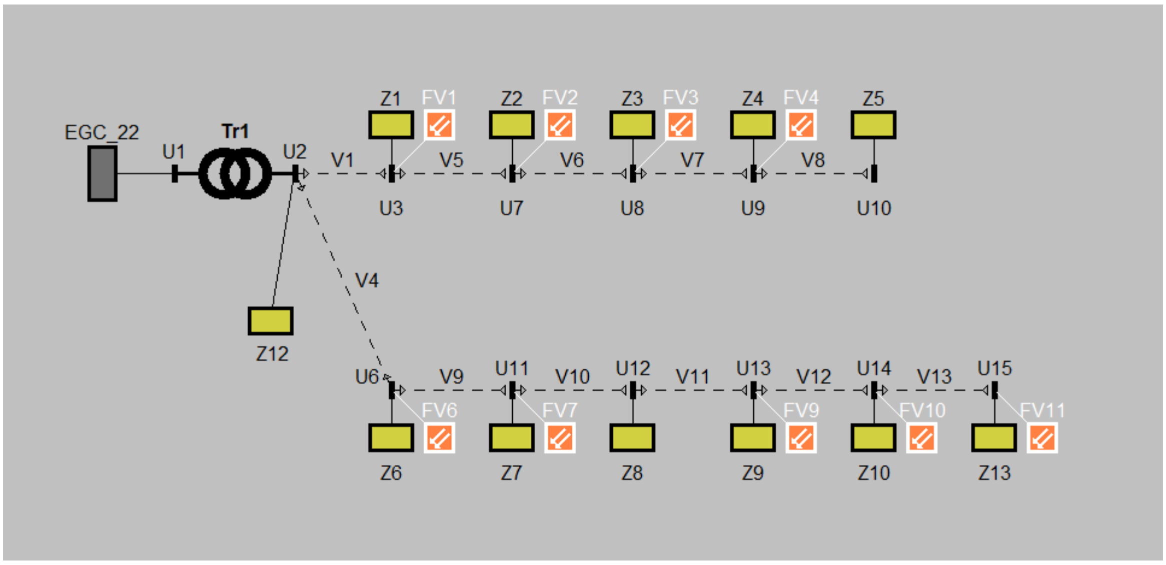


Fig.46 0.4 kV distribution system with non-operating Photovoltaics

Voltage profile in nodes and branches with load and no-load conditions

The graphs have been constructed as the relation between Voltage and Distance, by showing the voltage change with respect to distance. Of course, the ideal result is considered to be as straight line, however the obtained results can be taken closer to ideal state, due to the low fluctuations of voltage between first and last node.

Table 7. Conditions in nodes 1) with load; 2) without load

Nodes	U [kV]	α [deg]	Sk [MVA]
U1	22.912	-0,140	36,000
U2	0.409	-31,203	5,339
U3	0.408	-31,148	3,044
U6	0.407	-31,102	2,592
U7	0.408	-31,131	2,621
U8	0.408	-31,121	2,317
U9	0.408	-31,115	2,059
U10	0.408	-31,112	1,859
U11	0.406	-31,078	2,309
U12	0.406	-31,061	2,076
U13	0.406	-31,047	1,892
U14	0.406	-31,035	1,713
U15	0.406	-31,029	1,569

Nodes	U [kV]	α [deg]	Sk [MVA]
U1	22.908	-0,176	36,000
U2	0.409	-31,464	5,339
U3	0.406	-31,442	3,044
U6	0.403	-31,424	2,592
U7	0.405	-31,425	2,621
U8	0.405	-31,414	2,317
U9	0.404	-31,407	2,059
U10	0.404	-31,404	1,859
U11	0.403	-31,404	2,309
U12	0.402	-31,389	2,076
U13	0.401	-31,378	1,892
U14	0.401	-31,368	1,713
U15	0.401	-31,364	1,569

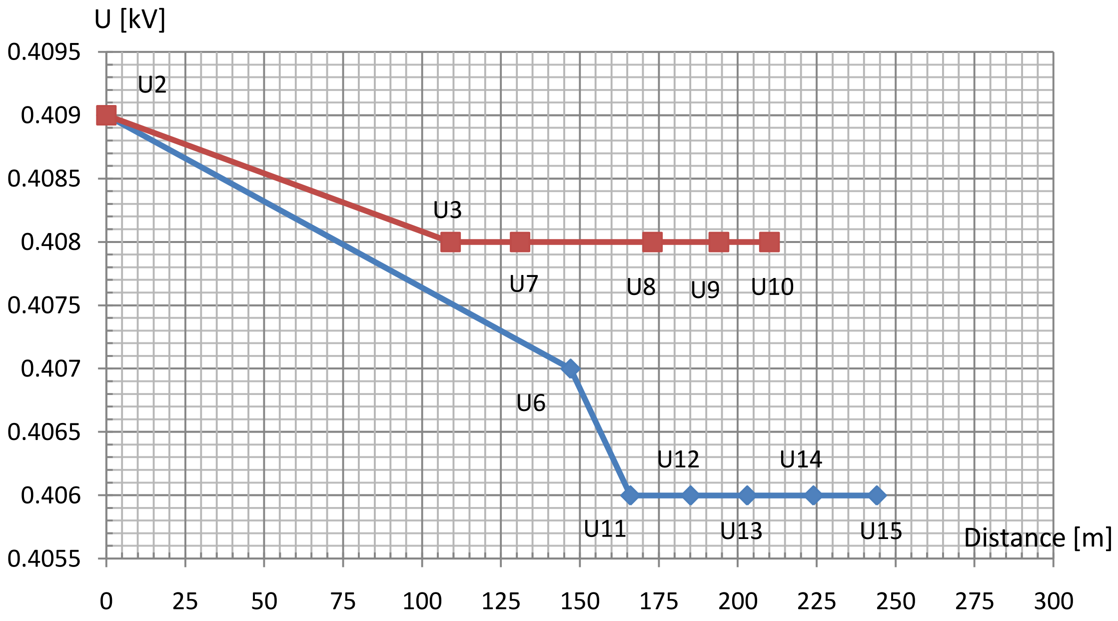


Fig.47 Voltage profile with maximum load conditions (PVs are operating)

Despite the voltage fluctiations in nodes, the values are still under IEEE standard limits ±5%. [44]

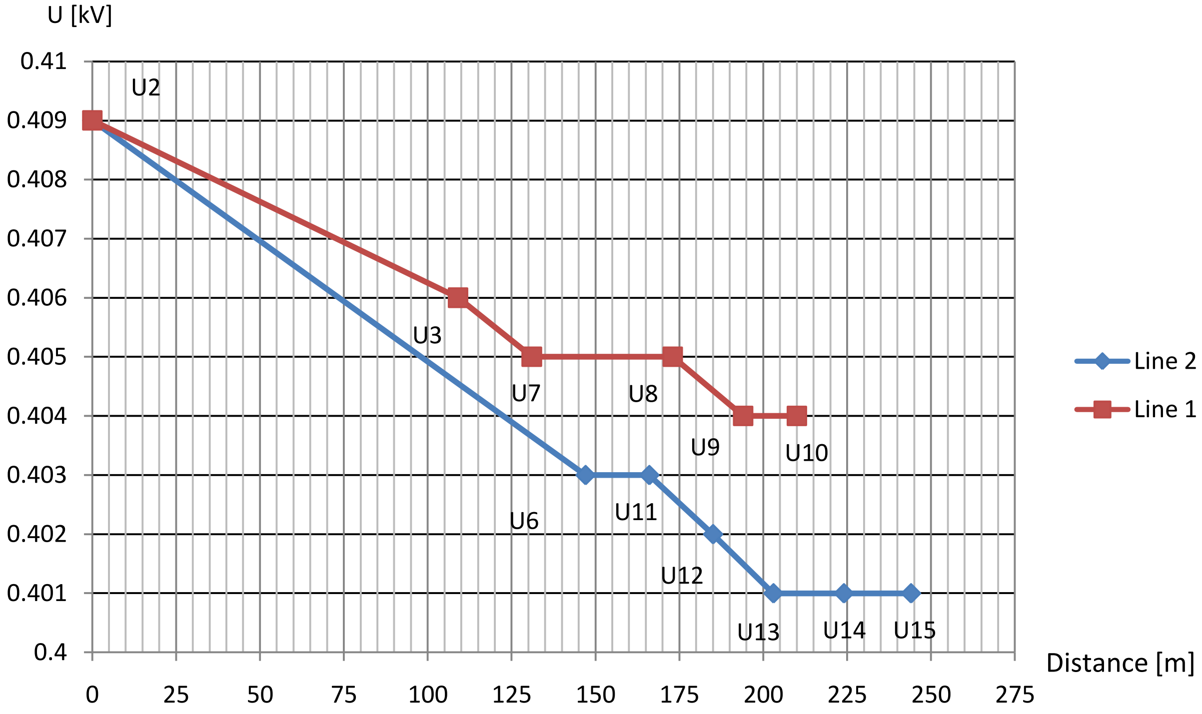


Fig.48 Voltage profile with no load conditions (PVs are off)

It should be mentioned that the difference between first node *U2* and the last consumer of each line *U10* and *U15* is equal to 0.005 and 0.008 kV respectively, which in their turn are not significant and accepted by the standard regulations.

Measurements of Voltage profile are generally carried out to determine the difference between sending and receiving ends. Photovoltaic panels, which are connected to the distribution line, considerably hinder voltage regulation. Voltage drops are specifically observed with increasing distance because of the line impedance.

In spite of the fact that the load is low, especially during night time, when PVs are inactive, current may flow in reverse direction towards the supply node, which leads to an increase in voltage drops.[45]

Table 8. Conditions in branches and nodes with active Solar panels

Branch	***Node***	***I [A]***	***P [kW]***	***S [kVA]***
EGC_22	U1	4.5	-158,158	177,342
Tr1	U1	4.5	158,157	177,341
	U2	245.8	-156,650	174,042
V1	U2	15.6	7,780	11,026
	U3	15.6	-7,759	11,008
V4	U2	33.9	20,070	23,998
	U6	33.9	-19,940	23,869
Z1	U3	8.5	5,700	6,000
FV1	U3	5.7	-4,000	4,000
V5	U3	12.0	6,059	8,481
	U7	12.0	-6,054	8,477
Z2	U7	8.5	5,700	6,000
FV2	U7	5.7	-4,000	4,000
V6	U7	8.4	4,355	5,954
	U8	8.4	-4,353	5,952
Z3	U8	5.7	3,800	4,000
FV3	U8	5.7	-4,000	4,000
V7	U8	7.6	4,553	5,351
	U9	7.6	-4,551	5,349
Z4	U9	5.7	3,800	4,000
FV4	U9	5.7	-4,000	4,000
V8	U9	7.1	4,751	5,001
	U10	7.1	-4,749	4,999
Z5	U10	7.1	4,750	5,000
Z6	U6	11.4	7,600	8,000
FV6	U6	5.7	-4,000	4,000
V9	U6	27.7	16,340	19,490
	U11	27.7	-16,321	19,472
Z7	U11	11.4	7,600	8,000
FV7	U11	5.7	-4,000	4,000
V10	U11	21.4	12,720	15,092
	U12	21.4	-12,708	15,081
Z8	U12	8.5	5,700	6,000
V11	U12	13.4	7,008	9,388
	U13	13.4	-7,004	9,384
Z9	U13	7.1	4,750	5,000
FV9	U13	5.7	-4,000	4,000
V12	U13	11.1	6,255	7,815
	U14	11.1	-6,252	7,811
Z10	U14	10.0	6,650	7,000
FV10	U14	5.7	-4,000	4,000
Z11	U2	197.7	128,800	140,000
V13	U14	6.2	3,602	4,383
	U15	6.2	-3,601	4,383
Z12	U15	11.4	7,600	8,000
FV11	U15	5.7	-4,000	4,000

Table 9. Conditions in nodes and branches with inactive Solar panels

Branch	***Node***	***I [A]***	***P [kW]***	***S [kVA]***
EGC_22	U1	5.0	-183,469	197,828
Tr1	U1	5.0	183,467	197,826
	U2	274.2	-181,590	194,091
V1	U2	57.1	38,375	40,384
	U3	57.1	-38,100	40,100
V4	U2	76.1	51,216	53,888
	U6	76.1	-50,556	53,207
Z1	U3	11.4	7,600	8,000
V5	U3	45.7	30,501	32,101
	U7	45.7	-30,440	32,040
Z2	U7	14.3	9,500	10,000
V6	U7	31.4	20,938	22,038
	U8	31.4	-20,912	22,012
Z3	U8	11.4	7,600	8,000
V7	U8	20.0	13,313	14,013
	U9	20.0	-13,302	14,002
Z4	U9	11.4	7,600	8,000
V8	U9	8.6	5,702	6,002
	U10	8.6	-5,700	6,001
Z5	U10	8.6	5,700	6,000
Z6	U6	14.3	9,500	10,000
V9	U6	61.8	41,056	43,206
	U11	61.8	-40,960	43,110
Z7	U11	14.3	9,500	10,000
V10	U11	47.5	31,460	33,110
	U12	47.5	-31,403	33,053
Z8	U12	11.5	7,600	8,000
V11	U12	36.0	23,804	25,054
	U13	36.0	-23,773	25,023
Z9	U13	10.1	6,650	7,000
V12	U13	25.9	17,122	18,022
	U14	25.9	-17,103	18,003
Z10	U14	14.4	9,500	10,000
Z11	U2	141.3	92,000	100,000
V13	U14	11.5	7,603	8,003
	U15	11.5	-7,599	8,000
Z12	U15	11.5	7,600	8,000

Obviously, our scheme has almost ideal parameters for voltage regulation, however in reality there is a huge need to apply various types of equipment, such as inverters with volt-VAR control, which can significantly reduce the diurnal voltage swings on the feeder of photovoltaics.

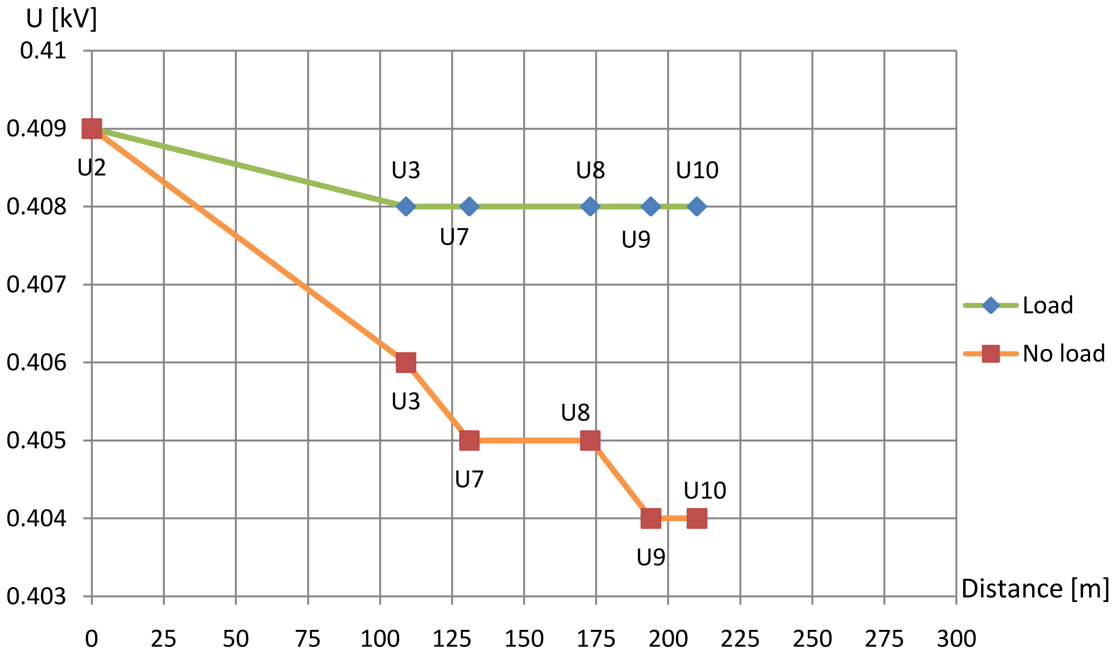


Fig.49 Voltage profile of Line1

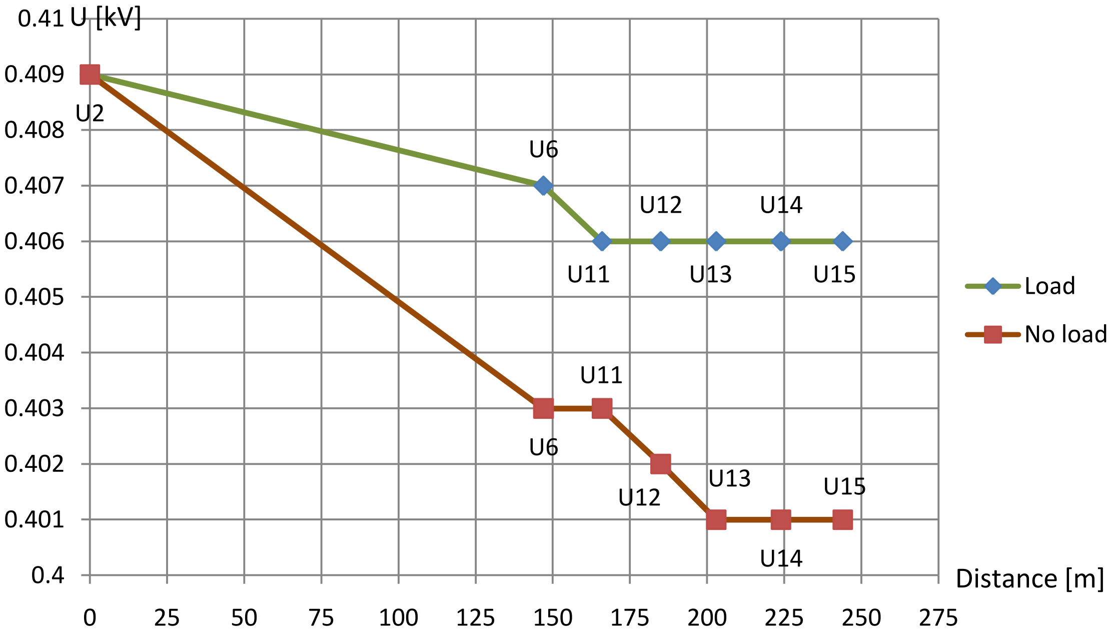


Fig.50 Voltage profile of Line2

Regardless of whether the research has been carried out on model or in real conditions, there are always losses, even when Photovoltaic installations are not at their operating state.

Harmonic analysis

Harmonic current are generally caused by the large amount of inverters which are being utilized within the PV system in order to convert DC to AC. Therefore it may seriously affect on Low Voltage distribution network by increasing the value of Total harmonic distortion.

Thus, harmonic analyses are carried out in nodes *U2, U6* and *U15* which are most likely to be affected by the harmonic distortion due to PV panels.

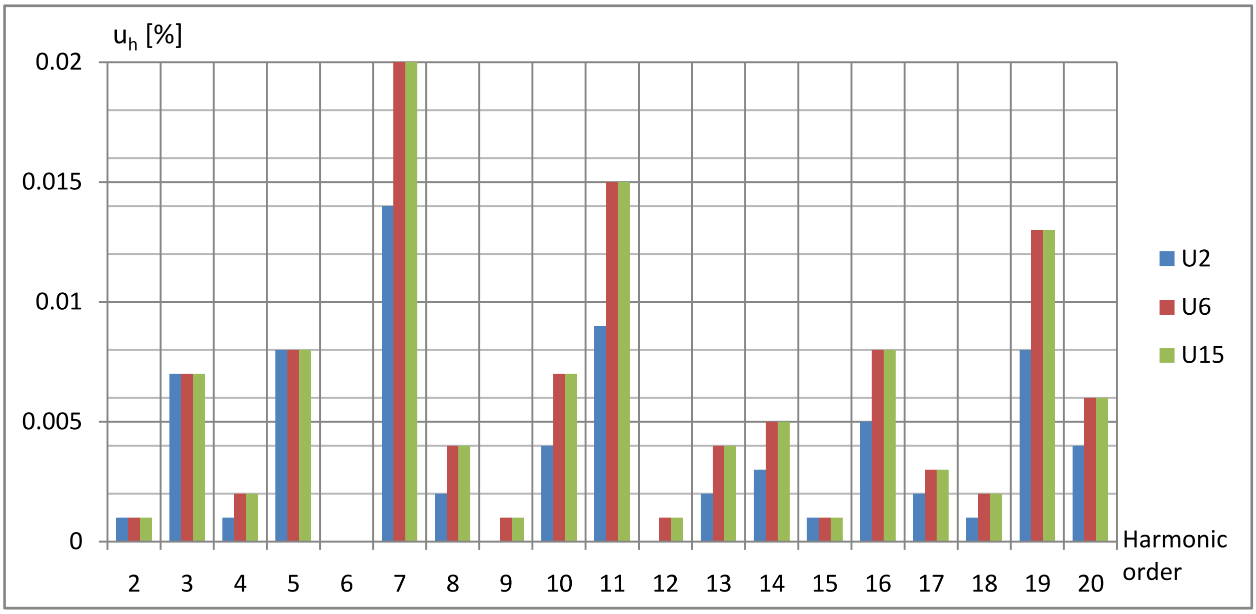


Fig.51 Harmonic analysis in nodes U2, U6, U15

Abovementioned graph illustrates the difference between the voltage distributed through the selected nodes. It can be seen that the highest value of distortion, which is recorded at 7th order of harmonic, doesn't exceed 0.02 % and stays between the range of standard limits.

According to IEEE std. 519-1992 the limitation of Total harmonic distortion voltage at Point of common coupling should be less than 5%. [46]

Power losses

General Power losses are related to the difference in I-V characteristics of PV modules.

Table 10. Power losses in branches during: 1) Day;   2) Evening

Branch	***dP [kW]***
Tr1	0.82
V1	0.02
V4	0.129
V5	0.004
V6	0.002
V7	0.002
V8	0.001
V9	0.019
V10	0.011
V11	0.004
V12	0.003
V13	0.001

Branch	***dP [kW]***
Tr1	1.021
V1	0.27
V4	0.649
V5	0.06
V6	0.026
V7	0.011
V8	0.002
V9	0.095
V10	0.056
V11	0.03
V12	0.018
V13	0.003

According to the obtained results it can be seen that the overall losses in branches during the period starting from 6 am until 6 pm is equal to 0.196 kW. These values are low for the reason that there is not much consumption of electric energy during daytime.

However, the losses recorded during evening are much higher and equal to 1.22 kW due to significant increase in energy utilization during that time. It means that generally there is not much influence of PV penetration in distribution grid to the power losses of such system.

Power losses in Transformer are also not significantly affected by the operating state of PV modules: 0.82 kW when PVs are ON, and 1.021 kW during inactive state of photovoltaic panels

Calculation of short-circuit currents

The minimal values of voltage and impedance, during single-phase short circuit condition in node *U10,* are calculated by EVlivy software.

Table 11. Minimum values of Voltage in nodes

Nodes	***U_a [kV]***	***U_b [kV]***	***U_c [kV]***
U1	11,672	12,067	11,908
U3	0,105	0,216	0,220
U2	0,187	0,216	0,220
U6	0,187	0,216	0,220
U7	0,077	0,216	0,220
U8	0,052	0,216	0,220
U9	0,025	0,216	0,220
U10	0,000	0,216	0,220
U11	0,187	0,216	0,220
U12	0,187	0,216	0,220
U13	0,187	0,216	0,220
U14	0,187	0,216	0,220
U15	0,187	0,216	0,220

Table 12. Minimal values of Impedance

Sequence type	***Z_{re} [Ω]***	***Z_{im} [Ω]***	***Z [Ω]***
Positive sequence	0,071	0,033	0,079
Negative sequence	0,071	0,033	0,079
Zero-sequence	0,070	0,029	0,075
Total	0,212	0,095	0,233

Table 13. Minimum values of Currents in node U10

U_{nom} [kV]	0,400
I_k [kA]	2,827
I_1 [kA]	0,942
I_2 [kA]	0,942
I_0 [kA]	0,942

The results obtained during the experiment show that the difference between normal operational state and short-circuit conditions of PV integrated system are nearly negligible basically due to inverters applied to photovoltaics, which are able to determine small changes in network, thereby disconnect PV from the grid.

Conclusion

The analysis of the impact of Rooftop Photovoltaic modules on Low-voltage 0.4 kV network in small village Pátek, located in Nymburk district of the Czech Republic is discussed in this paper.

According to the location of chosen area, integration of PV modules in distribution system should meet the requirements of the Czech Republic's standards **ČSN EN 50 160.** Therefore, the measurements of voltage profile, power losses, short-circuit conditions of single-phase line and harmonics analyses were carried out with accordance to the operating states of PV modules.

The comparison of distribution system's voltage profile during day and night time, when the PV system was active and inactive respectively, helped us to identify the pros and cons of investigated network.

In spite of the fact that Photovoltaic systems are considered to be problematic due to an array of disturbances and generally doesn't meet the minimal requirements of standards in order to be connected to the grid, the results of our measurements proved the opposite. Nevertheless, the following fact should be taken into account that experiments were carried out mostly on assumed data and obtained results are the consequence of theoretical model's study.

Integration of small rooftop photovoltaic panel systems in distribution network, especially in rural areas is likely to be profitable also from the economical point of view because of the supplementary generation of electricity from consumers' side and reduction of the generated electricity costs. These active energy consumers can be named as prosumers.

To sum up, there are great opportunities to integrate prosumers into the distribution system and investigate their contribution to the development of the prospective electricity networks.

References

[1] International Energy Agency (2014). "Technology Roadmap: Solar Photovoltaic Energy" (PDF). iea.org. IEA. Archived (PDF) from the original on 7 October 2014. Retrieved 7 October 2014.

[2] http://www.solarpowereurope.org/strong-global-solar-market-outlook/

[3] https://www.evwind.es/2012/10/14/history-of-solar-energy/24735

[4] UN Environment, Bloomberg New Energy Finance 2018

[5] http://www.bp.com/statisticalreview

[6] https://specializedsolarsystems.co.za/product-category/ac-solar-power-solutions/complete-off-grid-solar-system-solutions/

[7] https://www.acemco.com.lb/solar-on-grid-system.html

[8] http://highupsolarsystem.com/hybrid.php

[9] https://www.cleanenergyreviews.info/blog/2014/5/4/how-solar-works

[10] Vaclav Smil (2017). Energy Transitions: Global and National Perspectives. & BP Statistical Review of World Energy.

[11] Wind Europe Annual statistics 2017

[12] Price, Trevor J. (2004). "Blyth, James (1839–1906)". Oxford Dictionary of National Biography (online ed.). Oxford University Press. doi:10.1093/ref:odnb/100957

[13] "Costa Head Experimental Wind Turbine". Orkney Sustainable Energy Website. Orkney Sustainable Energy Ltd. Retrieved 19 December 2010

[14] https://community.ieawind.org/publications/communitylibraries

Dalla Riva, J. Hethey, A. Vitina. Impacts of Wind Turbine Technology on the System Value of Wind in Europe. IEA Wind TCP Task 26 Report. October 2017

[15] Syed M. Islam, ... Md Mubashwar Hasan, in Power Electronics Handbook (Fourth Edition), 2018

[16] https://www.omniflow.pt/

[17] Association for Industrial Archaeology (1987). Industrial archaeology review, Volumes 10-11. Oxford University Press. p. 187.

[18] https://www.dwr-uisce.eu/hydro-bpt/hydropower-guide

[19] Boyle, G. (Ed.). (2004). Renewable Energy (Second.). Oxford: Oxford University Press.Canadian Electricity Association. (2013). Data World | Power for the Future. Retrieved June 03, 2014, from http://powerforthefuture.ca/data-world/

[20] https://news.nationalgeographic.com/2016/05/160512-china-nu-river-dams-environment/

[21] The National Energy Education Project (public domain)

[22] https://www.nationalgeographic.org/encyclopedia/biomass-energy/

[23] https://www.canadianbiomassmagazine.ca/boilers-boiled-down-1167/

[24] gasification plant in Maui, Hawaii, converts sugar cane to electricity.Photograph courtesy Warren Gretz/NREL

[25] http://www.bp.com/statisticalreview

[26] http://electricalschool.info/energy/1923-geotermalnaja-jenergija-i-ee.html

[27] http://solnechnyepaneli.ru/img/krysha-iz-solnechnyjh-panelej.jpg

[28] https://www.solarpowerworldonline.com/2014/03/anatomy-rooftop-solar-mounting-system/

[29] https://sovet-ingenera.com/eco-energy/sun/sxema-podklyucheniya-solnechnyx-batarej.html

[30] https://lampaexpert.ru/alternativnye-istochniki/ustanovka-solnechnyh-batarey-vybor-mesta-pravila-montazha-i-razmescheniya#rekomendatsii-po-ustanovke-solnechnyh-batarej-v-svoemdbatharej

[31] http://cxem.net/arduino/arduino20.php

[32] http://solarrezerv.ru/tracker/

[33] https://batteryk.com/solnechnyj-treker

[34] http://ru.sinergo.lv/solarlog-monitoring/

[35] http://www.swhgroup.eu/en-net-metering.html

[36] National Assessment & Action Plan on Demand Response. ferc.gov

[37] Demand Response. energy.gov.

[38] Explicit Demand Response in Europe - Mapping the Market 2017 (англ.). Smart Energy Demand Coalition(SEDC) (6 April 2017).

[39] http://www.res-legal.eu/search-by-country/czech-republic/single/s/res-e/t/promotion/aid/feed-in-tariff-act-on-the-promotion-of-the-use-of-res/lastp/119/

[40] https://geoportal.cuzk.cz/(S(vpz2z2cftpzodsavs4iyuvtm))/Default.aspx?head_tab=sekce-01-gp&mode=Mapa&menu=11&news=yes&side=prohlizet

[41] http://sgi-nahlizenidokn.cuzk.cz/marushka/default.aspx?themeid=3&&MarQueryId=6D2BCEB5&MarQParam0=718262&MarQParamCount=1&MarWindowName=Marushka

[42] Siemens AG Energy Management, Medium Voltage and systems; © 2016 Siemens AG Berlin and Munich

[43] https://www.infiniteenergy.com.au/solar-system-sizes/4kw-solar-system

[44] Anis Ur Rehman, M. Iftikhar Khan, Sheharyar Mehmood and Bilal Khan, "Comparison based Distributed Generation Implementation Algorithm for the performance enhancement of radial distribution system". Proceedings of Power Generation System and Renewable Energy Technologies (PGSRET), 2015 . 10-11 June, 2015. PP: 1-9

[45] von Meier, Alexandra (2006). Electric Power Systems: A Conceptual Introduction. Wiley-IEEE Press. p. 186. ISBN 0471178594.

[46] IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, IEEE Std. 519-1992.