Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Power Engineering

Bachelor Thesis

Low Carbon Technology in the Distribution Network
Nízkouhlíková technologie v distribuční síti

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Study Program: Electrical Engineering and Computer Science
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2. Renewable energy source – focus on small solar application in combination with batteries or hot water production
3. Integration RES into the distribution network
4. A case study for connection of the small PVPP into distribution network

Bibliography / sources:

[1] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf accessed on the 4th of May 2018.
[2] https://www.carbonbrief.org/global-solar-capacity-grew-faster-than-fossil-fuels-2017-report accessed on the 6th of May 2018.
[3] http://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PVs%20Bio%20final.pdf
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III. Assignment receipt

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I hereby declare that this thesis is the result of my own work and all the sources I used are in the list of references, in accordance with Methodological Instructions of Ethical Principle in the Preparation of University Thesis.

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Acknowledgement
I would like to thank my supervisor and teacher Mr.Vybiralik for his guidance and to my family who supported me morally.

Abstract
This thesis is about the general information on renewable energy sources and types of power plants. The focus of this thesis is on solar power generation, also in the case study model of small low voltage distribution network with photovoltaic power plants connected to it was created.

Keywords
Renewable energy sources, power plants, solar power, wind power, hydropower, biomass power, geothermal power, photovoltaic cells, low voltage, distribution system.

Abstrakt
Tato práce pojednává o obecné informace o obnovitelných zdrojích energie a typech elektráren. Tato práce se soutředila na výrobu sluneční energie, a to také v případové studii modelu malé nízkonapěťové rozvodné sítě s připojenými fotovoltaickými elektrárnami.

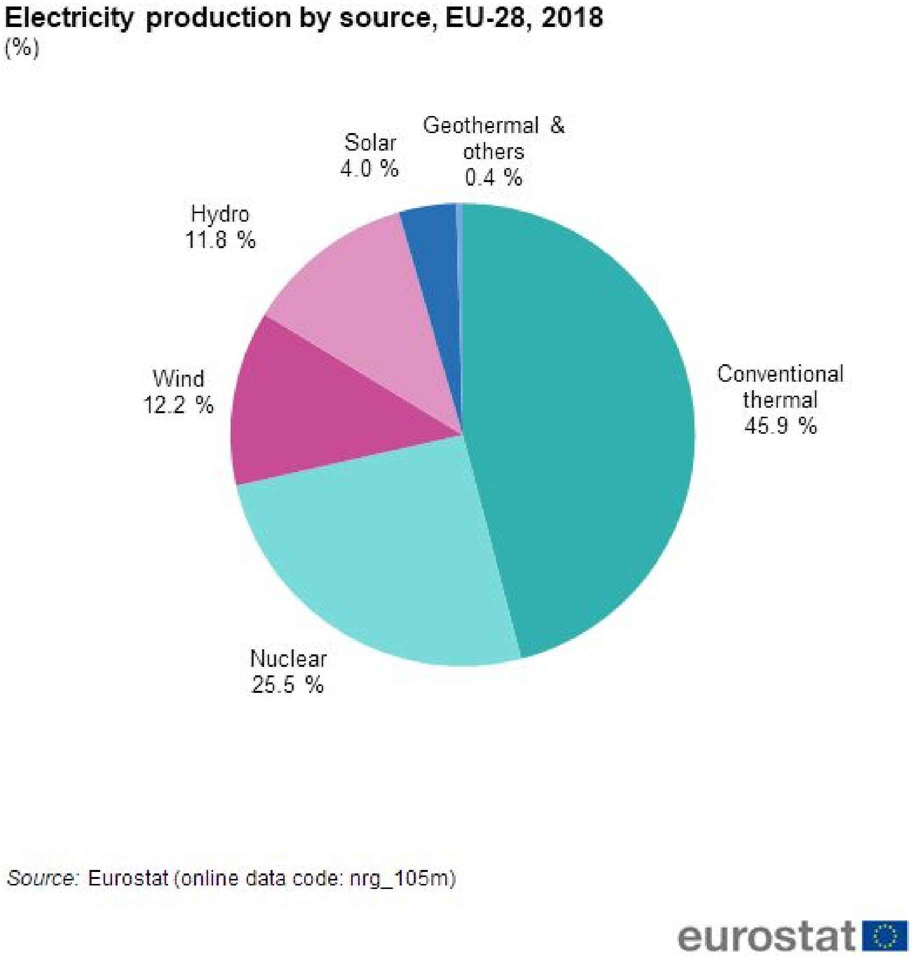
Klíčová slova
Obnovitelné zdroje energie, elektrárny, solární energie, větrná energie, vodní energie, energie z biomasy, geotermální energie, fotovoltaické články, nízké napětí, distribuční systém.

Table of contents

Renewable energy sources - general overview

1.1 Meaning of RE in the power sector

Nowadays renewable energy is the fastest-growing energy source in the world. In 2017, newly installed renewable power capacity in the world achieved 167GW what more than 60% of all new electricity capacity was. One year after, in 2018, the part of renewable energy in total energy production reached 26%, continuing the acceleration of trends noticeable since 2010.
Such problems as climate change and air pollution are the key drivers for the energy transition away from fossil fuels to low-carbon solutions. And in the future transition will play an essential role, as around two-thirds of global greenhouse gas (GHG) emissions is attributed to fossil fuel energy supply and use. This energy transition can be enabled by technological innovation, notably in the field of renewable energy. However, despite this growth of renewables in terms of the emissions the transition is not happening fast enough: CO2 energy emissions rose in 2017 by 1.4% and almost all countries are contributing to the rise in it.



Also record new additions of installed renewable energy power capacity can be attributed to rapidly falling costs and competitiveness, particularly for solar photovoltaics (PV) and wind power. For a long time, financing entities recognized renewables as risky because of high cost, leading to high lending rates for individuals, businesses and companies that need funding for RE power generation. But now the cost of electricity from different renewable energy sources (RES) is going down year-on-year, in 2018 biggest decrease was for concentrated solar power (CSP) systems - 26%, followed by bioenergy (-14%), wind (-14%), solar PV (-13%), hydropower (-11%) and geothermal (-1%). [7]

1.2 Wind energy

1.2.1 Electricity from wind

In wind power plants the kinetic energy of wind is transferred to the mechanical energy, then the mechanical energy is transformed into electricity. The main part of the wind power plant is a wind turbine. There are two types of it divided according to the position of a rotation axis, horizontal- (HAWT) and vertical-axis (VAWT) turbines. Nowadays, the majority of turbines in big wind applications employs a horizontal axis. It means that the rotating axis of the wind turbine is parallel with the ground. The rotor of the horizontal axis wind turbine is constructed with two or three wing-like blades. The wind turns the blades and they spin a generator to create electricity. Still, in small and residential wind applications, VAWT are also used. [2]


Figure 1.2.1 Horizontal axis wind turbine (left) and vertical axis wind turbine (right)

The amount of power that can be harvested from wind is proportional to the size of the turbine and the length of its blades and to the cube of the wind speed. The equation::

$$P = \frac{1}{2}\varphi A v^3$$

where:

P - power of the wind turbine [W]

φ - incoming wind density [kg/m^3]
A - cross-sectional area of turbine blades [m^2]
v - wind velocity [m/s]
Wind turbines are one of the fastest-growing energy technologies. Usage is increasing worldwide. Global installed wind-generation capacity onshore and offshore has increased by a factor of almost 50 in the past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 591 GW by the end of 2018. [16]

1.2.2 Components of the wind turbines

1.2.2.1 List of basic components of a horizontal-axis wind turbine

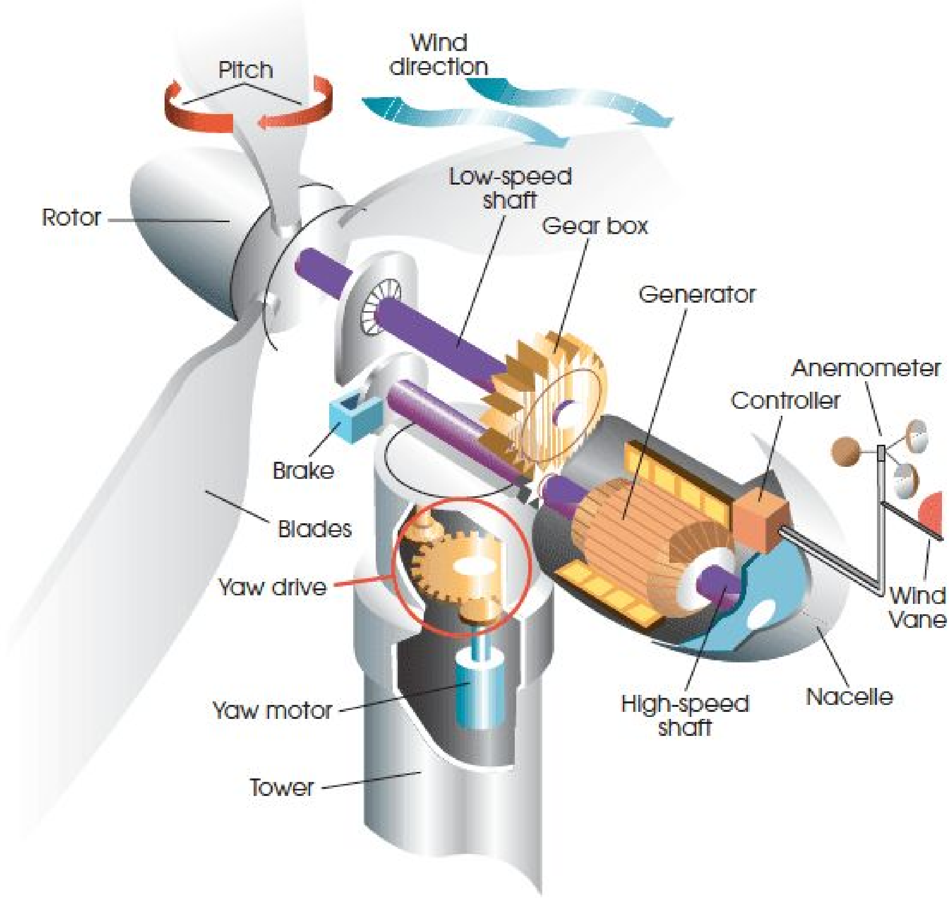


Figure 1.2.2 Components of a horizontal axis wind turbine [9]

Anemometer:
Device for measuring the speed of the wind. Transmits information to the controller.
Blades:
Rotates when the wind is blown over them, causing the rotor to spin.
Brake:
Stops the rotor.
Controller:

Controls the braking system and the yaw system of the wind turbine, starts up it at wind speeds of about 12 to 25 kilometres per hour (km/h) and shuts off the machine at about 89 km/h.

Gearbox:

Connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30-60 rotations per minute to almost 1.800 rpm.

Generator:

Produces AC electricity.

Nacelle:

It is a cover which contains all the mechanical components (gearbox, low-speed and high-speed shafts, generator and brake)

Rotor:

Transfers the wind mechanical energy into the drive train with several loading components.

Tower:

Supports the structure of the turbine. Height range: 30 to 178 meters (highest wind turbines located in Gaildorf, Germany) [10]

Wind direction:

Determines the design of the turbine.

Wind vane:

Measure direction of the wind and communicate with the yaw drive to orient the turbine properly.

Yaw drive:

Changes the orientation of the wind turbine to keep them facing the wind when its direction changes.

1.2.2.1 List of basic components of a vertical-axis wind turbine

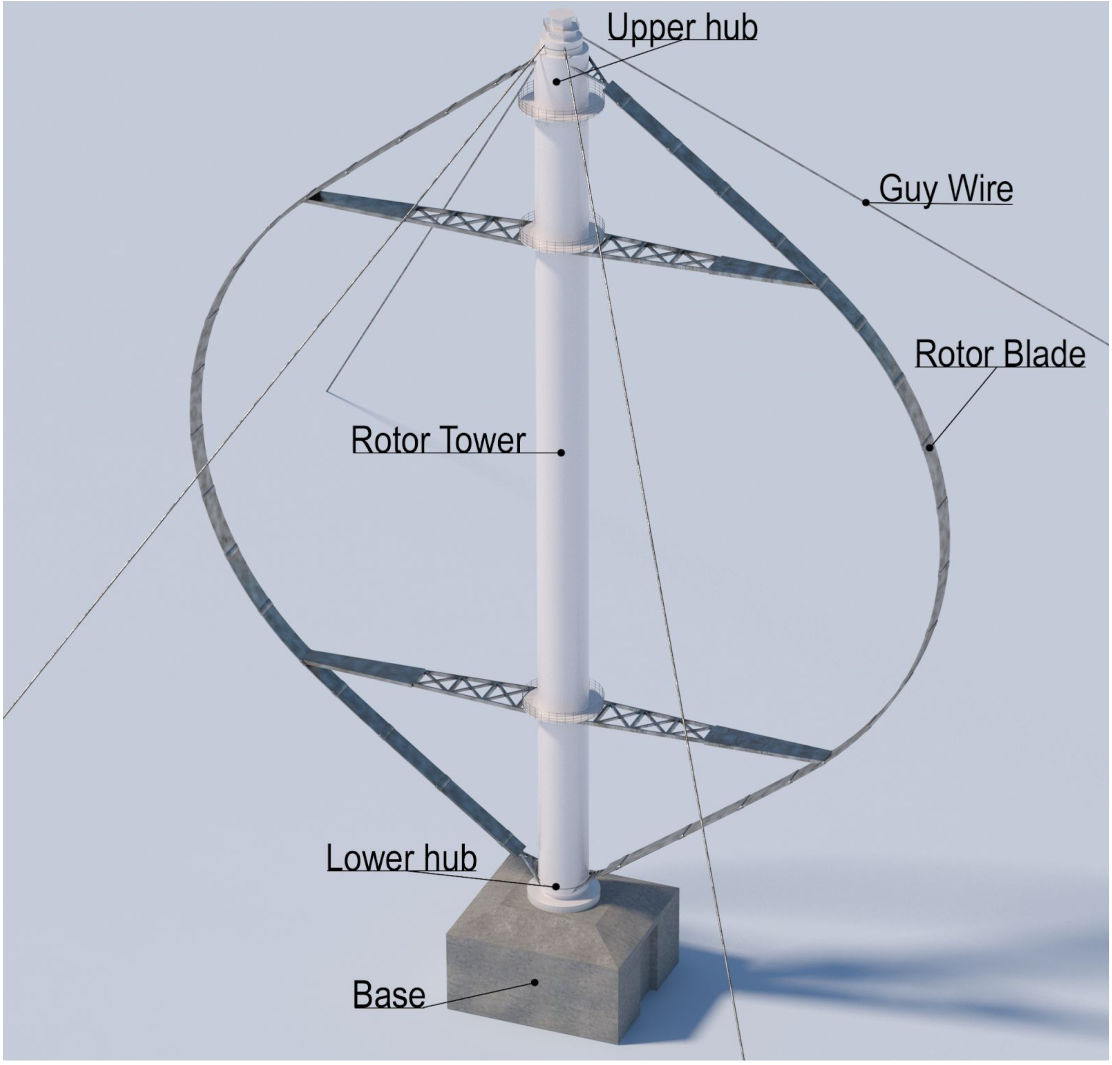


Figure 1.2.3 Components of a vertical-axis wind turbine

Guy wire:
Keeps the rotor in one fixed position and minimize mechanical vibration
Hub:
In this type of wind turbine blades are attached at two points, so there are two hubs - upper and lower. They are the centres of the rotor to which the rotor blades are attached.
Rotor Tower:
This component of the turbine is responsible for collecting wind energy and transforming it into mechanical motion.
Blades:
Convert kinetic energy of the wind into the rotation of the hub.
Brake:
Stops the wind turbine.
Gearbox:
Converts low rotational speed from shaft and increase it to increase the rotational speed of the generator.

Generator:
Produces AC electricity.
Base:
Supports the structure of the turbine, in VAWT it is usually the roof of the building on which it is installed.

1.3 Biomass energy

1.3.1 Electricity from organic material. Classification

Biomass energy is the way to generate electricity by using organic materials. As an energy source can be used any organic matter like wood, crops, seaweed or organic elements of industrial and other wastes. It can generate electricity in a number of different ways, but the most frequent is combustion. It is the way when waste or woody materials are burned on the power plant in order to heat water and produce steam, which spins turbines.
There are two different classification types of biofuels based upon production technologies and biomass source.

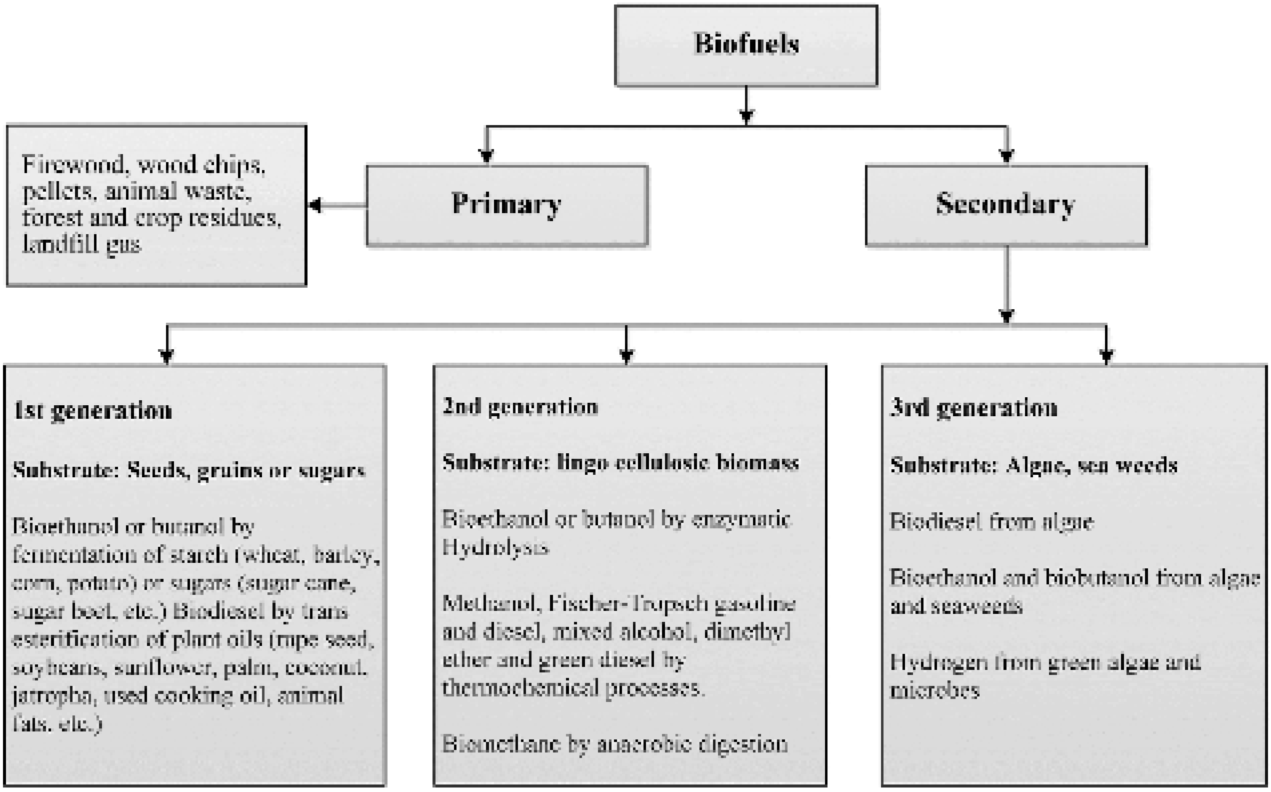


Figure 1.3.1 The classification of the generation of biofuel feedstocks [4]

	Woodfuels	Agrofuels		Others
	Wood biomass	Herbaceous biomass	Biomass from fruits and seeds	
Direct	、forest trees 、plantation trees 、thinning by-products 、logging by-products	、energy grass 、energy whole cereal crops 、straw	、energy grain 、stones 、shells 、husks	、animal by-products 、horticultural by-products 、landscape by-products
Indirect	、wood processing industry by-products 、black liquor	、fibre processing industry by-products	、food processing industry by-products	、biosludge 、slaughterhouse by-products
Recovered	、used wood	、used fibre products	、used products of fruits 、used products of seeds	**Municipal by-products** 、municipal solid wastes 、landfill gas 、sludge gas

				、sewage sludge

Table 1.3.1 Classification According to the Food and Agricultural Organization (FAO)

1.3.2 General overview of types of biomass sources

1.3.2.1 Wood and agricultural products

About 44 per cent of biomass energy are logs, chips, bark and sawdust, mainly used to generate electricity. Also, a big part of biomass energy is produced from agricultural waste. Much of the electricity produced from it are used by the industries making the waste - this process is called cogeneration. For example, papermaking and sawmilling facilities use their waste to generate electricity for their use.

Figure 1.3.2 Steven's Croft Biomass Power Station with wood logs, UK.

1.3.2.2 Solid waste

Solid waste is burned at so-called waste-to-energy power plants that use produced heat to create steam for electricity production. This type of biomass has good efficiency - one ton of garbage contains as much heat energy as about 225 kilograms of coal. Half of waste energy content comes from plastics, which are made from petroleum and natural gas. Generating electricity is not only one advantage of waste-to-energy power plants - but it also reduces the amount of material that would be buried in landfills. [12]

Figure 1.3.3 Trucks unloading waste to fuel storage groove in a MSW power plant, China.

1.3.2.3 Landfill gas and biogas

Anaerobic decomposition is a process of production of biogas from biomass. Anaerobic bacteria are bacteria that do not live or grow when oxygen is present. These bacteria eat and break down biomass and produce biogas. Biogas is mostly composed of methane (CH_4) and carbon dioxide (CO_2). Due to the fact that methane is flammable biogas can be very dangerous to people and the environment. The composition of biogas varies from 40–60% of CH_4 to 40–60% of CO_2, with small amounts of other gases.

Landfill gas - biogas produced by anaerobic bacteria in MSW landfills. Different regulations and laws in the world require MSW landfills to install and operate a landfill gas collection and control systems. Some landfills lower landfill gas emissions by capturing and burning it. Many landfills collect landfill gas, treat it to remove all gases except the CH_4 and then sell it. Other landfills use methane gas in order to produce electricity.

Furthermore, many municipal plants and makers like paper mills and food processors use anaerobic digesters as a part of their waste treatment processes. Some industrial facilities use the biogas produced in anaerobic digesters to heat the digesters, in order to boost the anaerobic digestion process and destroys pathogens, and a few use it to generate electricity to use at the facility or to sell. [12]

Figure 1.3.4 An anaerobic digesters at a dairy farm (left) and at the Nebraska wastewater-treatment facility, Lincoln, USA (right)

1.3.2.4 Alcohol fuels. Biodiesel and bioethanol

The two most common types of biofuels are ethanol and biodiesel. Both of them can be used for power production in most types of power generators built for gasoline or diesel.
Biodiesel is a fuel made by chemically reacting alcohol with vegetable oils, animal fats, or greases, such as recycled restaurant grease. Most biodiesel today is made from soybean oil. Biodiesel is most often blended with petroleum diesel in ratios of two per cent (B2), ve per cent (B5), or 20 per cent (B20). It can also be used as pure biodiesel (B100).
Ethanol is an alcohol fuel (ethyl alcohol) made by fermenting the sugars and starches found in plants and then distilling them. Any organic material containing cellulose, starch, or sugar can be made into ethanol. The majority of the ethanol produced in the world comes from corn.

1.4 Hydroelectric energy

1.4.1 Electricity from water

This must be one of the oldest methods of producing mechanical and electrical energy. By using the flow of water, rivers and streams, generate a huge amount of kinetic energy that can be used by water turbines to generate electricity. Amount of produced energy dependents on the speed and volume of the flow and the height from which it falls.

Figure 1.4.1. Hydropower plants

1.4.2 Components of hydropower plant

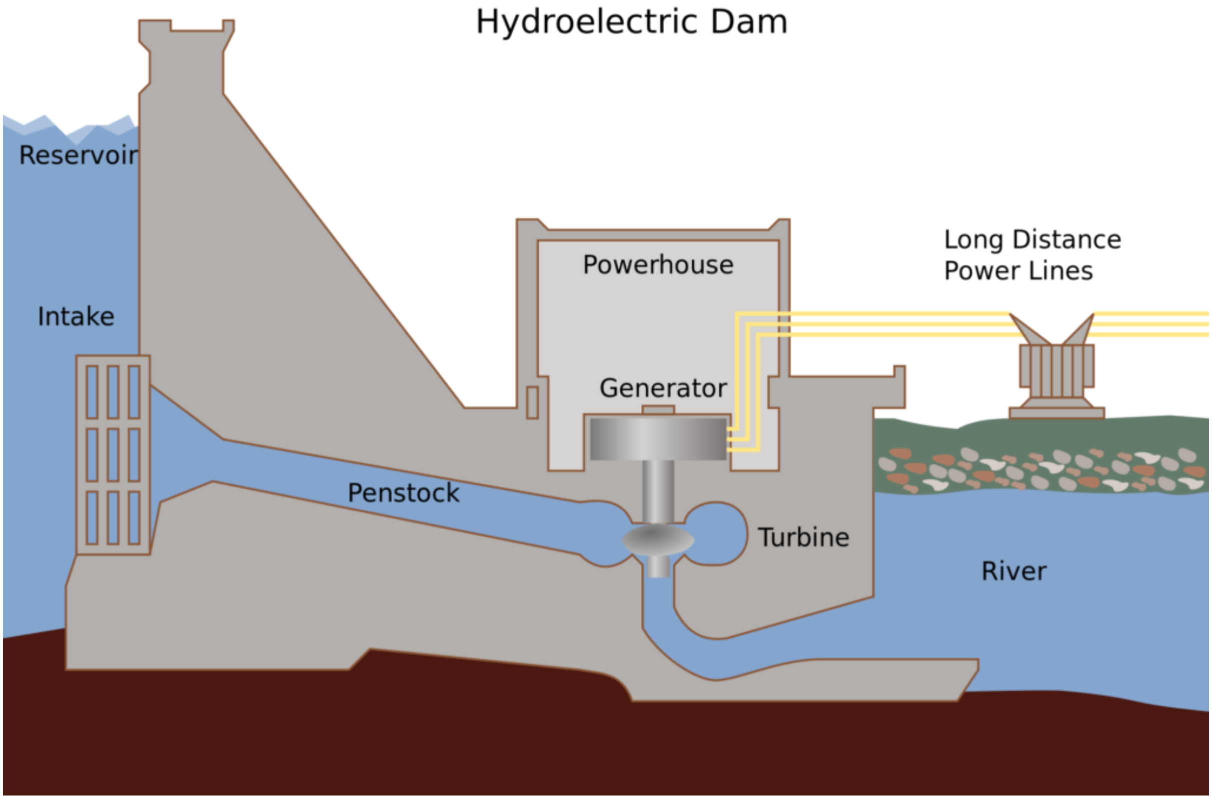


Figure 1.4.2 Components of hydropower plant

Reservoir:
It is the storage area of water behind the dam. More the height of water in reservoir more will be the power generated. Reservoir stores water in rainy season to be used in dry conditions.
Dam:
structure built to so that water gets stored in reservoir upto a greater height thus giving water the required potential energy.
Intake gate:
This gate is used to regulate the flow rate of water striking the turbine blades. The main purpose is this gate in hydropower plant is to regulate the amount of water going out from a reservoir to the power generation unit.
Penstock:
it is the pipe that carries water from reservoir to turbine. It's the kinetic and the potential energy of water in penstock that decides the amount of power produced by the turbine. The flow of water in penstock is controlled by the intake gate.
Trash rack:
As the name suggests it prevents the debris (mud) or other impurity from entering into the turbine. It is located between the reservoir and turbine somewhere between the lengths of penstock. In winters it is often heated electrically to prevent choking from ice.
Surge tank:
The surge tank is one of the most important safety parts of the hydropower plant which is mounted on the penstock. Its work is to prevent the penstock from water hammering. When

the load on the turbine decreases suddenly then the gates controlling the flow of water to the turbine shuts down suddenly, creating a huge pressure in the penstock. To prevent the penstock from exploding by such high pressure the water is transferred to the surge tank. Similar is the action when the load on the turbine increases suddenly then gates opens in a short period of time creating an air gap in penstock which can make trouble to the rotation of the turbine, so surge tank fills that gap too. The gates respond to the varying load on the turbine by the governor action.

Spillway:

In hydropower plant, Spillway is the safety feature of the dam. It prevents the dam from damage in case to too much rain or in situation of a flood. It should be able to discharge the required amount of water and keep the level of water in the reservoir at its safe maximum level.

Water turbine:

It is a machine that converts the energy of water into rotation of a shaft which further drives a generator to produce electricity in a hydropower plant, there are more than one turbines,that converts the energy of water into mechanical energy. There are different types of turbines used depending upon the height of reservoir, water quantity and amount of power to be generated.

Generator:

Generator is used to convert the rotational motion of shaft attached to turbine into electrical energy. This electricity is then converted to high voltage through a step-up transformer. This high voltage electricity is then transferred to different power stations through transmission lines.

1.4.3 Types of hydropower plants

There are a lot of different ways of categorizing hydropower plants. To start with, exist 4 basic ways to produce electrical power using hydro energy:

、Run of the river – this is the simplest form of hydro energy were a turbine is placed directly into the natural flow of a fast-flowing river or stream. The turbine is then rotated by the movement of the flowing water. Run of river hydro systems are commonly used near farms to lift water for the irrigation of surrounding or to produce mechanical power for grinding corn or grain. Also in order to increase or regulate the flow of water small dams or weirs can be built.

、Water impoundment – this is a large system that uses a dam or weir to store the potential energy of large volumes of water in a reservoir which can then be used to produce electricity. Water impoundment systems are the typical hydroelectric power plants placed in mountainous areas and countries were high dams or weirs can be built and deep reservoirs can be maintained.

、Water diversion – is similar to run of the river installation except only a small portion of the water is diverted to generate electricity. Sometimes there is a need to use of a dam to change natural course and through the penstock which travels downhill using the force of gravity to feed an overshot waterwheel from above.

、Pumped storage – pumped hydro storage facilities generate energy using turbine generators when water flows from the upper reservoir to lower, usually during periods of high electrical demand. In turn, when the need for electricity is low, like at night or on weekends, excess energy is used to pump water from a lower reservoir to an upper reservoir. [1] [19]

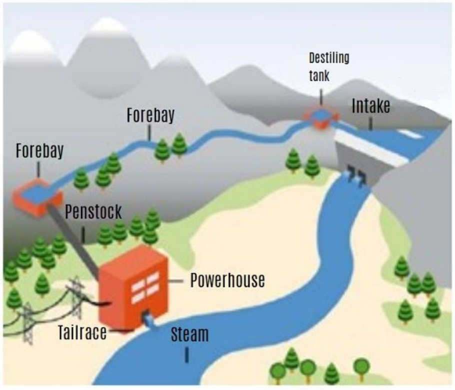


Figure 1.4.3 Run of river

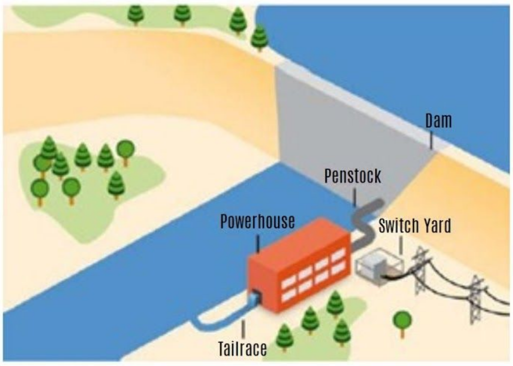


Figure 1.4.4 Water impoundment

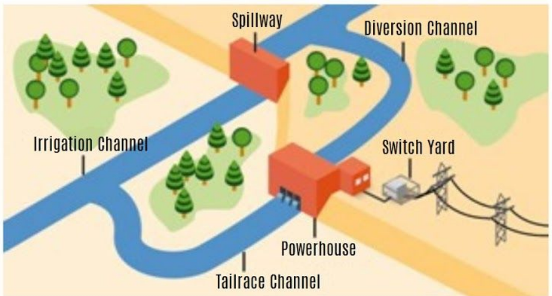


Figure 1.4.5 Water diversion

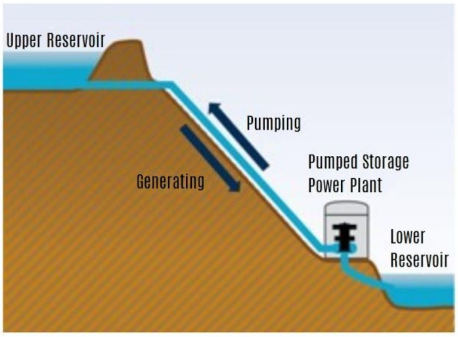


Figure 1.4.6 Pumped storage

Also, it is possible to classify hydropower plants by power output and head of water:

Power classification	
Name	Capacity
Micro	up to 100 kW
Small	up to 10 MW
Medium	between 10 and 200 MW
Large	above 200 MW

Head level	
Name	Height
Low	up to 20 m
Medium	from 20 m to 100 m
High	above 100 m

1.4.4 Rance Tidal Power Station

Rance tidal hydropower station in Brittany, France is the oldest tidal project in the world opened in November 1966. Now it is one of just two such powerful tidal installations in the world and its main feature is that the Rance River has a large tidal range, with an average of 8 meters between low and high tide. In some seasons, this difference can jump to as high as 13.5 meters.

Figure 1.4.7 Rance Tidal Power Station, satellite photo from Google Maps

The La Rance plant has an installed capacity of 240 MW which is distributed between 24 bulb-type turbine generators (each with a capacity of 10 MW). For almost half of the century, it has been producing around 500 GWh/year, which is equal to the consumption of a city the size of Rennes, France.

This plant in two different modes: ebb generation (a) or flood and ebb generation (b).

、(a) the barrage's six valves are opened until the reservoir is filled. When the tide goes away, the difference created between the impounded water and the sea is enough to spin the turbines and alternators to generate electricity

、(b) during seasonal spring tides, electricity is also produced on the incoming and outgoing tides. The differential between the low tide and the level upstream from the barrage is sufficient to drive the bulb-type turbines and generate electricity on the flood tide.[14] [19]

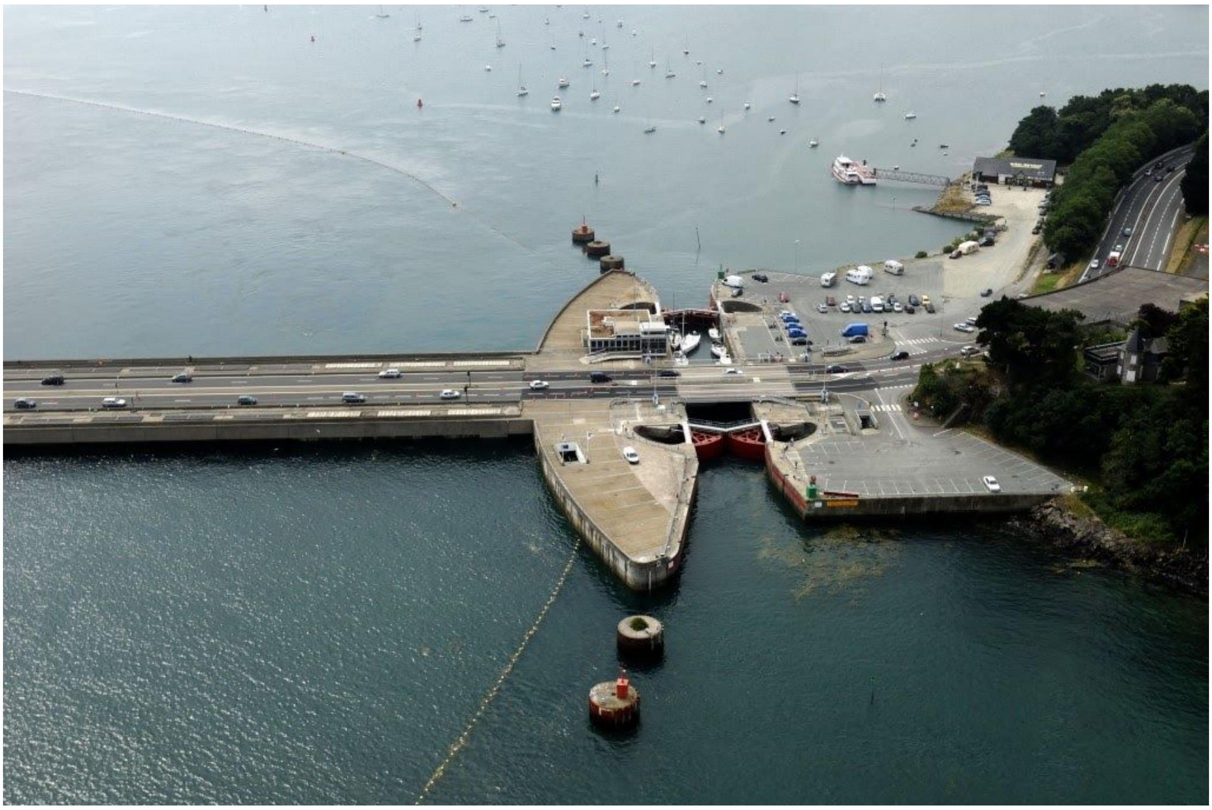


Figure 1.4.8 Rance Tidal Power Station

1.5 Geothermal energy

1.5.1 Electricity from the Earth

Hot water and steam stored in the Earth’s crust at depths up to 2000 meters are the main sources of energy for geothermal power plants. Nowadays, the most used way of capturing energy from geothermal sources is using hydrothermal convection systems. In such systems, cold water goes into Earth's crust, where it is heated up, and then rises to the surface. When this hot water is on the surface, it is a relatively simple matter to capture that steam and use it to start turbine generators.

1.5.2 Types of geothermal power plants

There are three basic types of geothermal power plants, all of which have a quite similar principle of working - pull hot water and steam from the crust, use it, and then return it. For all three types exist the three basic components of a geothermal plant: a pump mechanism which will bring heated water to the surface, an electric generator for energy conversion, and an injection well to return the spent geothermal fluids back into the reservoir. In the first type, known as dry steam, the steam goes directly through the turbines, then into a condenser where it is condensed into water.

Figure 1.5.1 Larderello Geothermal Complex - dry steam geothermal power plant, Italy

In a second type, hot water is depressurized or "flashed" into steam which can then be used to drive the turbine.

Figure 1.5.2 Hellisheidi Geothermal flash steam Power Plant, Iceland

In the third one, called a binary cycle system, the hot water is passed through a heat exchanger, where it heats a second liquid in a closed loop. Such liquids as isobutane boil at a lower temperature than water, so it is more easily converted into steam to run the turbine.

Figure 1.5.3 Berlin geothermal power plant of La Geo in El Salvador (binary cycle)

The choice of the design is determined by the resource. If the water comes out of the well as steam, dry steam can be used. Flash system can be used when it is hot water of a high enough temperature. Due to the fact that there are more hot water sources than pure steam or high-temperature water sources, the binary cycle has the biggest growth potential. [20]

Photovoltaic (PV) power plants

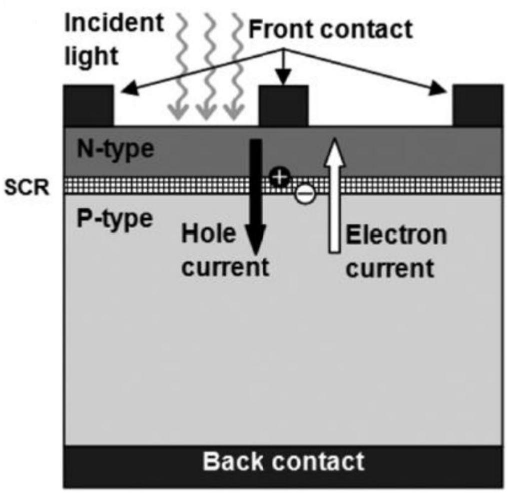
2.1 Introduction

Energy of the sun can be harnessed in a number of different ways, which include photovoltaics, solar heating and concentrated solar thermal energy. The biggest part of these technologies have been developed only in the past 50 years as a result of climate change and increasing of carbon dioxide level in the atmosphere from the burning of fossil fuels. The strength of solar resources lies in its tireless - the sun is radiating for billions of years and still doing it, a huge variety of ways how it can be harnessed ranging from small low voltage powerplants to utility-scale applications and also in the fact that solar panels do not emit GHG when they are generating electricity.
The two main types of solar power are photovoltaics and solar thermal. In thermal applications sun's rays are focusing onto a fluid, which vaporizes, expands and is used to drive a turbine. PV panels, in turn, generate electricity directly. Electricity is produced as a result of the sun's light striking a panel, which causes electrons to be released and travel through wires.

2.2 The basics of photovoltaic

、Photovoltaic effect

The success of the PV industry is the result of the development of the PV cells.
They are semiconductor diode structures that have been constructed to efficiently absorb and convert solar irradiation energy into electrical energy. Solar cells work on the principle that is called a photovoltaic (PV) effect. PV effect means the generation of a potential difference of two materials at the junction between them in response to the solar irradiation. In order to get a potential difference that may be used as a source of electrical energy, an inhomogeneous structure with an internal electric field is needed. The most suitable structure is the PN junction.



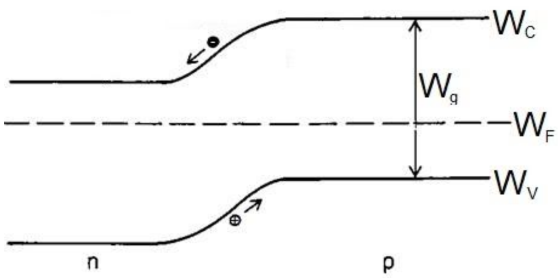
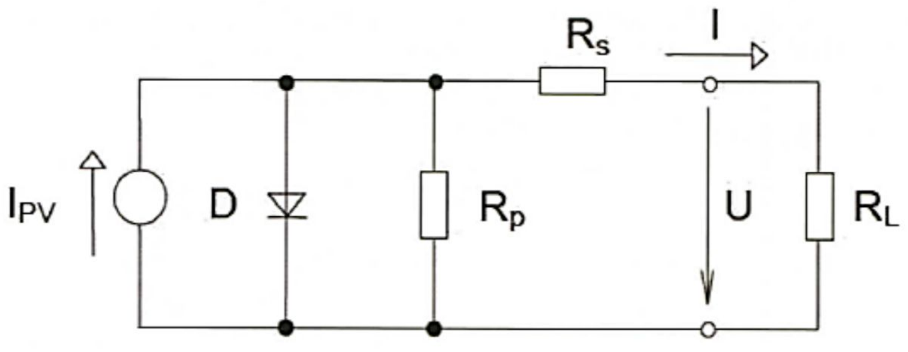


Figure 2.2.1 A schematic of the solar cell structure (left) and PN junction energy band diagram (right). [1]

The principle of working can be described in this way: incident light enters the structure and generates excess electron-hole pairs, then generated carriers diffuse to the space charge region at the junction. All holes generated in the n-type go into the p-type region by a strong built-in electric field and all electrons generated in the p-type region go into the n-type region. As a result, the n-type region is charged negatively, the p-type region is charged positively and a potential difference between the regions is created. This difference is capable of driving a current through an external circuit and thereby producing useful electrical energy.

- **Circuit diagram of a photovoltaic cell**



where:

- I_{PV} - current source
- D - diode that simulates the PN junction
- R_P - parallel resistance, representing the effect of technological imperfections of the actual PN junction
- R_S - resistance of the material and current collectors
- R_L - load

- **I–V characteristic of a PV cell, maximum power and efficiency**

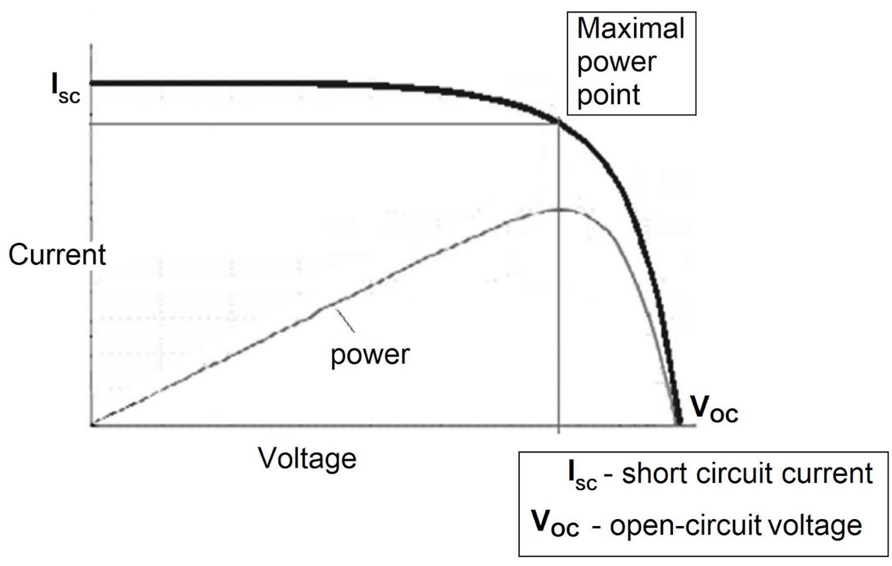


Figure 2.2.2 I–V characteristic of a PV cell and its most important points

Maximum power is achieved at voltage $U_{max\ power}$ and current $I_{max\ power}$

$$P_{max} = U_{max\ power} \cdot I_{max\ power}$$

Efficiency is determined as:

$$\eta = \frac{U_{max\ power} \cdot I_{max\ power}}{P_{IN}}$$

where:
- P_{IN} - the total power of the incident sunlight [W]

- **In-Series and In-Parallel Connection of PV Cells**

Solar cells can be connected in two different ways:
- series wiring in order to obtain a higher output voltage
- parallel wiring in order to obtain higher output currents.

In this case of series-connected sells the same current flows through all of them. In the case of parallel connection, there is the same voltage across all cells

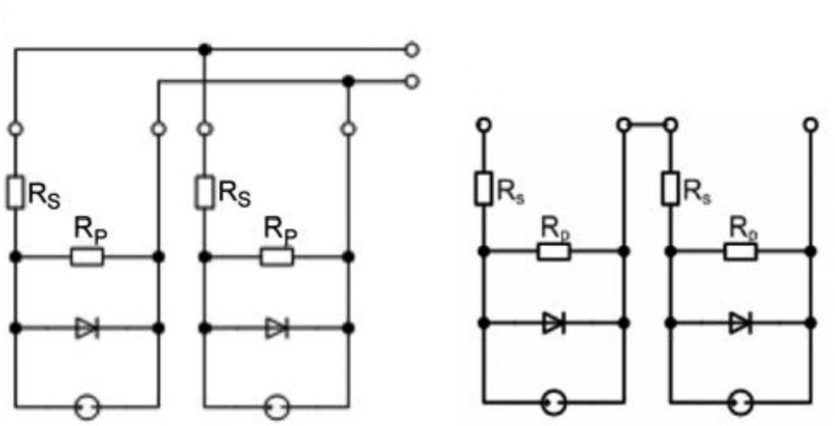


Figure 2.2.3 In-parallel connection of PV cells (left) and in-series connection of PV cells (right) [1]

- **Materials Used In Photovoltaics**

There are many types of photovoltaic cells, such as:
- Silicon monocrystalline and polycrystalline cells
- Thin-film cells
- Multi-junction cells

The main advantages of monocrystalline panels in comparison with polycrystalline cells are higher efficiencies and sleeker aesthetics. In the production of monocrystalline solar cells, silicon is formed into bars and cut into wafers. These types of panels are called “monocrystalline” in order to indicate that the silicon is single-crystal. Polycrystalline solar panels generally are cheaper, because instead of using a single crystal of silicon, manufacturers mix a lot of fragments of silicon together to form the wafers.

In monocrystalline cells the electrons that generate electricity have more freedom to move when in polycrystalline there are many crystals in each cell and less freedom.

Figure 2.2.4 Silicon cells (left), thin-film cells (middle) and multi-junction cells (right)

Thin-film solar cells made from thin films of semiconductors placed on plastic, glass or metal are 10-20 times thinner than silicon alternatives. Main advantages of these panels - they are flexible and lightweight. The main disadvantages of thin-film panels in comparison with silicon is lower efficiency, higher cost of production and ecologically harmful materials (CdTe, Cu-In-Ga-Se, GaAs).

Multi-junction cells are made from different photovoltaic materials located on top of each other. The shortest wavelength material is placed on top and absorbs blue light. Other materials are layered below and absorb narrow segments of the solar spectrum. The bottom cell is absorbing infrared light. The main advantage - high efficiency, disadvantage - price. [17] [18]

2.3 Cells, modules, panels and arrays

The photovoltaic cell is a basic building block of the photovoltaic system. It can vary in sizes from about 1 cm to about 10 cm across and produces only 1-2 watts of electricity, which is not enough for most applications. The way to increase power is to connect solar cells electrically and package them into weathertight modules, panels and arrays to provide useful output voltages, currents and power levels.

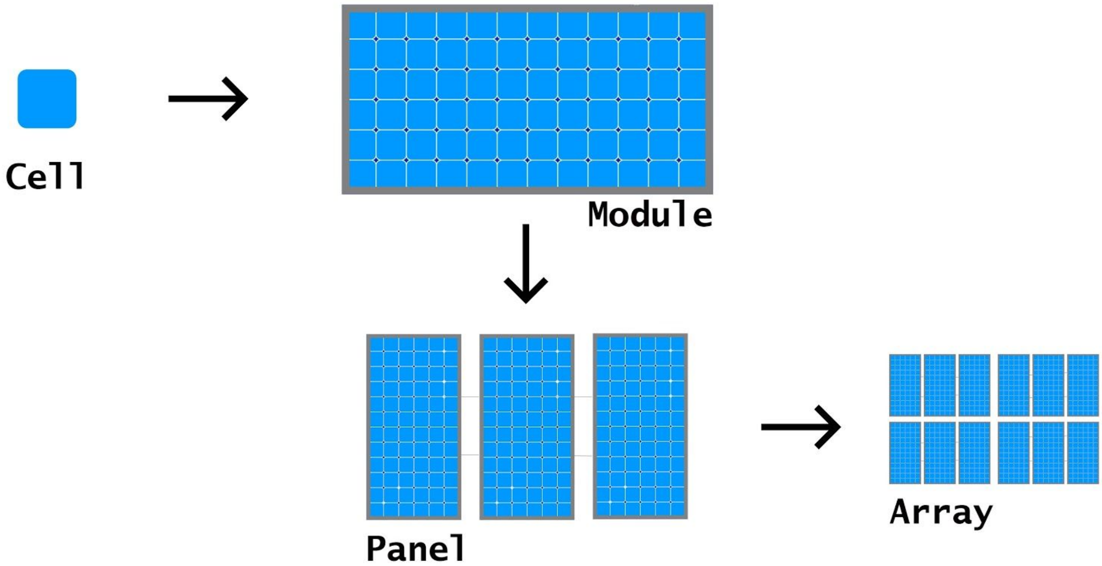


Figure 2.3.1 Cell, module, panel and array

2.4 Solar irradiation in central Europe

The amount of solar radiant energy incident on a surface per unit area and per unit time is called irradiance. The total amount of the shortwave radiation received by a surface horizontal to the ground is called Global Horizontal Irradiance (GHI) and it can be divided into two components. The first one is Direct Normal Irradiance (DNI). It comes directly from the sun and it is the principal component of the sunshine. The second one is the Diffuse Horizontal Irradiance (DHI). This type of solar radiation is absorbed and reflected within the Earth's atmosphere and comes equally from all directions.

The mean intensity of sunlight incident on Earth's upper atmosphere is known as the *solar constant* which is 1366.1 W/m2 according to the most recent estimate.

$$I_D = I_0 \cdot 0.7^{AM} \cdot \cos\gamma$$

where:

- Io - the solar constant
- 0.7 - the fraction of incident sunlight directly reaching the surface
- AM (-) is the atmospheric mass coefficient

The total intensity is given by both direct and indirect sunlight (scattered and reflected sunlight reaching the ground).

Figure 2.3.1 presents the solar irradiation and photovoltaic power generation potential in central Europe in kWh/kWp of installed power. Europe receives average annual energy around 1.200 kWh/m^2.

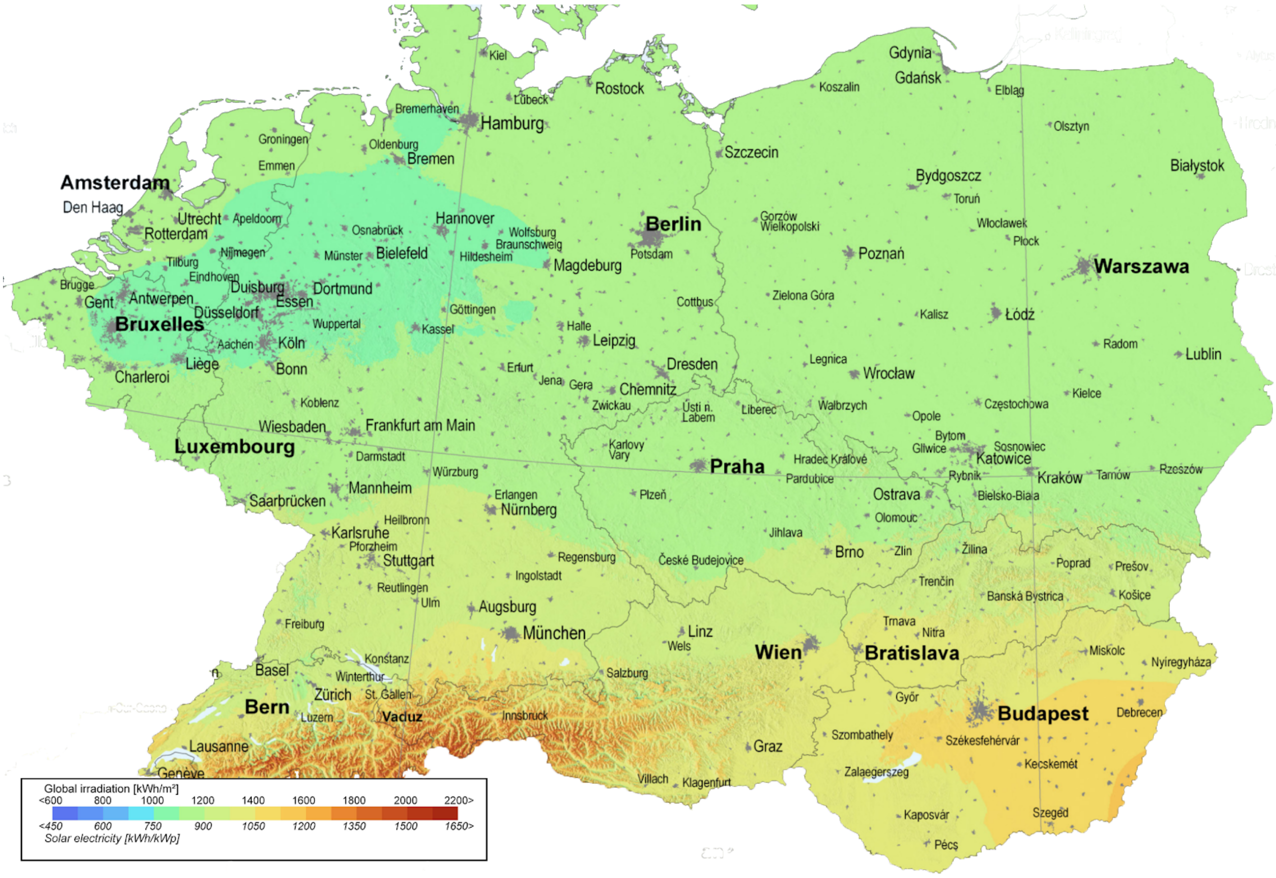


Figure 2.4.1 Solar irradiation in central Europe [11]

2.5 Concentrating Solar Power (CSP) systems

Concentrating Solar Power plants concentrate direct solar radiation to heat a fluid and produce steam (or vapour of another working fluid). The working fluid runs a steam turbine connected to a generator, producing electricity.

There are four major types of CSP technologies: parabolic troughs, central receiver towers, parabolic dish systems and Linear Fresnel reflectors and all of them can be integrated with thermal storage.

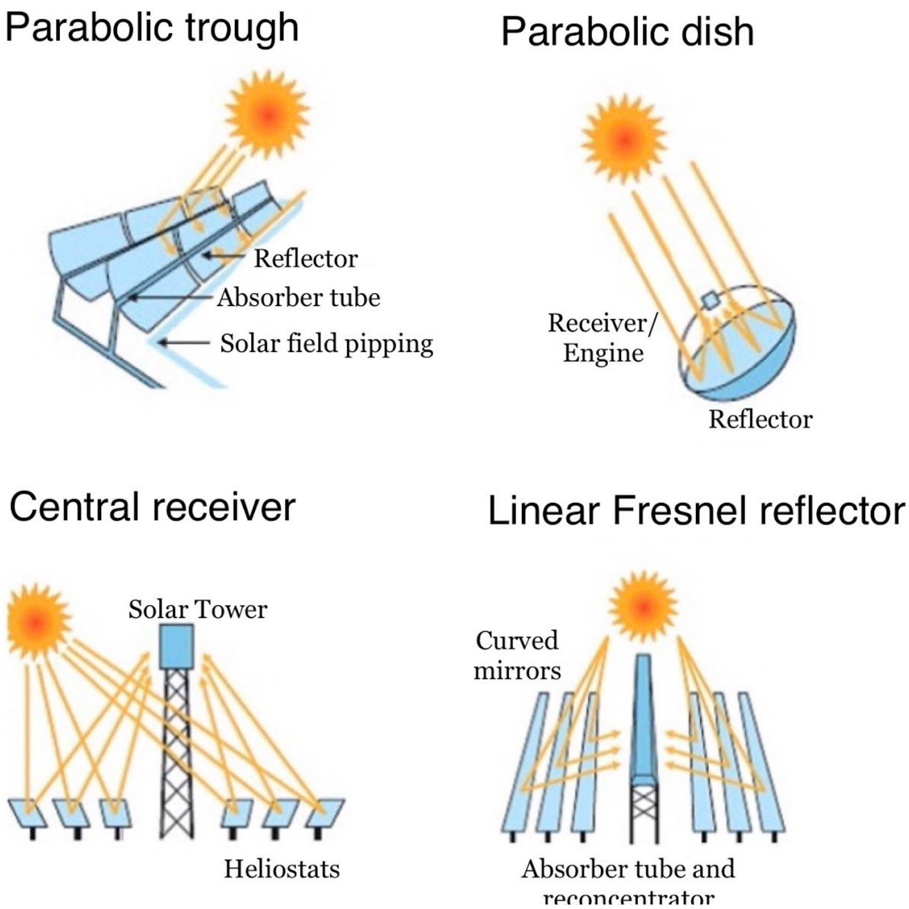


Fig 2.5.1 Types of Concentrating Solar Power systems

、Parabolic trough systems are the most used technologies, they use large parabolic reflectors (mirrors) to concentrate sun's light on heat receivers. The receiver is located along the centre of a reflector and is filled up with fluid (synthetic oil or water). The reflectors are inclined towards the sun and focus insolation on the tubes to heat the fluid up to the working point, which is around 150-350 °C. The hot fluid is used then to boil water, which creates steam to make conventional steam turbines system work and to generate electricity.

、Parabolic dishes consists of a parabolic dish-shaped concentrator that reflects irradiation onto a receiver. A solar dish system employs a working fluid like hydrogen or helium gas. The receiver is placed at the focal point of the dish and can be represented in the form of the Sterling engine. The main advantages of solar dishes systems are high efficiency and in contrast to other CSP features, there is no need for cooling systems for heat exhaust, therefore, it is suitable for use in water constrained regions.

、A solar tower (or central receiver) generates electricity from sunlight by focusing concentrated solar energy on a heat receiver. The heliostats track the sun and focus irradiation onto a receiver. The concentrated energy is used to heat the working fluid to produce steam for further electricity generation. Solar tower plants can produce higher temperatures than other CSP plants.

、Linear Fresnel reflector is based on the principle of series of ground-based, flat or slightly curved mirrors, which are placed at different angles to concentrate the sun's irradiation onto fixed receivers located near the mirrors. Main advantages of Linear Fresnel reflector are the small cost of the mirrors and solar collectors.

2.6 Stand-alone photovoltaic systems

Stand-alone PV systems are the most effective way to provide electricity in the building or some other object located in a remote area. Also it useful in some other applications where other sources of energy are unavailable. A stand-alone photovoltaic is not connected into a network and uses battery to store energy. Very often it used with small diesel generators in order to produce energy at night and during cloudy weather (especially in mountains).

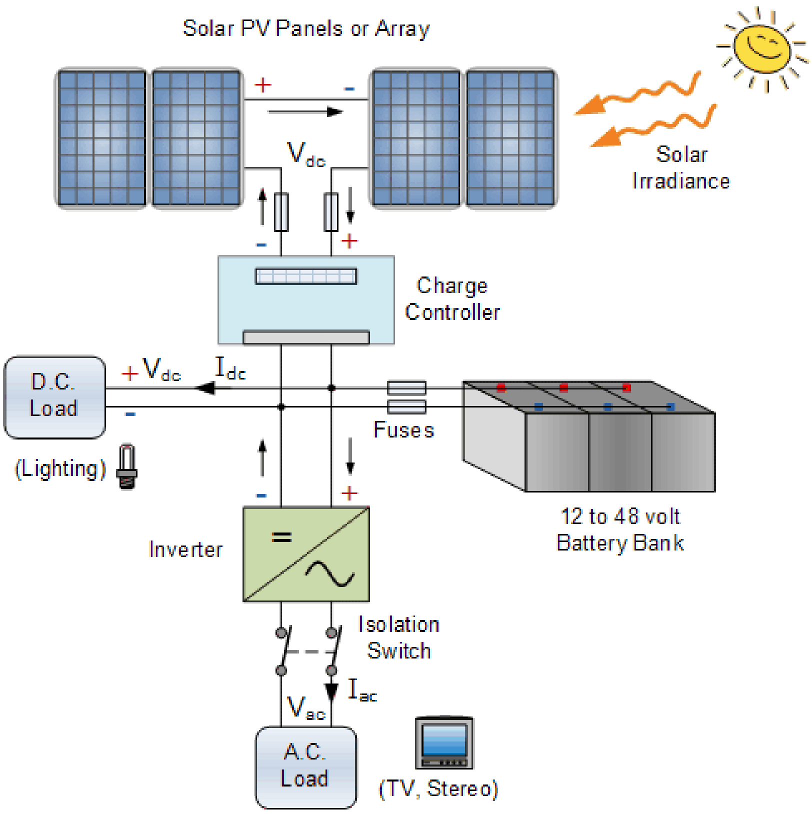


Fig 2.6.1. A typical stand-alone PV system

2.7 Solar collectors. Combinations of PV systems with boilers

Approximately half of the domestic water is used as hot water. Solar heating of domestic hot water is the most cost-effective use of renewable energy. Water use profiles affect the sizing of the collector and storage tanks.

A solar water heating system includes a solar collector that collects solar radiation and converts it to heat, which is then absorbed by a heat transfer fluid (water, antifreeze or air).

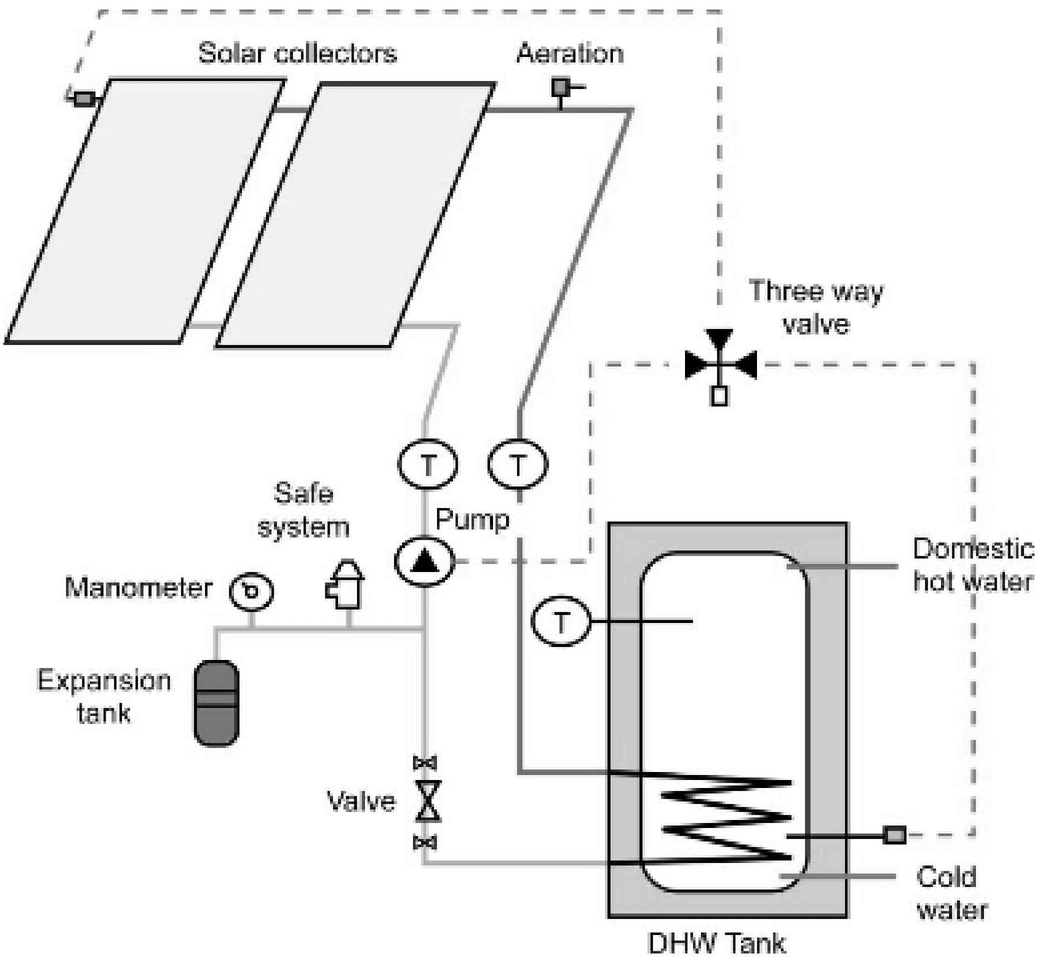


Figure 2.7.1 A solar water heating system

For the storage water heaters, the required heating rate can be computed using the equation:

$$Q_{hw} = \frac{G_{hw} \rho c_p \Delta t}{\eta},$$

where:

Ghw - the maximum flow rate of hot water [m³/s]
ρ - the water density [kg/m³]
Cp - the specific heat of water [J/(kg*K)]
Δt - the temperature rise [K]
η - heater efficiency.

The volume of hot-water storage tank VST, in m³, can be computed using the equation:

$$V_{\mathrm{ST}} = \Delta\tau \frac{Q_{\mathrm{hw}}}{\rho c_{\mathrm{p}} \Delta t},$$

where Δτ is the heating time of water [s].

The volume of domestic hot water storage tank VST, in litres, can be expressed as

$$V_{\mathrm{ST}} = \frac{2 V_{\mathrm{dhw}} N_{\mathrm{p}} (t_{\mathrm{dhw}} - t_{\mathrm{cw}})}{t_{\mathrm{ST}} - t_{\mathrm{cw}}},$$

where:
V_{dhw} - the specific DHW volume [litres]
Np - the person number
T_{dhw} - the DHW temperature [°C]
t_{ST} - the water temperature in the storage tank [°C]
t_{cw} - the cold water temperature [°C]

Solar PV panels are newer technology compared to solar collectors. They collect sunlight and transform it directly into electricity and can't freeze in wintertime, which is a sufficient advantage comparing to solar collectors. Excessive electricity produced by PV panels can be stored in the form of hot water instead of storing it in batteries. [15]

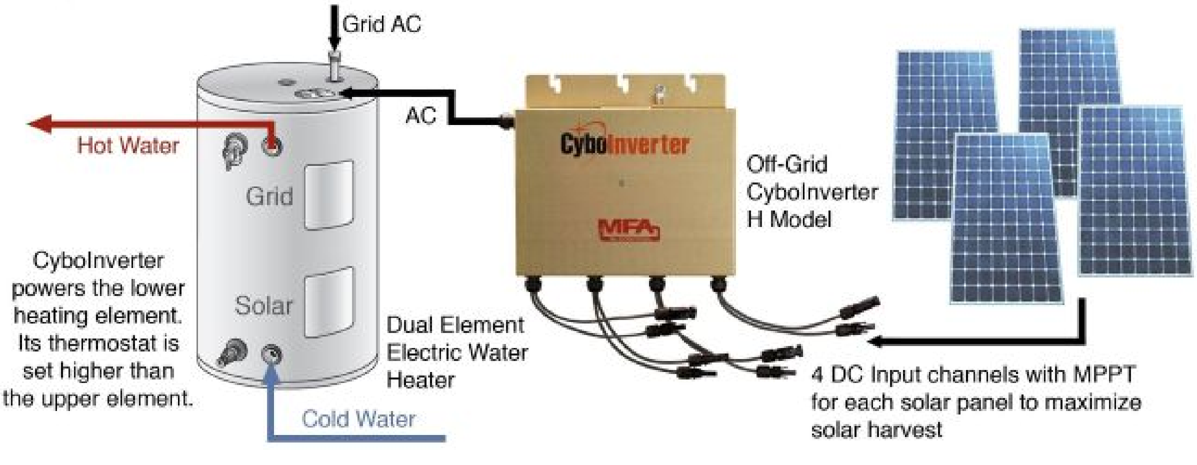


Figure 2.7.2 Off-grid PV solar water heating

2.8 Combinations of PV systems with batteries

Batteries accumulate excess energy and store it to be used at night or for times of zero insulation. Adding battery minimises user reliance on the grid and in some cases, when net metering is forbidden or not in use, it helps to reduce the cost of electricity bills.
There are four main types of batteries which are used with PV systems:
- Lead-Acid Battery
- Lithium-Ion Battery (Li-Ion)
- Nickel-Based Battery
- Sodium-Sulfur Battery.

Lead-Acid Batteries are commonly used in the automotive industry and as a backup system for telecom and other applications. These batteries are operating through chemical reactions involving lead dioxide, lead, and sulfuric acid. They are cheap and easy to install, but they are also well known for low energy density and short life cycle.
Li-Ion Batteries technology is based on moving lithium ions between a positive electrode which consists of a lithium and transition metal compound and negative electrode material. They have a very long life cycle and high discharge and recharge rates.
Nickel-based Batteries consist of a positive electrode with nickel oxyhydroxide as an active material and a metallic cadmium-based negative electrode. They are highly toxic, but they are still in use because of a long life cycle, temperature tolerance and high energy density, especially comparing to lead-acid batteries.
Sodium-Sulfur Batteries consist of liquid sulfur at the positive electrode and liquid sodium at the negative electrode as an active material. They have a long life cycle, high round-trip energy efficiency and high energy density, which makes them suitable for use in solar power.
The capital cost of a battery is also important. The main components for comparing energy storage technologies are the costs per unit charged/discharged power ($/kW) and costs per unit energy capacity ($/kWh) stored in the storage system. From this view lead-acid battery is the best option for distributed power storage. [5]

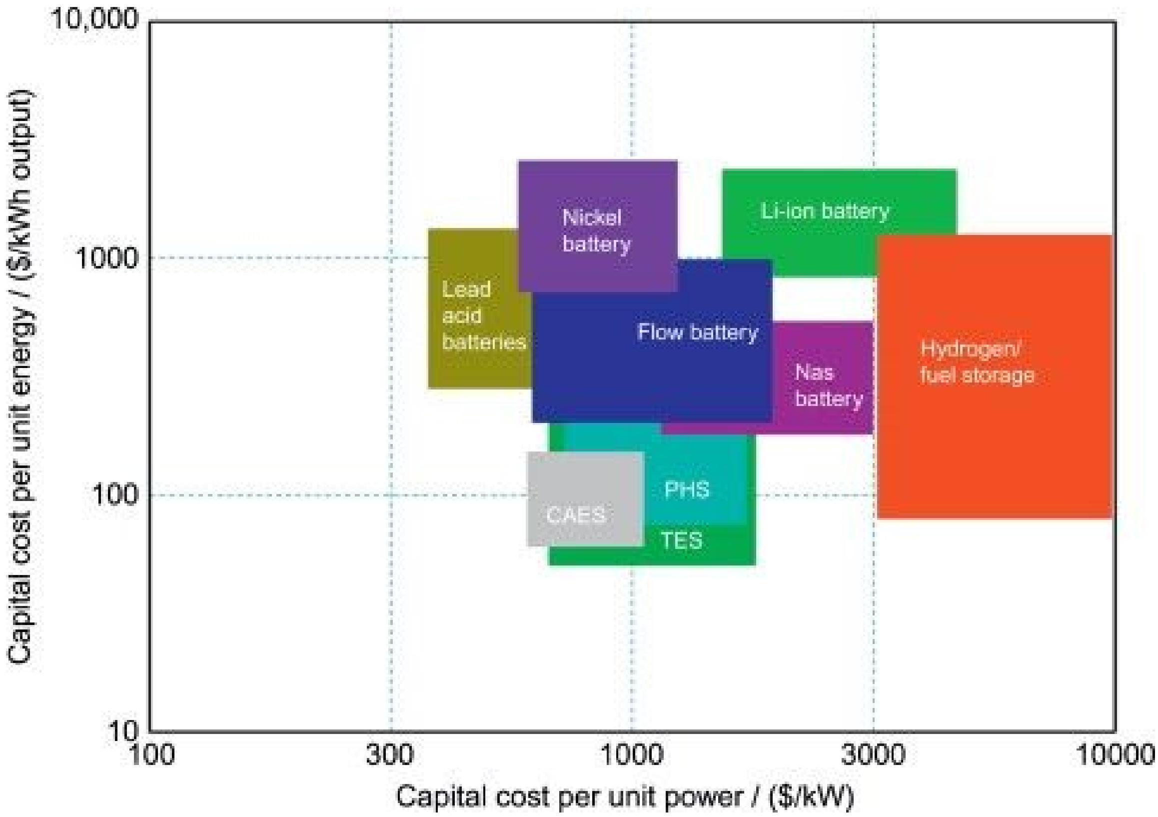


Figure 2.8.1 Capital costs of different electrical energy storage technologies

Integration RE sources into the distribution network

3.1 Rules for connection of RES to distribution network by Czech standard

An electricity production level of renewable energy system can vary depending on a day or season, e,g. on a sunny day solar panel generate approximately on 75-90% more of power output than on a cloudy or rainy day, which means that excess electricity can be produced. It can be stored in a battery or it can be sent back to the electricity grid.
The advantage of using grid-connected system is that it can supply a user (a home or a small enterprise) with electricity even when renewable resources are not producing enough of power and save costs on buying storage devices.
Another advantage of it is net metering when utility companies are compensating user for excess electricity generated by renewable energy system which is connected to the grid. This means that user is paying only for the difference between what was produced and what was used during a certain period of time.

Connection to the grid can be performed at low voltage lever or at medium level. The level depends on many factors like generator nominal power, operation mode and total power of renewable energy system.
The way of connecting RES to the grid is defined based on detailed technical and economical analysis, which helps to ensure the consistently good quality and performance of RES and safety for user. The technical part of this analysis includes calculation of load flow, voltage drops, short circuit current and total harmonic voltage distortion. Technical requirements for connection to the grid are defined by system operator of the grid, as well as technical information about the design of power plant: short circuit power, way of earthing, load profiles, nature and extent of reactive power exchange, continuous operating voltage, fault clearance time etc.
For photovoltaic plants main focus is on:

- Voltages changes when operating an electricity-generating plan
- Current harmonics
- Effect on device ripple control.

For the case study described in this thesis important rules set by ČEZ are:
Variation in voltage distribution system low voltage by connecting power plant at the connection point must not exceed 3%. Voltage changes when switching electricity generating plant 3%. Variations at the connection point in voltage caused by connecting/disconnecting the electricity generating plant must not be connected to low voltage (0.4 kV) exceed 2%.

3.2 Net metering

Prosumer is motivated to use net metering by saving on variable components of electricity prices (linked to electricity consumption) and also on taxes. Net metering originated in the US in the early 1980s, when owners of small solar and wind power plants wanted to be able to use the electricity generated for their own needs at a different time than when it was produced. One of the first states where net metering began to develop was Minnesota, where since 1983 prosumers have been allowed to create energy credits of up to 40 kW. Prosumers could either transfer the energy credit to the next billing period or even have it reimbursed. Currently, net metering operates in most states in the USA, Canada and Australia and is gradually expanding in Europe.
Regarding the current state of the use of net metering, the available data show that the principle of this system varies from country to country. In the EU countries where net metering is already in use, this is mostly operational support for decentralized production, an alternative to operating support in the form of feed-in tariffs or green bonuses. In most of these countries, the costs associated with the use of net metering are passed on to final consumers of electricity who do not use net metering, however, this is not a main goal in the Czech Republic and is not supported. According to the available information, net metering cannot be combined with any other form of support in any of European countries. From the EU countries, Italy is the closest one to the functioning of net metering on the market principle, without passing on costs to other consumers. However, this is not a balancing of production and consumption, but a deduction of the allocated credit for the supply from the payment for electricity. Prosumers in Italy also pay an annual fixed fee to cover the administrative costs of the distribution system associated with net metering.
In general, the biggest differences in net metering systems are in the settlement of a positive surplus (surplus of production). If we take a closer look at this question, for example, in the US, the net metering framework rules are usually specified by law or regulated by a statutory act of the regulator, and the actual form then depends on the agreement between the prosumer and the trader. In the United States, clearing is usually carried out on a monthly basis and total balancing is performed at the end of the year. If a prosumer has surpluses on a monthly basis (ie its production exceeds consumption), these surpluses are usually transferred as credit to the next month. The surpluses for the whole year can be treated differently, eg the surplus is paid to the owner of the resource and starts again from scratch in the new period, the surplus is paid to the owner but only up to a certain amount (eg x% of its annual consumption). period or forfeit to the trader, the owner of the power source pays nothing but receives nothing more and in the new billing period starts again from scratch

Similar to the management of annual surpluses, there are many methods to determine the price of reimbursed electricity produced from own resources. Several methods are used.
Standard Retail Price - electricity is delivered to the trader at the same price at which it would be purchased at the moment (depending on the tariff, peak or off-peak). This billing model is called "time-of-use metering" (TOU).
Wholesale market price, “market rate net metering” - the trader shall base its valuation on market prices of power electricity at the time the surpluses were delivered to the trader.
Price set by decree - the regulator sets a fixed price for surplus from net metering (but then it is practically a guaranteed feed-in price).
'Avoided costs' - prosumer's own electricity production will save the energy system the cost of generating such electricity from conventional sources, and will, therefore, be compensated for these costs.
In the Czech Republic, net metering is allowed only on a purely economic basis (not only power electricity), as mentioned by the NAP SG. Its use is based on the business relationship of the prosumer and the trader who is responsible for the deviation in the OM. If the plant is connected in a simplified way, net metering cannot be used logically. Legislative conditions for the use of net metering from the technical and regulatory point of view have already been set, however, additional questions arise in practice. It is up to the traders how to use the new possibilities and eventually net metering. It is interesting to note that, paradoxically, there is a call from traders asking for setting rules for using net metering on a commercial basis. Yet we often complain in the energy sector that we are bound by rules and regulations. When there is suddenly an area where there is no fundamental reason for binding rules and the most natural thing is to leave it to the free market environment, it seems that we suddenly miss the rules [6].

A case study for connection of the small PVPP into distribution network

4.1 Description

In this simulation a model of small low voltage (0.4 kV) distribution network with photovoltaic power plants connected to it was created by eVlivy application. As a model we took a block of new buildings in a small village located in Central Bohemia Region, Czech Republic. This small low voltage network consists of 10 buildings-consumers with 7 integrated PV systems on the roof of the buildings.

We create a voltage profile in two basic states:

- nominal PV production and small consumption
- no PV production and nominal consumption

The first state describes the situation for noon and afternoon (from 12:00 to approximately 18:00) when almost all consumers are away from home and just some basic devices like fridge, boiler and air-conditioner can be working.

The second one describes the situation for the evening (from 18:00 to approximately 00:00) when all consumers are at home and a lot of different electric devices are working.

Also, we calculate network losses for these 2 states in order to see the influence of PVPP.

The main goal of this simulation is to come to the conclusion if this model would satisfy criteria for connecting electricity generating plants to the distribution network set by ČEZ (České Energetické Závody).

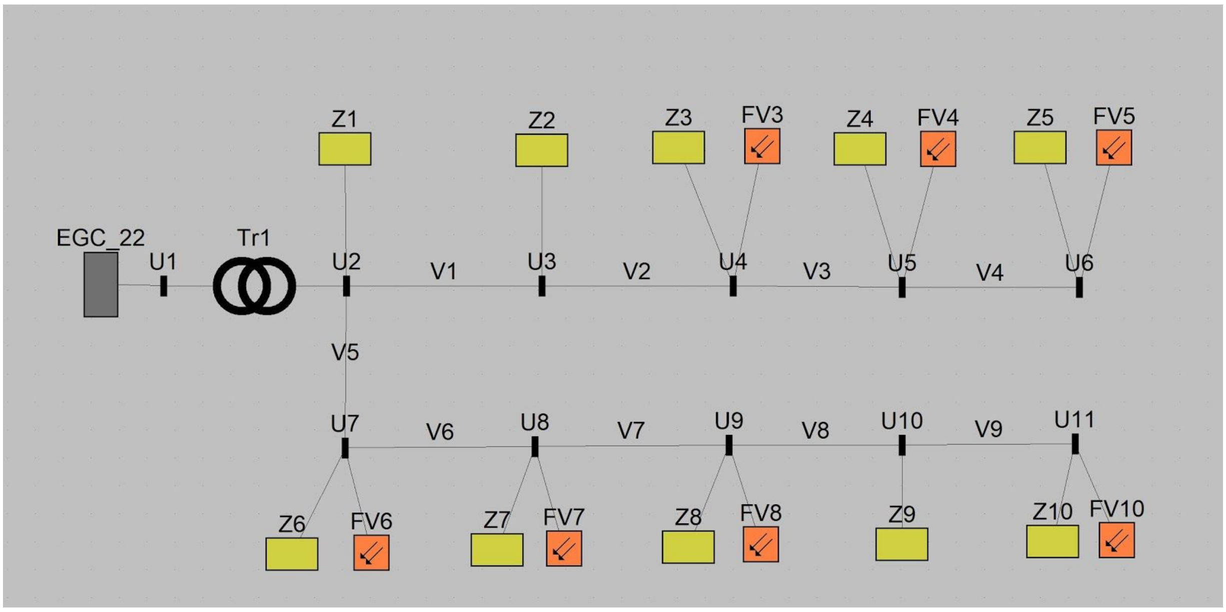


Figure 4.1.1 Schematic of the distribution network

4.2 Distribution network parameters

Parameters of the transformer					
Type of transformer	Primary voltage [kV]	Secondary voltage [kV]	Power [MVA]	Pk [kW]	uk [%]]
Tr1	22	0.4	0.4	4.6	4

Parameters of lines								
Type of line	Nominal voltage [kV]	Cross-section [mm^2]	B[μS/km]	R [Ω/km]	X [Ω /km]	Max current [A]	R0/R1	X0/X1
50AYKY50	0.4	50	1	0.619	0.077	147	1	1

Distance of lines	
Name	Distance [m]
V1	30
V2	30
V3	30
V4	30
V5	100
V6	30
V7	30
V8	30
V9	30

4.3 Calculation results

Case 1 - Nominal PV production and small consumption			
Name of consumer	S [kVA]	Name of PVPP	S [kVA]
Z1	0.1		
Z2	0.2		
Z3	0.1	FV3	8
Z4	0.3	FV4	7
Z5	0.2	FV5	8
Z6	0.1	FV6	7
Z7	0.2	FV7	8
Z8	0.1	FV8	8
Z9	0.1		
Z10	0.3	FV10	6

Case 1 - Nominal PV production and small consumption		
Node	Voltage [kV]	Difference between nominal voltage and voltage in Case 1 [%]
U1	23.000	
U2	0.418	4.5
U3	0.418	4.5
U4	0.418	4.5
U5	0.418	4.5
U6	0.418	4.5
U7	0.418	4.5
U8	0.419	4.75
U9	0.419	4.75
U10	0.419	4.75

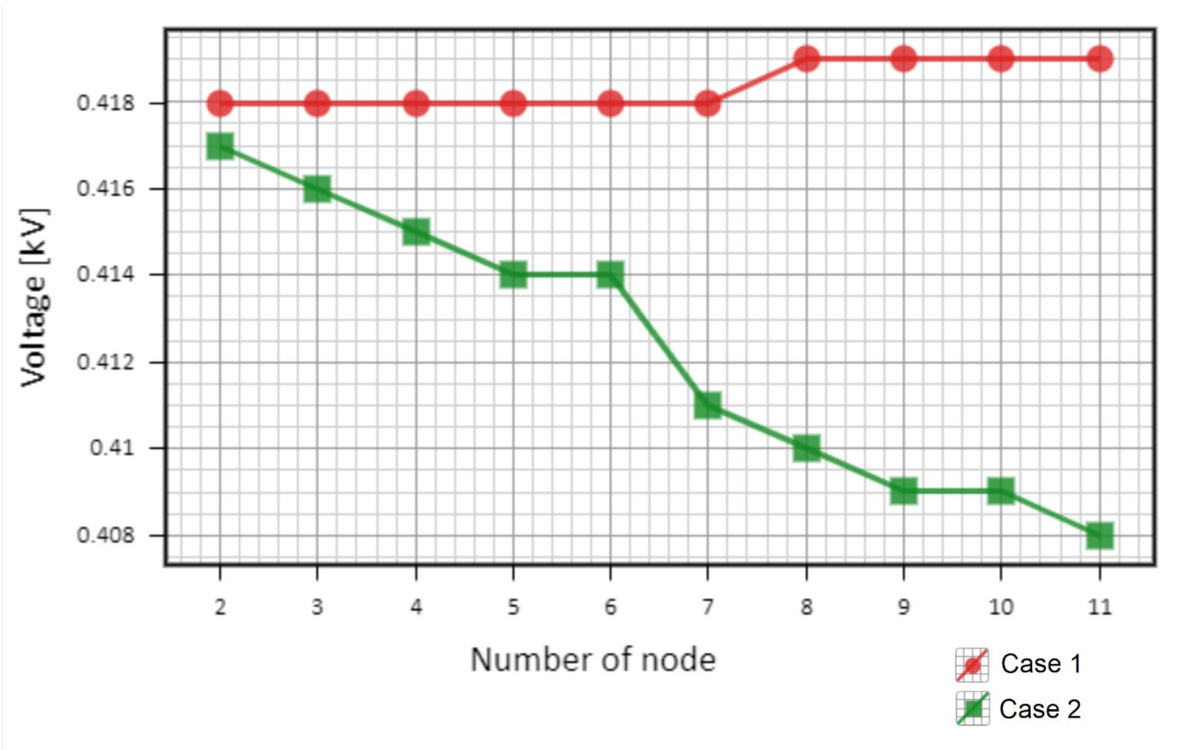
U11	0.419	4.75

Case 2 - No PV production and nominal consumption			
Name of consumer	S [kVA]	Name of PVPP	S [kVA]
Z1	8		
Z2	7		
Z3	6	FV3	0
Z4	8	FV4	0
Z5	6	FV5	0
Z6	9	FV6	0
Z7	7	FV7	0
Z8	7	FV8	0
Z9	6		
Z10	5	FV10	0

Case 2 - No PV production and nominal consumption		
Node	Voltage [kV]	Difference between nominal voltage and voltage in Case 2 [%]
U1	22.978	
U2	0.417	4.25
U3	0.416	4
U4	0.415	3.75
U5	0.414	3.5
U6	0.414	3.5
U7	0.411	2.75
U8	0.410	2.5
U9	0.409	2.25
U10	0.409	2.25

U11	0.408	2

Voltage profile for Case 1 and Case 2



Difference between Case 1 and Case 2	
Node	Difference between voltage in Case 1 and voltage in Case 2 [%]
U1	
U2	0.25
U3	0.5
U4	0.75
U5	1
U6	1
U7	1.75
U8	2.25
U9	2.5
U10	2.5
U11	2.75

Network losses		
	dP [kW] for Case 1	dP [kW] for Case 2
Tr1	0.0009083	0.1401681
V1	0.0000032	0.0787130
V2	0.0000150	0.0432685
V3	0.0000024	0.0212228
V4	0.0000017	0.0039008
V5	0.0000885	0.5052309
V6	0.0000080	0.0870495
V7	0.0000024	0.0490576
V8	0.0000006	0.0218321
V9	0.0000001	0.0071350
Total	0.0010301	0.9575782

4.4 Conclusion of the case study

As a result of simulation, it can be seen that the variations in voltage between the two cases were not more than 3% (maximal value is 2.75%). This result is within the standards set by ČEZ.
Also it can be concluded that the benefit of installation of the PV systems is network losses reduction which leads to decreasing of transmission and distribution cost.

General conclusion

This thesis has 4 guidelines mentioned at the beginning:
1. Renewable energy sources – general overview
2. Renewable energy source – focus on small solar application in combination with batteries or hot water production
3. Integration RES into the distribution network
4. A case study for connection of the small PVPP into distribution network

The first part was devoted to renewable energy sources. All types of renewable energy (wind, biomass, hydro and geothermal) sources were briefly described.

In the second part solar power was described in a more detailed way from technical and physical points of view.
In the third part information about rules for connection of RES to distribution network was given, also we used it in our case study.
In the case study we created a model of small low voltage distribution network with photovoltaic power plants connected to it. Calculations were done by using eVlivy application. Result were discussed and compared with Czech standards.

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