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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3. Integration RES to distribution network (guidelines, standards)
4. A case study for connection of the photovoltaic power plant to distribution network

Bibliography / sources:

[1] Distribution network codes
[2] eVlivy application manual
[3] SCHLABBACH, J, D BLUME a T STEPHANBLOME. Voltage quality in electrical power systems. London: Institution of Electrical Engineers, c2001, x, 241 p. IEE power and energy series, 36. ISBN 978-085-2969-755.

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In Prague 21.05.2018 N.Miljkovic signature:…………………..

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Abstract

Renewable energy sources are having larger impact and penetration every year in distribution networks. This thesis discusses in detail the current three most commonly used renewable energy sources; solar, wind and hydro. Every renewable source had its working principles described from a physics point of view as well as giving details on technologies that are being used currently in the industry. The focus of this thesis was on solar power generation as this was the generating source in the case study. The case study included a comprehensive simulation analysis of a real life scenario of a low voltage distribution system in Nymburk with small solar photovoltaic cells included. The simulation was done with the help of the simulation software eVlivy. The studies goals were to observe and analyse the effect of many private photovoltaic cells in a residential area on the distribution grid and its equipment.

Keywords: Renewable energy sources, Solar power, Wind power, Hydro power, Photovoltaic cells, Low voltage, Distribution system, Impact of PVPP.

Abstrakt

Každý rok mají obnovitelné zdroje větší dopad a více pronikají do distrubučních sítí. Tato diplomová práce podrobně popisuje tři nejčastěji využívané obnovitelné zdroje energie v současnosti - solární, větrnou a vodní. Pracovní principy každého obnovitelného zdroje byly popsány z hlediska fyziky, stejně tak jako podrobnosti o technologiích, které jsou v současné době používány v průmyslu. Tato práce se soutředila na výrobu sluneční energie, neboť tato výroba byla zdrojem v případové studii. Případová studie zahrnovala komplexní simulační analýzu scénáře reálného života nízkonapěťového distribučního systému v Nymburku s malými solárními fotovoltaickými články. Simulace byla provedena pomocí simulačního softwaru eVlivy. Cílem studie bylo sledovat a analyzovat vliv mnoha soukromých fotovoltaických článku v rezidenční oblasti na distribuční síť a její zařízení.

Klíčová slova: obnovitelné zdroje energie, solární energie, větrná energie, vodní energie, fotovoltaické články, nízké napětí, distribuční systém, vliv PVPP

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Chapter 1

Wind Power

1.1 Introduction

Wind energy has been used for thousands of years. Windmills were used to mill grains and at other times to pump water. Wind generators or wind turbines are the most popular form of wind energy used nowadays. Wind turbines convert the mechanical energy of the turning blades into electrical energy. The mechanical energy of the blades is due to wind. [3]

The earth's wind is due to variations in atmospheric pressures and these pressures in turn trying to equalize. Atmospheric pressure is the term for the weight of air above a certain location. Pressure variations are caused by the difference in solar heating of the earth's surface. As air is a gas and gasses expand relatively to how much they are heated the differences in solar heating creates differences in densities. These different densities cause air to shift and arrange to try and find equilibrium. Hence we have wind.

1.2 Energy and power the in wind

The energy of wind is its kinetic energy. Using the equation:

$$K.E. = \frac{1}{2}\, m\, v^2 \tag{1.1}$$

Where **K.E.** is kinetic energy [J],
m is mass [kg],
v is velocity [m/s].

To obtain the mass of air we must consider the flow of air through a volume per second (usually cylindrical volume) and its density. Therefore the equation for mass becomes:

$$\boldsymbol{m} = \rho * V. \tag{1.2}$$

Where **m** is mass per second [kg/s],
ρ is air density [kg/m^3],
V is volume per second [m^3/s].

This in turn can be simplified as **m** = air density *area*velocity.

$$\boldsymbol{m} = \rho * A * v. \tag{1.3}$$

Where **m** is mass per second [kg/s],

ρ is air density [kg/m^3],

A is area [m^2],

v is velocity [m^2/s].

This gives us the final equation for mechanical power of a wind power plant.

$$P = \frac{1}{2}\,\rho\,A\,v^3 \tag{1.4}$$

Where **P** is power [W].

$\boldsymbol{\rho}$ is density [kg/m^3],

A is area [m^2],

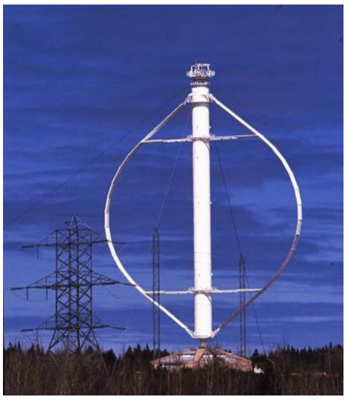
v is velocity [m/s].

We can see that the power of the wind (in equation 1.3) is proportional to the density of the air, the velocity with which the air is moving and the surface area. Not all of the power from the wind will be harnessed by the wind turbines as some of the air is not interacted with by the blades and therefore does not generate energy. This is known as 'Betz's law. According to this law the theoretical maximum of extraction of the total kinetic energy by a wind turbine is 16/27 (59.3%). [2]

1.3 Types of wind turbines

Most modern wind turbines have two basic configurations, horizontal axis and vertical axis. This describes in which way the primary axle of the wind turbine would rotate. The primary axle being referred to is the axle connecting the wind turbine blades and the generator.

(A)



(B)

Fig. 1.1 (A) Horizontal axis wind turbine [28], (B) Vertical axis wind turbine [1]

Vertical axis turbines have a slight mechanical advantage over horizontal axis turbines as they have the ability to convert any wind directions into electricity without the need to ‘face’ said wind direction unlike their horizontal counterparts. This system is known as the yaw system. It allows horizontal axis turbines to change the position of its rotors to more efficiently convert wind energy into electricity.

This adds complexity to horizontal axis turbines, nonetheless vertical axis turbines are still not economically competitive against horizontal axis wind turbines as for the time being [1]. However horizontal axis wind turbines have limitations when it comes to dimensions due to gravitational influences of fatigue on the blades as the blades turn. This has led to research on various models ,which have much bigger dimensions than today’s wind turbines, to be researched but without any practical implementation as of this point.

Horizontal axis wind turbines mainly come in 3 different configurations two-Blade, three-blade and multi-blade. Experimental one-blade configurations were also tried out but aren’t so popular. The two-blade and three-blade configurations are referred to as low-solidity wind turbines as these configurations do not have much solid mass in the swept area of the blades. Multi-blade configurations could be designed as both low-solidity and high-solidity turbines, however the latter is more frequent, such as shown in the water pump on figure 1.2

Fig. 1.2 high solidity water pump [1]

1.4 Number of blades

In theory the larger number of blades the more aerodynamically efficient a turbine is. However in practise these blades interfere with each other and only increase efficiency in a diminishing manner. At a certain point the cost for additional blades outweighs the benefits of the gains in efficiency.

Another reason for using low-solidity turbines is the difference in tip speed between high and low-solidity turbines. Tip speed is the tangential velocity of the tip of a turbines blade. Low-solidity turbines generally have higher tip speeds than high-solidity turbines and therefore require a smaller gear ratio to match the turbines angular velocity with that required for the generator. Generators generally require higher velocities than wind turbines can provide therefore gear systems are used. However special variable speed generators could be directly connected to the wind turbine rotor and therefore avoiding the need for a gear box. Examples of such generators can be seen in operation at Swaffham England. [1]

1.5 Aerodynamics of Blades

The study and development of aircraft components has led to a better understanding of aerodynamics. Wind turbine blades benefitted from this in their designs. Wind turbines have blades that resemble aircraft wings or propellers called ‘’aerofoil’’. Different types can be seen in Fig 1.3.

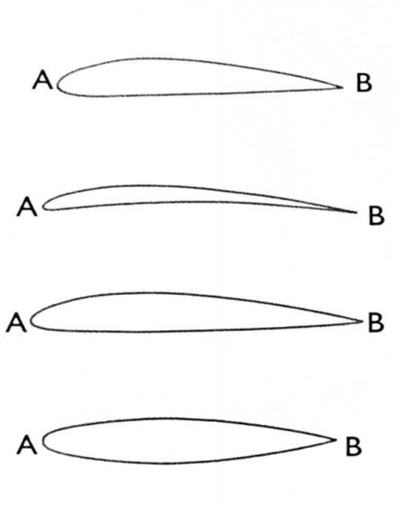


Fig. 1.3 Different types of Aerofoil.[1]

Aerodynamic forces can be simplified into two categories, Lift force and Drag force. These forces act perpendicularly to each other. Drag force describes the impact of the air with an object. The faster the air flow and the bigger the objects area in direct path of the air flow the bigger the Drag force becomes. Lift force is the force responsible for turning the wind turbines blades. Lift force is created when there is a difference in pressure between two sides of the same blade. This occurs by either having an asymmetrical aerofoil cross-section, having air flow direction at an angle to the aerofoils line of symmetry or both (See Figure 1.4).

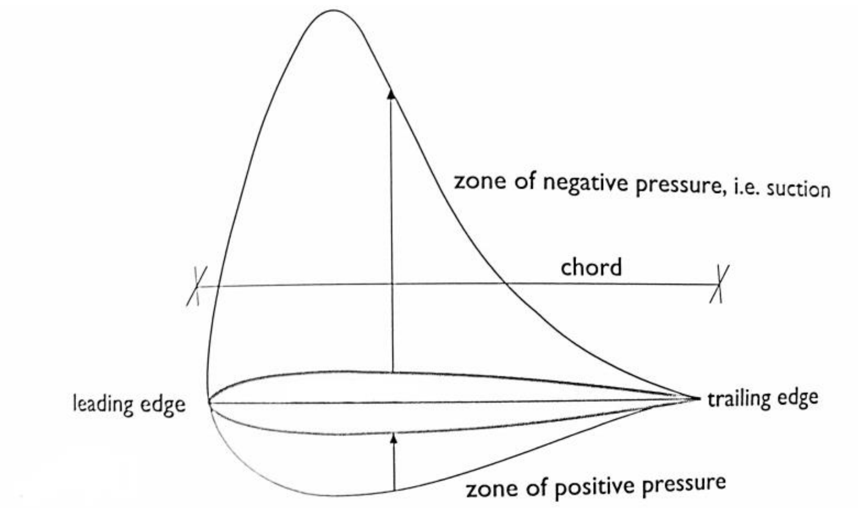


FIG 1.4 Zones of aerofoils [1].

The blade experiences different apparent velocities with difference in length (see Fig 1.5). Since Lift force is dependent on the angle at which the wind strikes the blade there exists an optimal 'angle of attack' for each different part of the blade. This forces designers of wind turbines to design a gradual twist on the blades to maximize efficiency. Although this also increases manufacturing costs.

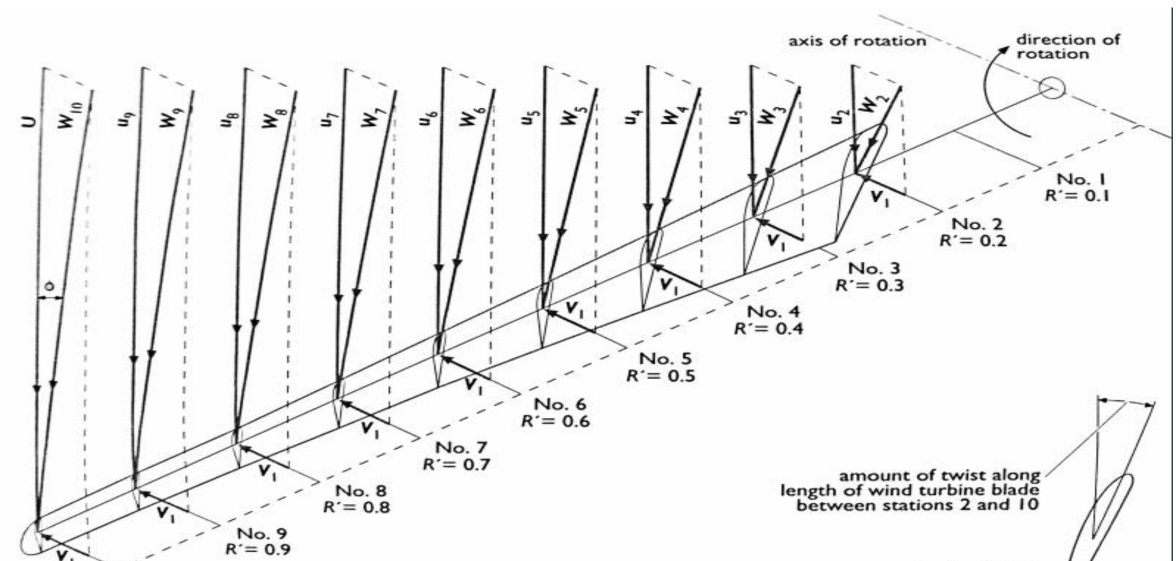


FIG 1.5 Apparent velocities along turbine blade [1].

1.6 Yawing system

Most modern wind turbines actively rotate their rotors to face the wind and so increasing effective power production. A wind vane would constantly keep track of the wind direction and then motors would realign the whole top of a wind turbine. The only issue with this system is the energy required to realign the turbine is significant compared to the energy produced at low wind speeds. This is made worse by the fact that low wind speeds tend to also have higher variabilities in direction than high wind speeds.

1.7 Distance between Turbines

Winds speed decreases after interacting with a wind turbine on close distances, as seen in Figure 1.6. Experiments in wind tunnels were carried out to better understand this. The studies concluded that 5-10 rotor lengths were needed for restoration of 80-90% wind flow respectively. For full flow restoration 20 rotor lengths were needed. (See figure 1.7). [3]

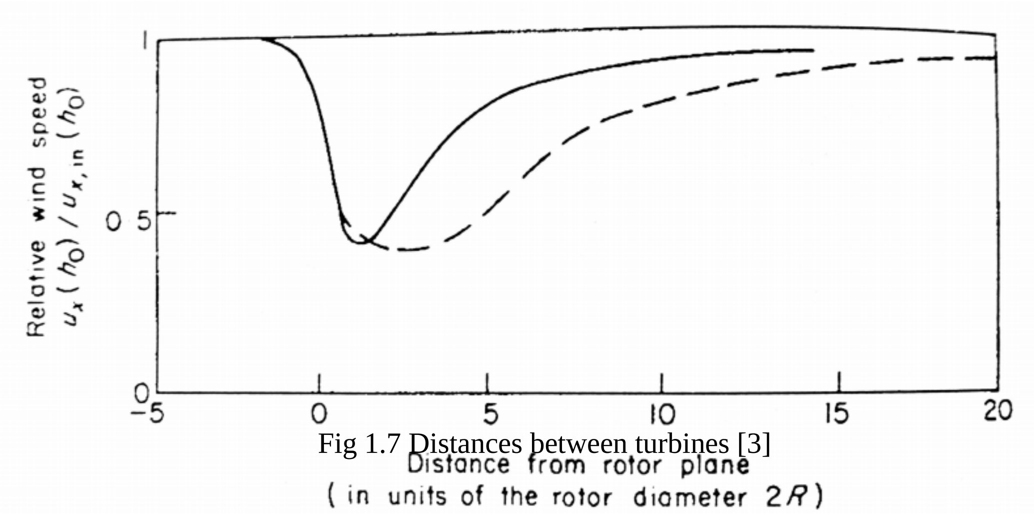


Fig 1.7 Distances between turbines [3]

1.8 Wind turbine components

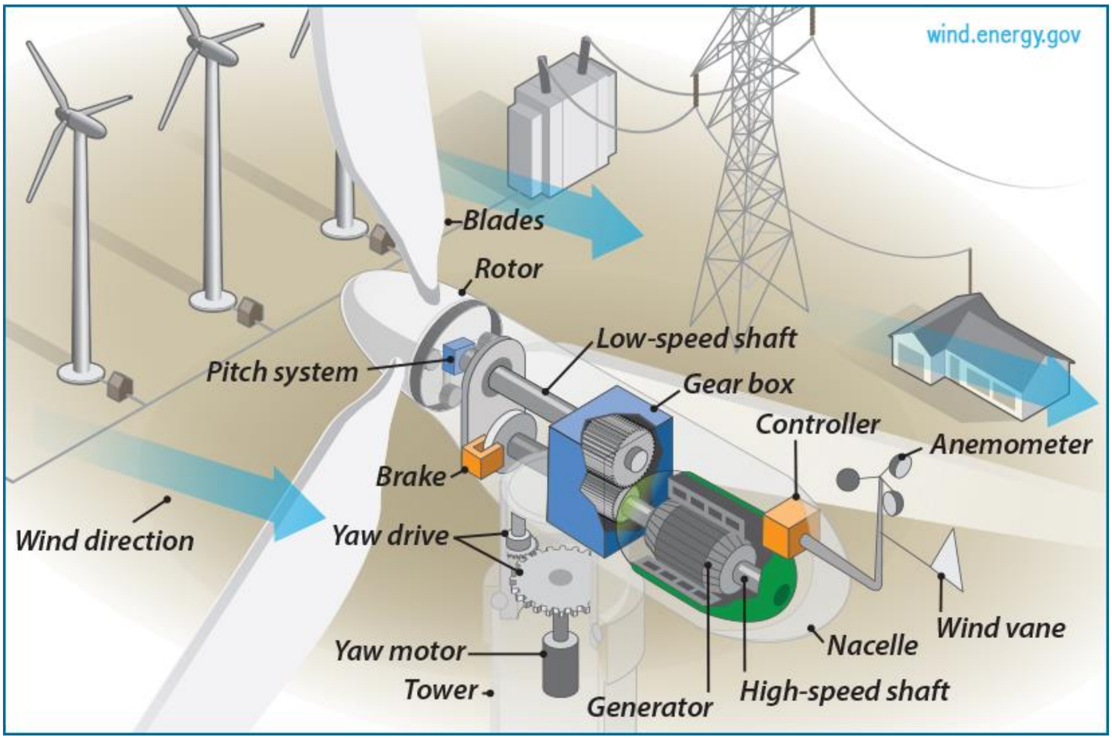


Fig 1.8 Turbine components [5]

Nacelle – This is the outer casing of the wind turbine encasing the mechanical components.

Generator – One of the most important components of a wind turbine. The generator converts mechanical rotational energy into electrical energy by induction. The generator can be synchronous or asynchronous.

Controller – The controller controls the braking system and the yaw system from inputs given by the anemometer and the wind wave.

Brake – The brake system slows the rotors down when the velocity of the blades increases too much due to very high wind speeds.

Gear box – Encases the gears to change the rotational speed of the rotor to the needed speed for the generator. As mentioned direct drive turbines do not need this part.

Yaw motor/drive – This moves the wind turbine to face the wind direction for the best power generation results.

Anemometer – Instrument that reads the wind speed.

Wind vane – instrument that reads the wind direction

Tower – The towers are usually built from concrete or tubular steel. It supports the turbine high above the ground as wind speeds increase with height. The average tower height is 30 metres although the range can be from 20 metres to 178 metres.

1.9 Synchronous vs asynchronous generators

There are multiple types of generators used in wind power generation, each with its own sets of advantages and disadvantages but the most prevailing technology is the induction generator. There are two types of induction generators: the squirrel cage induction generator (SCIG) and the wound rotor induction generator (WRIG). The SCIG is a synchronous generator which means that the generator has fixed rotating speeds possible. The WRIG on the other hand can have variable speeds and is therefore considered a more practical tool for wind power generation.[6]

The configurations for these two types of induction generators can be seen in Figs. 1.9,1.10.

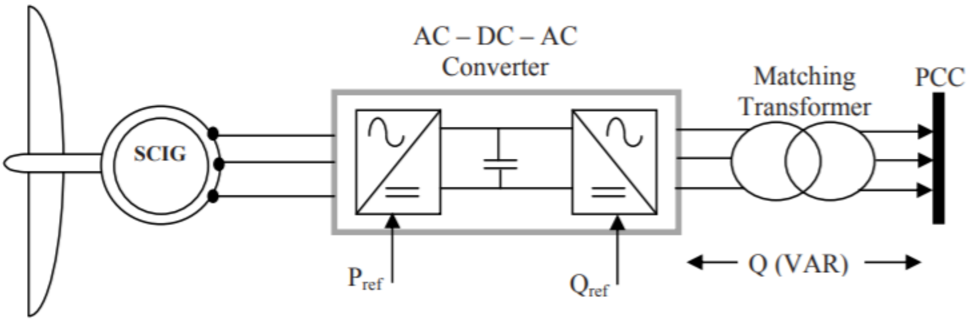


Fig 1.9. Squirrel cage induction generator. [6]

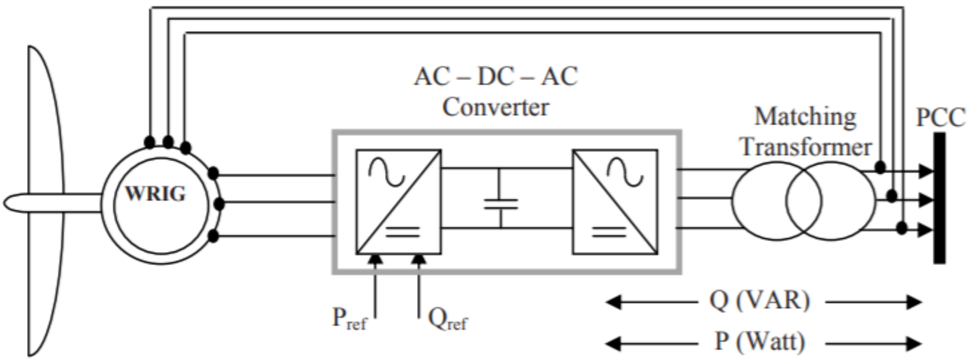


Fig 1.10. Wound rotor induction generator. [6]

1.10 Environmental Impact

Wind power is a renewable source of energy. It uses wind to produce electricity and while wind tends to fluctuate more than traditional fossil fuelled power generation systems it does not produce greenhouse gases such as carbon dioxide and other pollutants that cause acid rains, smog and contaminate land and water. The increase in pollution on a global scale and the growing concern around ‘climate change’ has led to an increase of interest in ‘green’ technologies such as wind power generation. The main example is that of the Paris agreement which came into effect on November 4th 2016. A wind turbine is able to produce 80 times the amount of energy needed to produce during its lifetime [1].

On the other hand wind turbines can cause some negative effects such as flickering, electromagnetic interference and noise. Flickering is cause by interaction between the blades and the light of the sun. Electromagnetic interference depends on the materials used for construction of the wind turbine. Metal blades and towers will interfere with electromagnetic waves while laminated timbre blades would not. The materials used therefore must be taken into consideration depending on where the wind turbine farm is located. A useful guide for avoiding electromagnetic interference was done by Chignell, 1987 [4]. The third impact is the noise wind turbines produce from the blades interacting with the wind and the mechanical noise from the generators and gears. Nowadays most mechanical noise is rather low compared to aerodynamic noise from the wind. The average wind turbine will produce noise of 35 to 45 decibels at a distance of 350 metres [1].

1.11 Grid Influence

Wind power was estimated to generate 4% of the electrical demand of the whole world at the end of 2016 [9]. 487 Gigawatts was the installed capacity of the total wind power installations around the world as estimated by the “Renewable global status report, REN21” [9].This data can be observe in Fig.1.11 below.

Wind power generation is known as intermittent power generation technology as power production can vary depending on the weather. It has been argued that with diversity in supply this issue can be managed. An example of diversity of supply would be if wind stopped blowing at one point of a country then possibly at another geographical location the wind wouldn’t have stopped. This would be a possible solution over very large geographical areas. These areas would also have to be interconnected.

There are two extreme possibilities that require the most attention when wind power generation is discussed. The possibility of all wind turbines not producing wind and when all wind turbines produce at full capacities. For the first possibility this would mean that a grid must have a 100% capability to replace the wind turbines power production with some other means. With the second possibility we are forced to consider frequency and voltage stabilities of the grid. This requires systems of stability control to be installed with wind turbines, naturally this increases costs.

Another way to decrease the impact of the intermittency of this technology with the use of other renewable sources is discussed in sections 2.6 and 2.8.

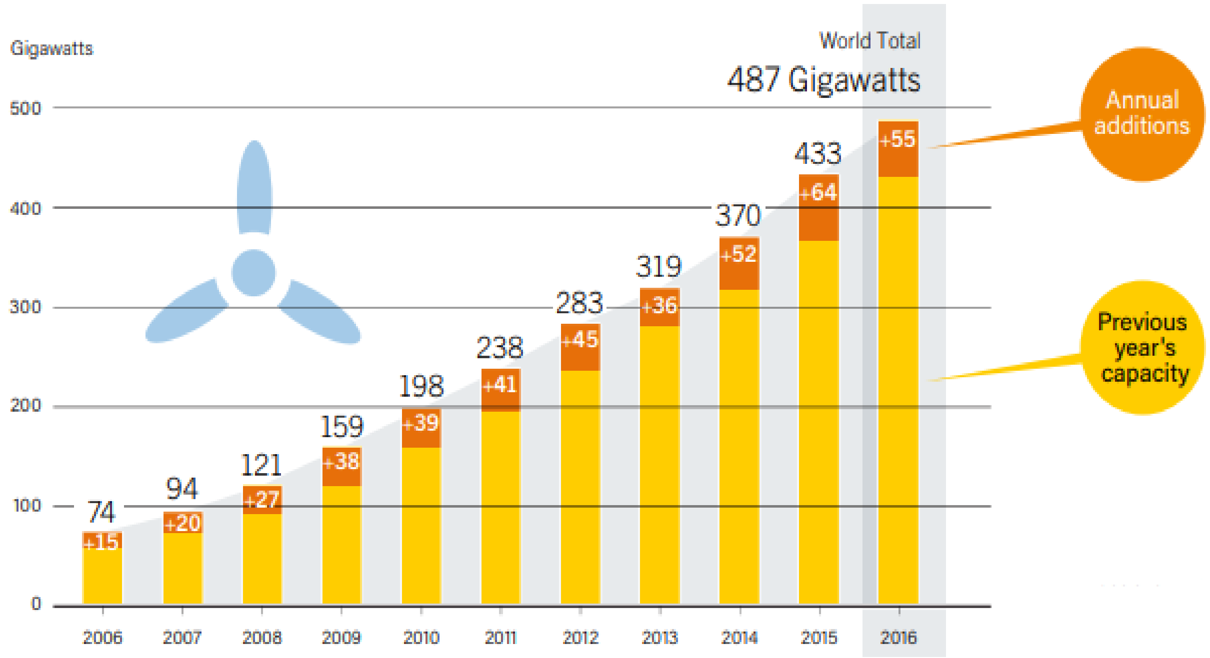


Fig 1.11. Global capacity for wind power [9].

Chapter 2

Hydro power

2.1 Introduction

The hydrologic cycle keeps evaporating water from the surface of the earth. This evaporated water is then deposited back on the surface in the form of water or ice. The primary energy exploited from this cycle is potential energy. As water is deposited back on the surface some of the water will be on deposited on higher altitudes then the water level. This means that the water will have gained potential energy. This is the reason rivers flow into the sea. By using the flow of water, created by the difference in potential energy, turbines are spun which can be used to generate electricity through a generator. This process is similar to the one used by wind turbines except it doesn't use air flow but water flow.

River flows are not the only energy resource being used to generate electricity. There are several tidal power stations using tidal water flow to generate electricity. One of the biggest tidal power plants under construction is the MeyGen tidal energy project situated in the United Kingdom at Pentland Firth, estimated to have a capacity of 398 Megawatts. Research on tidal technology is limited and therefore there isn't a prevalent technology therefore many tidal power plants use different methods of harnessing the power of the tides.

Ocean currents are also a noteworthy mention. The water in the oceans is in constant movement. These currents of water are created from various reasons such as from a combination of temperature, wind, salinity, and the rotation of the earth. Limitations in technology, and large concern for wildlife and ecology, have limited progress in implementation of marine current power plants.

2.2 Water flow and reservoir, energy and power

A reservoir holding water at a certain height can be equated to stored gravitational potential energy. Potential energy can be described by the following equation:

$$P.E. = M * g * H \tag{2.1}$$

Where **P.E.** is potential energy [J],

M is the weight of the water [kg],

g is acceleration due to gravity [m/s],

H is the height of the water above a pre-defined zero potential level [m].

The power of the hydroelectric potential energy can be estimated by the following equation:

$$P = \eta * g * H * \rho * Q \tag{2.2}$$

Where **P** is power [W],

g is acceleration due to gravity [m/s],

H is metres of head (water height) [m].

ρ is specific weight of the water.

Q is the number of cubic metres of water per second [m^3/s]

η is the efficiencies of the system. Namely the generator, the turbine and torque transfer to the generator shaft.

2.3 Types of hydroelectric plants

Up until 1837 the world did not have water turbines as we know of today. Instead inefficient water wheels were used. In 1832 a French engineer 'Benoit Fourneyron' patented the very first water turbine. The water turbine was different from the water wheel as it ran completely submerged and had guide vanes to direct water flow. A picture of the fourneyron's turbine can be seen at Fig. 2.1.

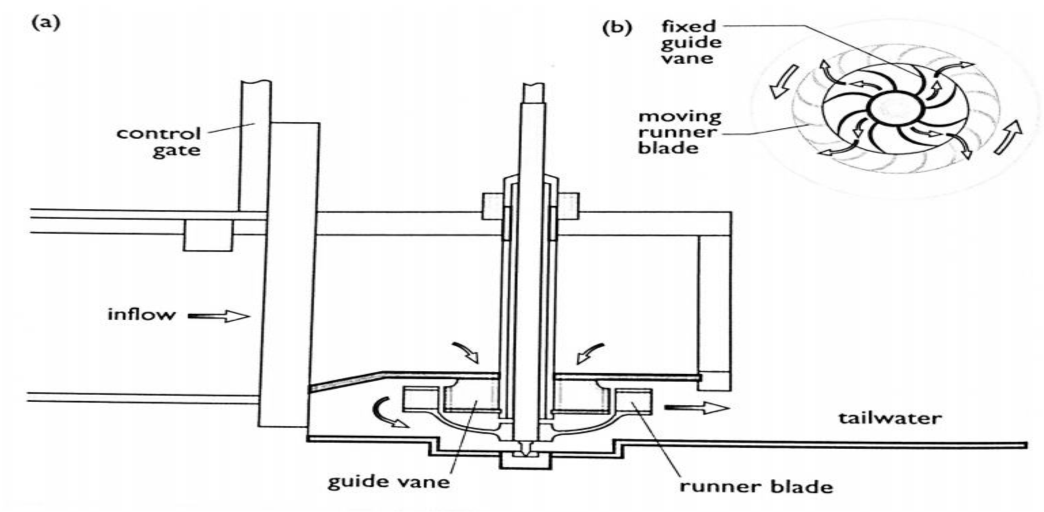


Fig 2.1 Fourneyron's turbine [1].

There are multiple ways of categorizing hydroelectric plants, they are the following [1]:

- Power output
- Head of water
- Type hydroelectric installation
- Type of turbine used (This will be discussed in more detail in section 2.4)

Modern hydroelectric plants all use turbines, although the turbines themselves may differ from one another depending on the characteristics of the hydroelectric plant. As no river and stream has the same shape and size and does not have the same water flow, the choice for which system to use is taken on as a case by case basis by engineers. While the type of turbines used are usually dependent on the head of the water and the head dependent on the type of installation this is not exclusive. However the type of installation and head of water are very closely related.

Some rivers are in suitable geographical positions for having a dam built while others could only support a free flowing water system with a very small head. This leads to classifying hydroelectric plants in terms of power capacities of little use. Two hydroelectric plants could have the same power outputs with very distinct systems to generate such power [1].

Power classification:

Micro – a capacity of up to 100 kW
Small – a capacity of up to 10 MW
Medium – a capacity between 10 and 200 MW
Large – a capacity of above 200 MW

Availability of head:

Low head - up to 20 m
Medium head - from 20 m to 100 m
High head - head above 100 m

Type of hydroelectric installation:

Run-of-the-river – little or no water storage is provided. Water flow is governed by the natural flow of the river or stream
Reservoir – Head created by a dam
Derivative – similar to run-of-the-river except only a small portion of the water is diverted to generate electricity
Pumped storage – This plant accumulates water in a reservoir above the generators as a power reserve. (More details in section 2.6)

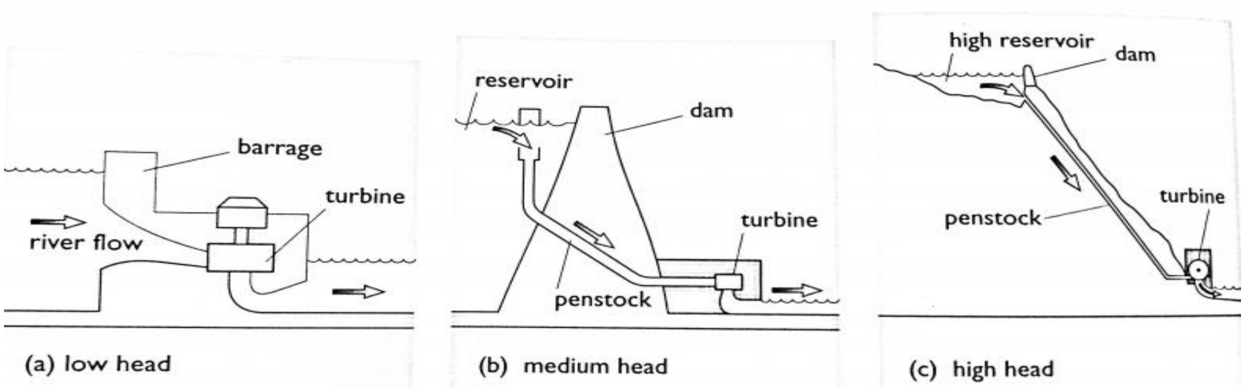


Fig 2.2. Type of hydroelectric installations [1].

2.4 Types of turbines

There are two types of turbines: reaction turbines and impulse turbines. These two turbines differ in the way that the energy from the water flow is converted into the mechanical rotation of the axis shaft. Impulse turbines such as the Pelton turbine use the kinetic energy of the water flow to push the turbine fins and therefore power the generators. On the other hand reaction turbines such as the Francis and the Kaplan turbines owe the rotational forces to pressure in the entrance of the water flow with the turbine chamber and the suction effect at the exit.

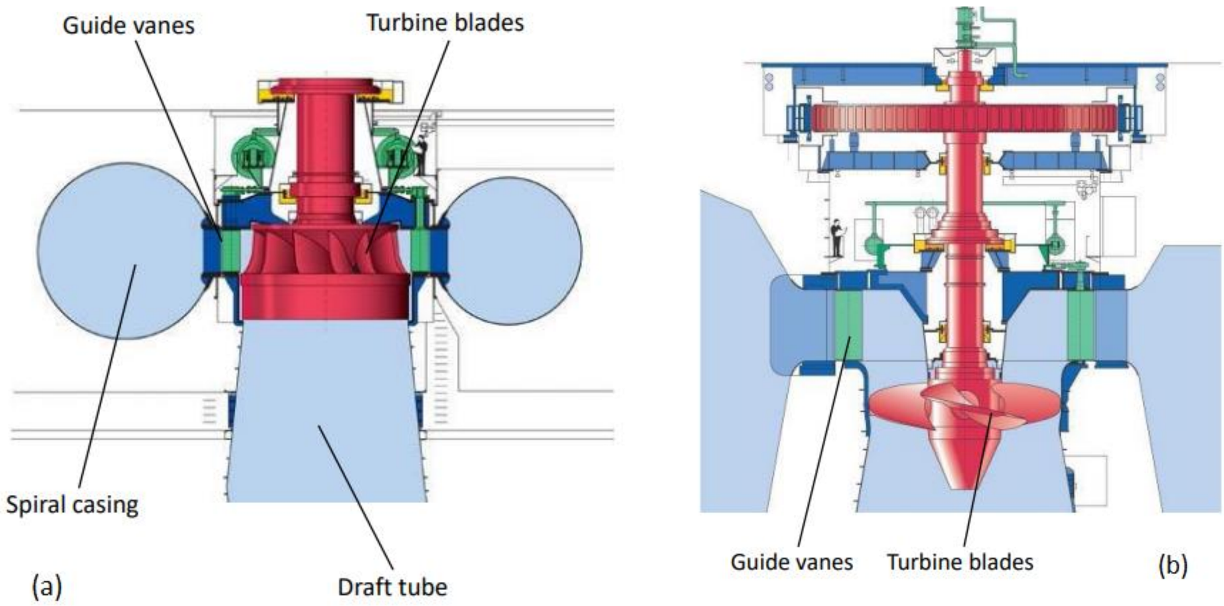


Fig 2.3. Kaplan(a) and Francis(b) [7].

The Pelton turbine is essentially a wheel with cups on the edge. A nozzle pressurises incoming water and directs it into the cups rotating the turbine. The Pelton turbine requires high pressures so that the water exiting the nozzle will have a high enough speed and therefore high enough kinetic energy to rotate the Pelton turbine. That's the reason Pelton turbines are used in high head installations. As the high pressure stream of water turning the Pelton turbine is not large the flow rate of water entering the reservoir must also be low. The control of power can be achieved adjusting the water jet volume or by deflecting the entire water jet away from the turbine.

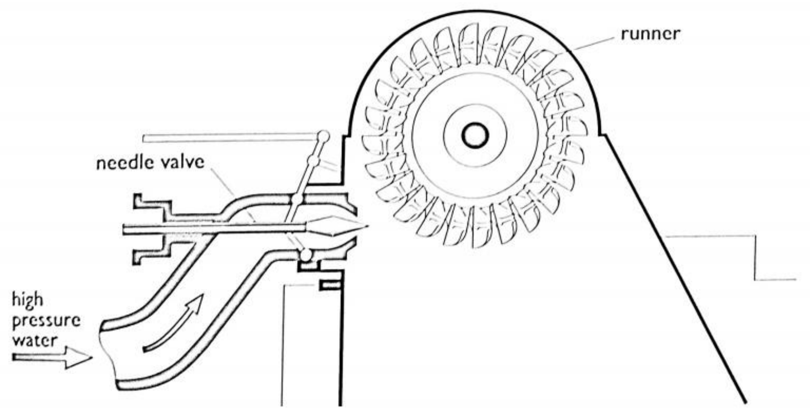


Fig 2.4 Pelton [1].

The Francis turbines are highly versatile as different dimensions and different installations can provide the necessary conditions so that the Francis turbine works at high efficiency. The Francis turbine for large and medium heads usually has a spiral casing perpendicular to the rotation of the turbine. The spiral casing is called the ''volute''. This system directs water from the volute inwards through guide vanes and then onto the turbine itself and out through the centre and into the draft tube. The draft tube is shaped as a triangle to help maximize efficiency as decrease in pressure on the exit of the water flow will increase the energy converted to turning the turbine. The major limiting factor with the Francis turbine is the fact that the best efficiency is achieved when the rotational speed of the turbine is only slightly less than the water flow. This means that at high water flow scenarios the Francis turbine will rotate at speeds which are too high. Controlling power on a Francis turbine is done by changing the volume of water flow through the guide vanes. This however changes the angle of attack on the turbine blades and causes loss in efficiency.

This is where the Kaplan turbine comes in. The Kaplan turbine is mostly used in low head and high water flow installations. The Kaplan turbine as seen in Figure 2.3(a) has a similar construction as the Francis turbine except for the direction of water flow and the turbine blades. The Kaplan turbine is an axial reaction turbine meaning that the water flow is parallel to its rotational axis. The turbine blades are smaller in number than the Francis turbine and use the physics described in section 1.5. High water flow does not equal to high water speeds but merely to the fact that high amounts of water goes through the turbine. Low heads usually equal to low water speeds. The Kaplan turbine is used in these conditions as its optimal rotational speed is around twice as much as the speed of the water [1]. This means that the Kaplan turbine can best convert these low water speeds for power generation. The control of the Kaplan turbine is similar to the control of the Francis turbine. The guide vanes are closed or opened until a satisfactory water flow is achieved however the Kaplan turbine has an advantage. The turbine blades in the Kaplan turbine have adjustable pitch. This means that the Kaplan turbine has a much more balanced efficiency even at different water flows.

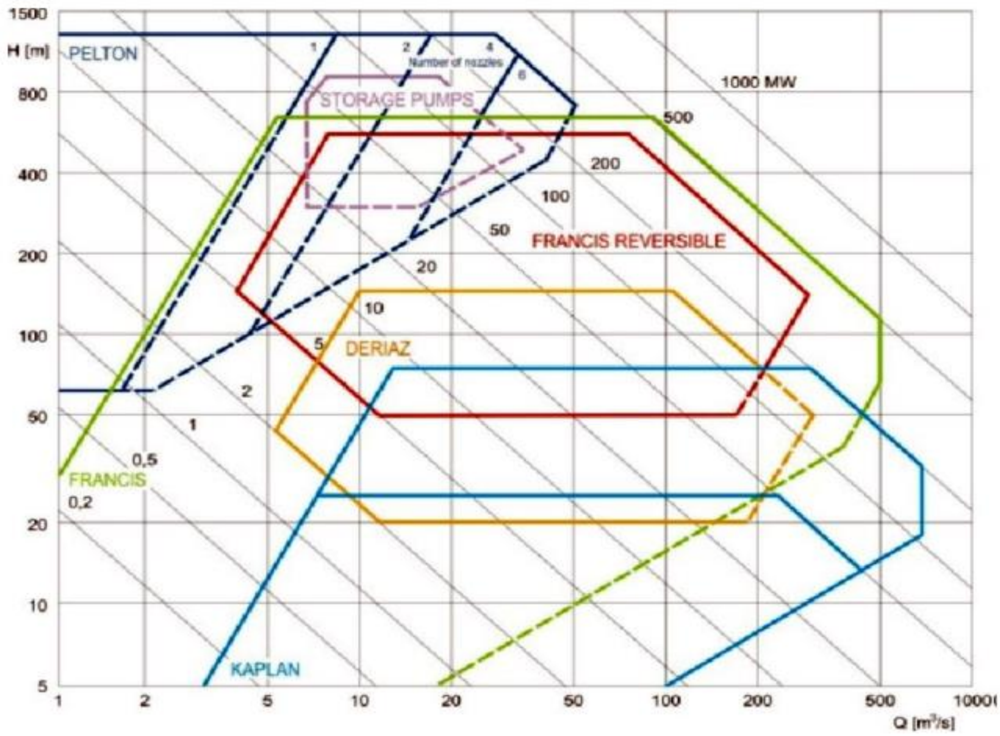


Fig 2.5 Graph of Ranges of application of different turbines. [7]

2.5 Water flow speeds

As mentioned in section 2.4 the rotational speeds vary for the different types of turbines. A method for better assessment was developed. This method is called 'Specific speed'. Specific speed (N_s) takes into account the rate of rotation of a turbine, the height of the head and the estimated power of the turbine.

$$N_s = \eta * H^{\frac{4}{5}} * P \tag{2.3}$$

Where $\mathbf{N_s}$ is specific speed,

$\boldsymbol{\eta}$ is rate of rotation of the turbine [Hz],

H is the height of the hydraulic head [m],

P is the estimated power of the turbine [W].

Different turbines work better at different speeds as discussed in the previous section. However to better assess which speeds exactly are the preferred ones we use the N_s to determine that. The following table shows the different speeds for different turbines:

Table 2.0 Specific speeds. [1], [3].

Type of turbine	Specific speed N_s
Pelton	10-80
Francis	70-500
Kaplan	300-1000

*Note that the speeds in the table 2.0 are approximations and further data would be needed in practise.

Specific speed is not the only and defining factor when choosing a suitable turbine for a new installation. Factors such as cost, manufacturing difficulty and availability come into play in real life scenarios.

2.6 Pumped storage

The concept of pumped hydro storage is very important regarding the management of the electricity grid. What pumped storage facilities essentially do is displace masses of water vertically up or down. The reason for this displacement is that the water from a higher altitude can be allowed to flow downwards to rotate turbines and generate electricity via electric generators. But why would we want to pump water upwards then?

Electric grids do not have stable consumers, i.e. the consumption varies through time. This means that supply must also vary. However some types of power plants such as nuclear, solar farms, wind farms... etc. cannot vary their supply or take a long time to do so. This is where a big amount of stored energy is useful. Pumped hydro storage effectively store energy by pumping masses of water into higher altitude reservoirs to be used when needed. An example of such a facility can be seen in figure 2.6.

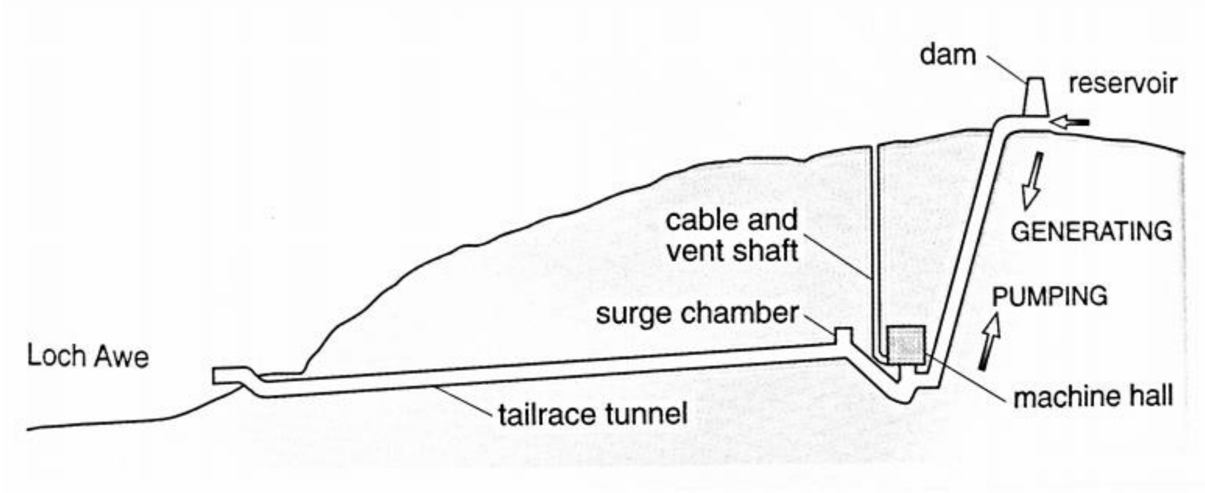


Fig 2.6. Pumped hydro storage layout example.

Two big factors in decreasing costs for building such facilities are generators that can function both as motors to power the pumps and as generators to generate electricity and turbines that are able to work both as pumps and as turbine, working in both directions of water flow. However as we shall see there are some possible reasons to have tandem systems with different turbines doing the pumping and the generation. The choice for different turbine systems is largely due to the head of the installation.

Kaplan turbines do not work well at high heads and are inefficient when used as pumps. Not many Kaplan turbines are found at pumped storage facilities. Francis turbines on the other hand work well with medium heads and are pretty efficient at pumping water upwards [3]. Also multistage versions with multiple Francis turbines have been used with extremely high heads such as the 'Entracque' power plant in Italy. Pelton turbines have also been used, however since they cannot be used as pumps there must be accompanying Francis turbines such as at the 'Grand'Maison' Dam in France.

Average efficiency of such a facility is around 0.8 but that number varies from installation to installation. The important thing is that these facilities do have losses and not all the energy used for storage will be used. Losses in water through evaporation if the upper reservoir is open to the elements, losses in the fact that not all the water interacts with the turbine called 'leakage losses' and losses due to friction all contribute to the imperfect efficiency.

Some already built hydropower plants have been fitted with additional equipment to also make use of this pumped storage principal. Not all power plants are able to use this feature as a low and a high reservoir are both required.

Pumped hydro storage may be superseded by other storage technologies in the future such as hydrogen and other fuel cell storage but for now it is the most economical storage technology on large scales [1].

2.7 Environmental and social Impact

Hydroelectric power plants do not in fact consume water, merely divert the resources. However this can still affect the environment in several ways. Large dams with open reservoirs can cause a shortage of available water supply by increased evaporation in the reservoir as well as damaging agricultural assets further down the river by blocking nutrients and soil to be carried downstream. An example of this is the Aswan high dam in Egypt [1]. This dam also caused water snails to be able to migrate into the upstream areas. While this in itself is not such a catastrophe the water snails in question may carry parasites which harm humans [3].

The Aswan dam has been highly critiqued as it had several negative effects on the surrounding areas. Approximately 80,000 people have been relocated to make way for its reservoir. The soil and nutrients discussed above not only affected the farming lands downstream but also decreased significantly the volume of the usable reservoir. (This is not only happening with the Aswan Dam, many dams have had experienced decreased reservoir volumes as silt starts to accumulate).

Further opposition towards building large dams comes from previous catastrophes that had occurred when dams had collapsed. The biggest example in this case would be the 1975 dam failure in the Henan province in China. This tragic event took the lives of 171,000 people and left 11 million homeless. Such staggering numbers are sure to make anyone think twice of accepting a dam to be built in their vicinity.

Socially the building of large dams can vary from person to person. They might consider a large pond to be beneficial for recreational activities or they might have to be relocated to make way for the reservoir which would surely not make anyone's day.

Methane is also a problem with large dams. It has been found in a report by the "world commission on dams" in the year 2000 [8] that some dams were producing methane by anaerobic decay of vegetable matter in the reservoirs. This led to speculation about how 'green' in fact hydro power is. More studies were carried out and found varying results. Some reservoirs were barely producing any methane while others were contributing to greenhouse emissions comparatively as much as thermal power plants using fossil fuels. This brought forward new regulations regarding reservoirs.

While all of these notions have merit still hydroelectricity is relatively positive. If planned well a hydroelectric power plant can hugely curb carbon dioxide and other greenhouse gas emissions while still being a socially positive endeavour. One must remember that the option to not build a hydropower plant means only that it will be replaced with a different power plant. In this respect hydropower is still one of least harmful ways to produce electricity.

2.8 Grid influence

Hydropower was estimated to produce around 16.6% of the worlds power demand in 2016 [9]. Around 25 Gigawatts were added in 2016 alone. Total power production by hydropower was estimated to be 1096 Gigawatts at the end of 2016. This makes hydro power the largest producer of renewable energy by a margin of 2/3 versus all the other renewable energy producers combined. Clearly hydropower is a very vast industry. Pumped storage also appreciated a growth of 6 gigawatts of new installed capacity by the end of 2016 [9].

The fact that hydropower is the largest renewable energy is not surprising as humans have been developing this technology for hundreds of years all around the world as a source for generation of electricity. Hydropower is also pretty flexible compared to other power generation sources. It has the ability to track the difference in supply vs demand very well.

Pumped storage plays a very important role in the world's current grid system. The ability to store excess energy and use it later when needed deals with the issue that the intermittent renewable sources such as wind and solar have.

Hydropower in general is viewed as a positive industry in the power generation field, whether it be for the control of intermittent technologies or simply the fact that massive amounts of controllable generation is possible with renewable energies.

Chapter 3

Solar power

3.1 Introduction

The Sun radiates light; we make use of this sunlight in two ways which we will discuss in more detail later in this chapter, generating electricity and using its heat. The Sun has been around for billions of years and yet it's still radiating. The way it does that is thanks to hydrogen atoms undergoing nuclear fusion to make heavier atoms which gives off huge amounts of energy in the forms of heat and light. Hydrogen atoms require enormous temperatures to undergo fusion but thanks to a phenomenon called 'Quantum tunnelling' the atoms still undergo fusion even without reaching these temperatures. Quantum tunnelling is out of the scope of this text but in very brief it means that there still is a tiny chance for an event to occur even when the conditions aren't met, such as fusion. The Sun being so large and having an extremely large number of hydrogen atoms these extremely tiny possibilities of quantum tunnelling start to occur.

Wind and hydro power sources use the Suns energy indirectly (as discussed in sections 1.1 and 2.1 respectively). Solar power is about how we use the energy given by the sun directly. As mentioned above two ways exist to use direct solar energy.

Solar photovoltaics let us generate electricity directly from the light waves through the photoelectric effect. The most popular form of photovoltaics is the silicon monocrystalline type which will be discussed in detail later.

Solar thermal energy is another form of direct solar energy use. The heat from the sunlight can be used to heat up water or buildings using solar collectors and it is also possible to concentrate the sunlight using mirrors to provide high temperatures needed for thermal-electric power stations.

3.2 Energy of the Sun

It is estimated that the Sun radiates 1367 watts per metre squared [7]. Due to simple geometry only half of this radiation hits the top part of the Earth's atmosphere at any one time as shown in Figure 3.1. Another factor to take into consideration is the Earth's curvature. Not all the light will strike the earth at the same angle and will have to go through more of the atmosphere before reaching the surface. This effectively decreases the effectiveness of the radiation by an additional one half [13]. This leaves us with 341.75 watts per metre squared.

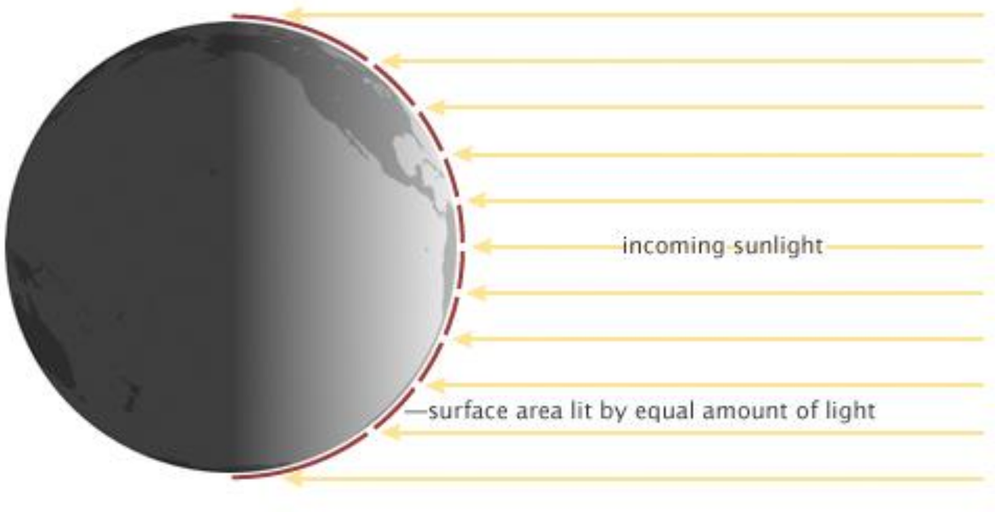


FIG 3.1. Incoming sunlight. [13]

Clouds reflect about 16% of that radiation back into space, 8% is reflected back by the scattering from atoms and 6% is reflected by some surfaces such as oceans, soil, etc.… in total the reflection is about 30%, this is known as the Albedo of the Earth [12], [3], [11]. Another 20% gets absorbed in the stratosphere by dust, ozone and clouds. This leaves about 50% of the solar radiation impacting the surface, which translates to an average of 178 watts per metre squared (as can been in figure 3.2).

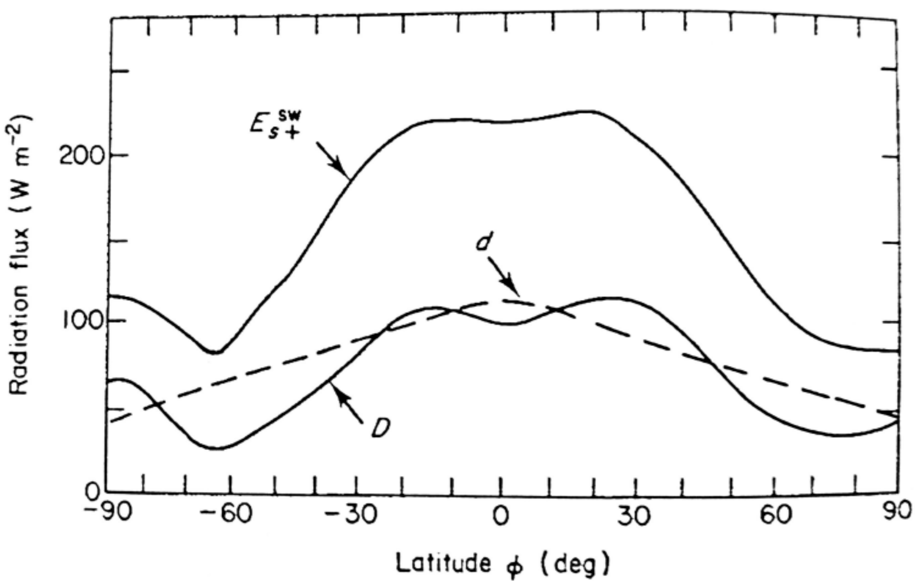


Fig 3.2. Average radiation on the surface [3] PG.46

This is not to be confused with the average instantaneous power of radiation when the sun is at zenith and there is a completely cloudless sky. This value is around 1000 watts/metre squared [7].

There are two types of radiation one must consider on the Earth's surface. The direct sunlight that comes as a straight line from the sun (typical rays of light on a clear sky) and scattered sunlight which occurs by distortion of the lights path by clouds and by reflection of the light rays off of objects. Both of these types contribute to the total amount of energy received by the sun and are crucial for calculations. Another aspect one must consider is the long wave radiation by the Earth and the objects on it. In fact glass insulators used in low temperature solar energy collection are chosen with properties such that the long wave radiation is not permitted to be re-radiated [1].

The Sun's radiation covers a wide range of the electromagnetic spectrum as can be seen in Fig 3.3 marked ''Top of atmosphere''. The absorption in the atmosphere happens at specific wavelength as is also visible in Fig 3.3 marked "Sea level (clear sky)". The reason behind this is due to the absorption by the elements H_2O, CO_2, O_2, NO_2 and other atoms that make up the atmosphere. Also in Fig 3.3 can be seen the spectrums of the scattered portions of the light radiation, clearly this portion cannot be neglected even in the case of clear sky.

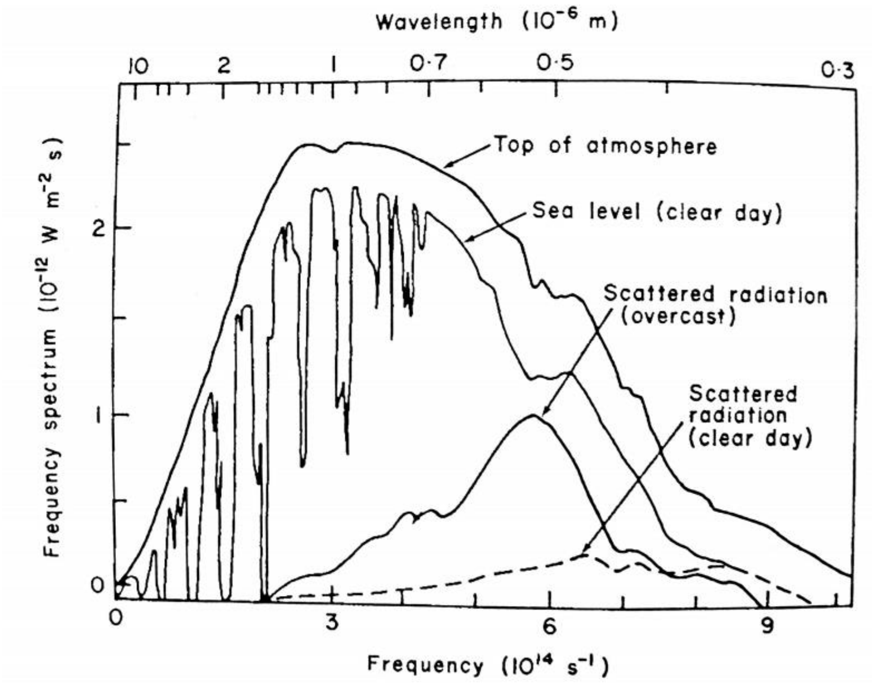


Fig.3.3. Frequency spectrum graph [3].

3.3 Photoelectric effect

The photoelectric effect describes how it is possible for a photon to excite an electron which means that it detaches from an atom. This effect is immensely important with regards to the physical properties of light. Due to experimental data gathered from experimentation on this effect it was established the ‘Wave-particle duality’ of light. This means that light could have electromagnetic wave like properties but also transfer energy in certain ‘packets’ which we now call photons.

Through experiments it was observed that intensity of light was not correlated with the emission of electrons but the frequency of the light wave. Max Planck’s equation (3.1) shed some light onto the strange discovery.

$$E = f * h \tag{3.1}$$

Where **E** is energy [J],
h is Planck’s constant,
f is frequency [Hz].

As seen in Fig. 3.3 some atoms absorbed certain ‘parts’ of the light spectrum. This is due to the same effect. Every distinct atom has a different energy with which the electrons inside this atom are attached to the nucleus. This means that only the photons with suitable energies are able to detach the electrons are absorbed. This causes every material to have different absorption bands. An example of such absorption band can be seen in Fig. 3.4. Absorption properties of different materials are being constantly researched with hopes of achieving better efficiency when generating electricity from light radiation.

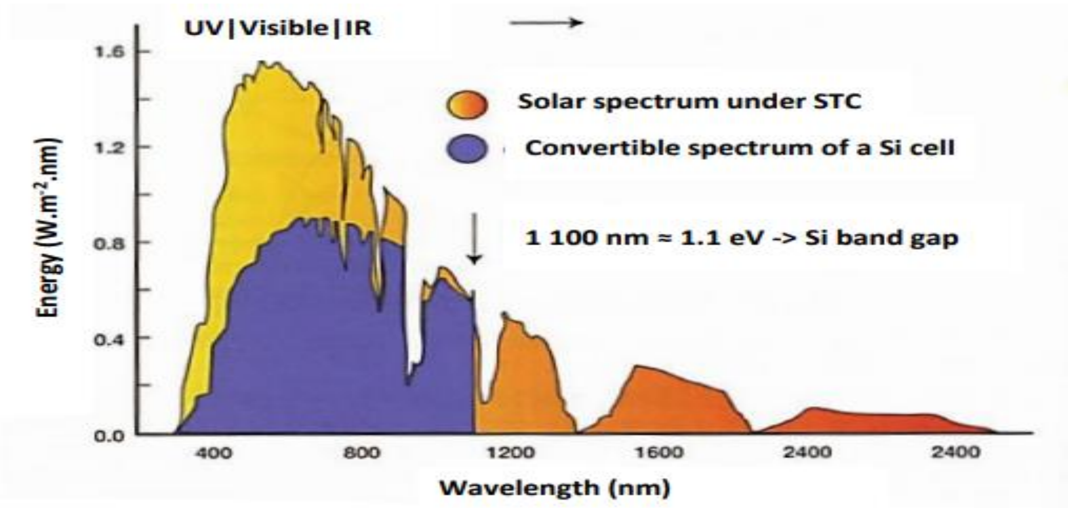


Fig. 3.4. Absorption spectrum of Silicon [7].

3.4 Solar thermal energy

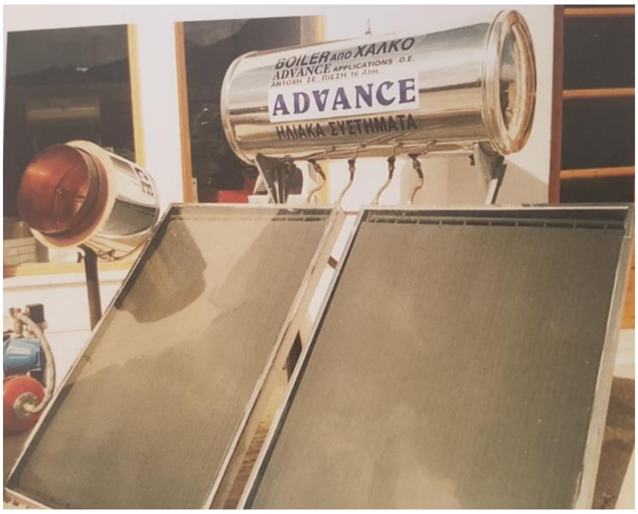
As was discussed in section 3.3 photons which collide with a material can cause its electrons to detach themselves by ‘giving’ the electron additional energy. This additional energy is considered to be an increase of net kinetic energy added to the atom. Therefore it can be said that the conversion light radiation to heat is created by an increase in kinetic energy on the atomic level by said light radiation.

This kinetic energy may be lost through re-radiation, convection and conduction. Re-radiation here refers to the material which absorbed the light radiation to emit its own radiation, conduction meaning the collisions between atoms and the dispersing of energy in this way and convection referring to the movement of gasses or fluids with difference in pressures created by the differences in temperatures.

There exist two different systems of making use of solar thermal energy, “Active” and “Passive”. Passive systems make use of natural flows of heat without additional energy inputs. Active systems do not obey this rule and have systems such as circulation pumps and other machinations to assist the system.

3.5 Passive solar thermal systems

The most typical example of a passive heating system is the thermosiphon. It is mostly used in climates frost-free climates as only then is it safe to have a water storage tank outside at the mercy of the elements [1], as even though the tank is insulated freezing temperatures might break the piping. Fig 3.5 shows a simple construction of the thermosiphon and Fig 3.6 shows the basic construction of a solar heating panel. The absorption plate in Fig.3.6 is usually combined with copper tubing [1]. Water flows freely in the pipes of the thermosiphon. As sunlight heats up the heating panels the water in the copper tubing gets heated up as well. The thermosiphon relies on the fact that natural convection will allow the free flowing water to separate the hotter water in the storage tank while the colder water is directed to flow through the heating plates. Thermosiphons are also usually equipped with a small electric heater for cloudy days and really cold weather.



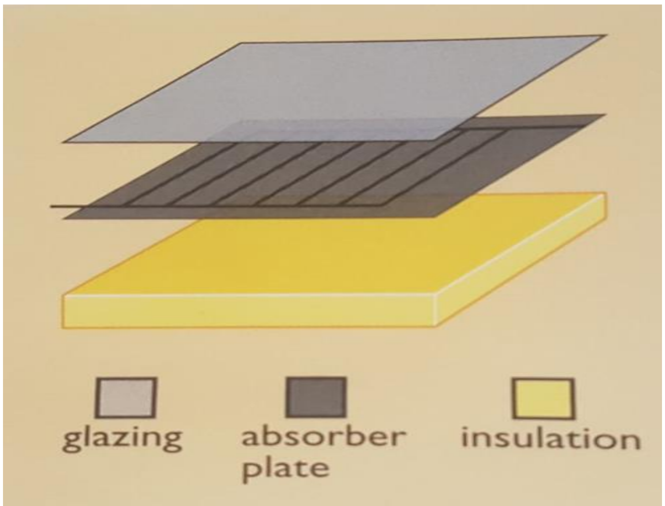


Fig 3.5. Thermosiphon [1]. Fig 3.6. Components of a solar heating panel [1].

Other examples of passive solar heating devices are architectural in nature as it mostly deals with the way buildings gather and release excess thermal energy. 3 of the most notable variates of passive solar heating are displayed in Fig.3.7. The conservatory is a combination of insulation, buffer and direct gain. It heats up the air inside the conservatory and then by natural circulation this air permeates through the building heating it up in the process. It is a very cheap method of upgrading an already built structure. The trombe wall is similar to the conservatory but on a smaller scale, usually pre-planned in the buildings construction phase. The direct gain effect is pretty self-explanatory.

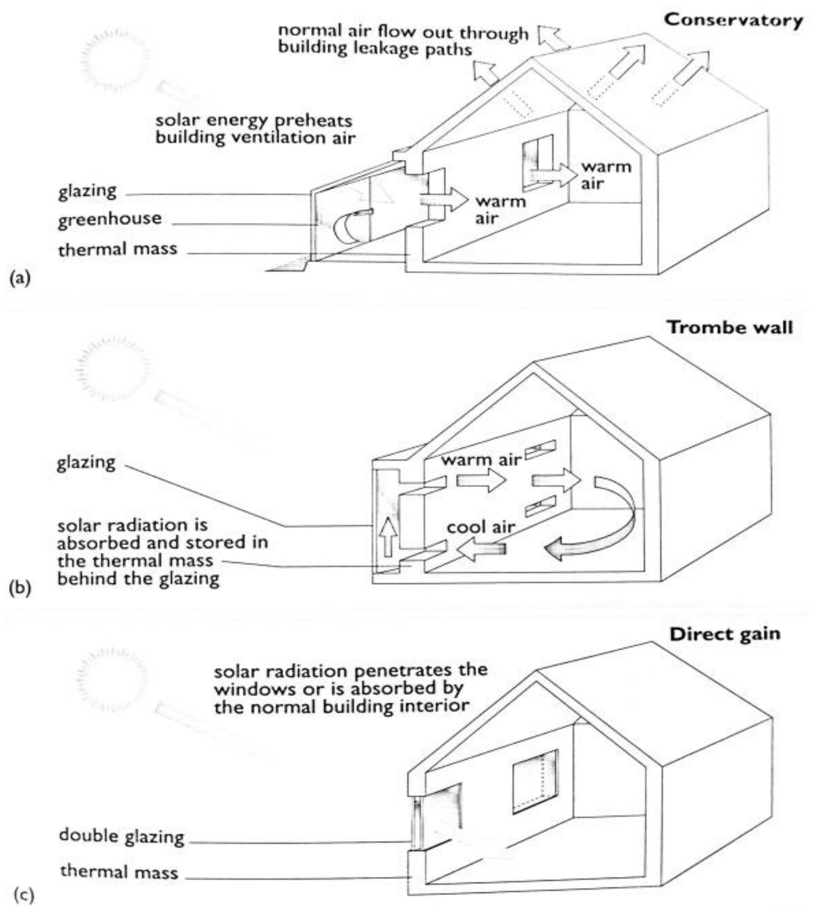


Fig 3.7 Types of passive solar heating [1].

3.6 Active solar thermal systems

Active solar thermal systems have a number of different types of collectors. While almost all types are used to heat water some types are better suited for high temperatures and others for low temperatures. Low temperature collection makes use of flat plate collectors similar to the ones the thermosiphon uses, except there is a pump in the system and the storage tank is usually inside a building. In Denmark there exist a large amount of low temperature collectors which heat up entire central heating systems [14].

High temperature collectors are mostly used for the generation of electricity. The most widely used high temperature collectors are the line-focus or parabolic through collector and the point-focus collector. The construction of each of these types of collectors can be seen in Fig 3.8.

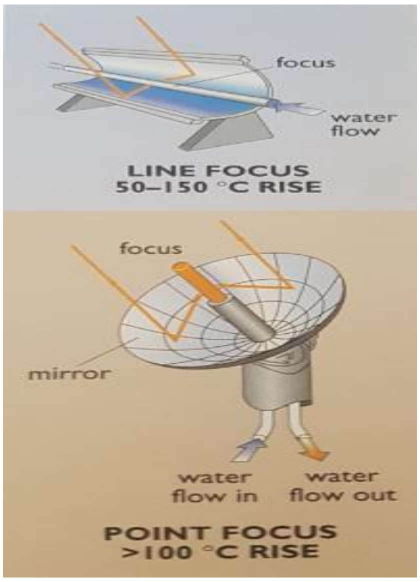


Fig 3.8. Types of high temperature solar collectors [1].

Parabolic through collectors heat water or other liquids to large temperatures by focusing the sunlight on a tube carrying the liquid. This liquid turns to steam as it reaches high temperatures and it is then directed to turbines to generate electricity. The line focus collectors must track the sun in at least one axis as it is imperative that the sunlight is focused in the correct direction. Focus-point collectors are rarely used except in some Stirling engines. For more information regarding these engines please see reference number [15].

Other systems for the generation of electricity using solar thermal systems are solar power towers and Fresnel reflectors.

Heliostats are usually used with the 'solar power towers' such as seen in Fig.3.9. Heliostats are simply mirrors of high quality that track the sun. These solar power towers are simply large towers with boilers on the top. The heliostats are turned so that the focus of their mirrors is aimed at the boiler on top of the tower. The fact that the sun constantly moves and that the focus of the heliostats must be always on the boiler means that a two dimensional tracker must be involved into the system to track the sun. Solar power towers may use different types of energy carrying 'fuels' such as water/steam or molten salt. The important thing is that the heat accumulated by the heliostats is used by the heat engine which is connected to an electrical power generator.

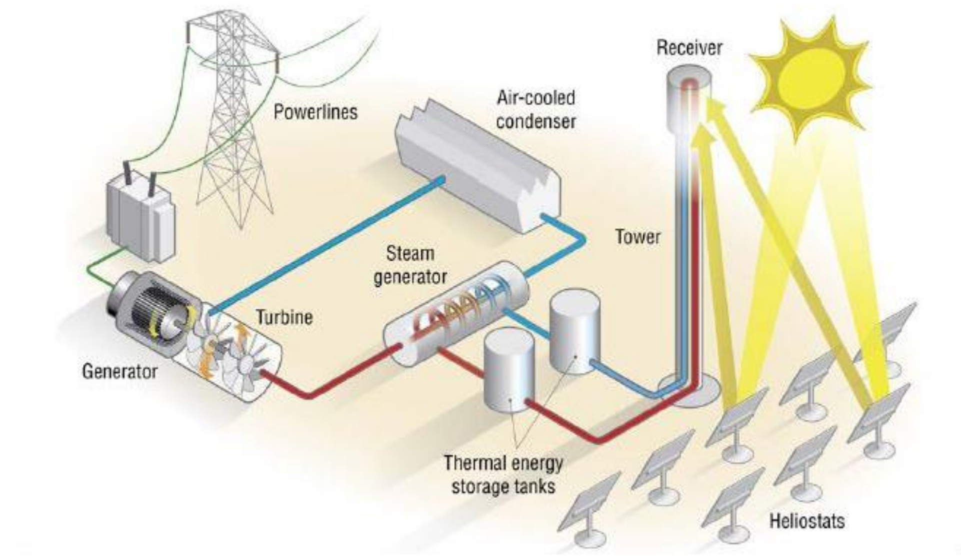


Fig 3.9. Solar power tower [18].

Fresnel reflector power plants are a combination of the solar power tower, as it uses small heliostats, and parabolic through power plants as the focus of the heliostats is directed towards a tube carrying some type of fuel. An example of such a plant is the Dhursar plant in the Jaisalmer district in India. Fig 3.10 shows the configuration of the plant in Dhursar. The plant has a capacity of 125megawatts and it is a steam Rankine output type [16] [17].

Fig. 3.10. Dhursar Fresnel reflector solar power plant [16].

3.7 Semiconductor and PN junction basics

Semiconductors are materials that are neither conductors, which have small resistance to electron flow, nor insulators, which have high resistance to electron flow, but rather something in-between. From the invention of the transistor at the 'Bell laboratories' in the United states researchers figured out that allowing certain impurities into the structure of the semiconductor greatly changes its electrical properties. This process was termed 'doping'.

Semiconductors usually have solid crystal lattices, meaning that every electron which is bounded into an atoms valence bond is also bounded by the neighbouring atom. An example of such a crystal lattice is from silicon and can be seen in Fig.3.11. Although there exist semiconductors with less rigid construction as we shall see later, still systems are put in place to revert back to a lattice structure to be able to create a PN junction.

Doping involves adding substances to a semiconductor with different atomic arrangements in such a way that additional electrons will not be bounded in the valance bonds or there will be 'holes' left as there weren't enough electrons in the doping material. Depending on the doping agent there are n-type and p-type semiconductors. N-type semiconductors have additional electrons while p-type semiconductors have additional holes, which is what is used to refer to the lack of electrons and this is still considered a charge carrier albeit a positive one.

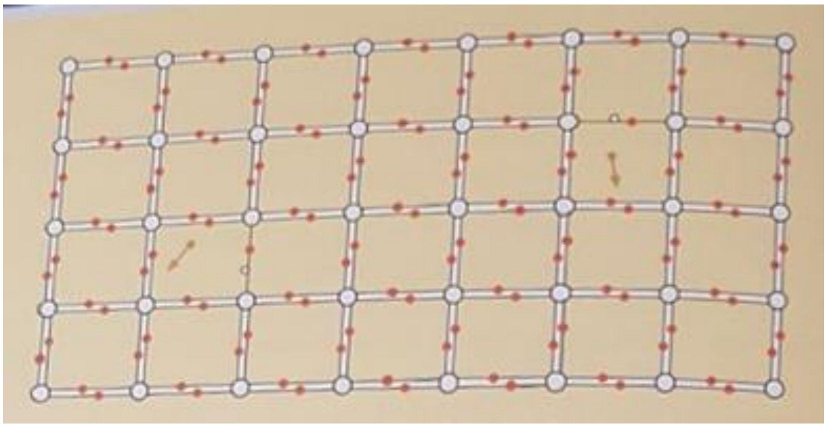


Fig. 3.11. Silicon lattice structure [1]. Where the full red dots signify the electrons and the hollow larger circles signify the nucleus of the atoms.

PN junctions are created by a strip of p-type and n-type semiconductors layered one on another. This creates a built-in electric field between the two strips. This is necessary as electrons that are struck by a photon create a free moving electron and leave a hole behind, if left without an electric field the electron might simply recombine with the hole after it loses its gained energy. A very good visual representation of this is show in Fig 3.12.

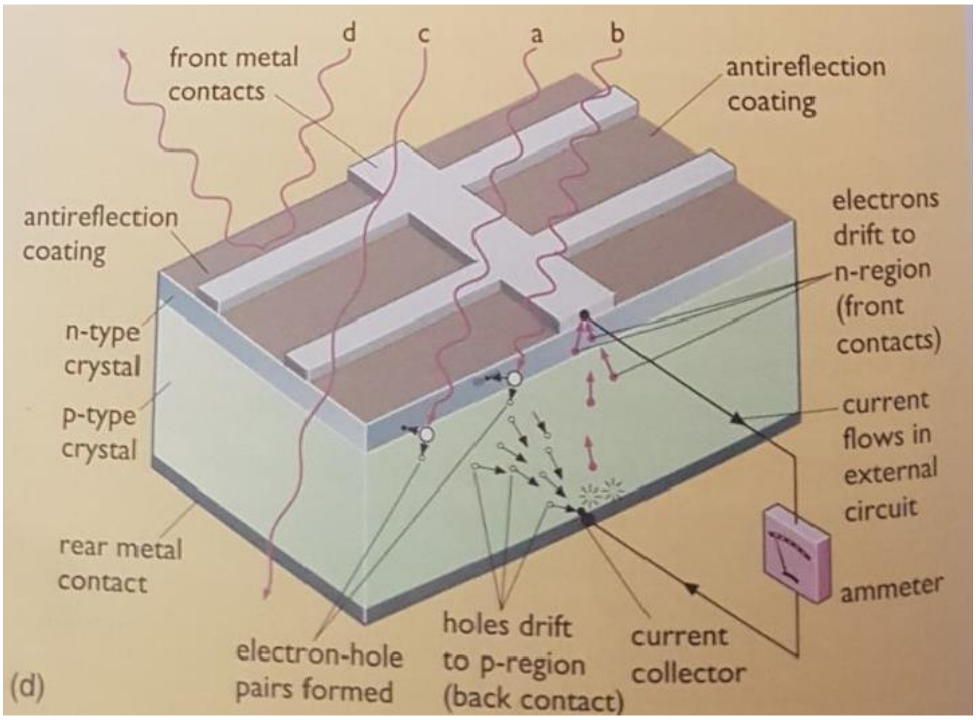


Fig 3.12. Visual representation of the PN junction in a silicon solar cell [1].

3.8 First generation of PV cells (Crystalline)

Photovoltaic cells using crystalline silicon were the first type of cells to be produced and researched. There are many types of photovoltaic cells that use a crystalline lattice in different ways, such as:

- Monocrystalline silicon
- Polycrystalline silicon
- Silicon ribbons
- Gallium arsenide monocrystalline

Monocrystalline silicon was one of the first types of cells to be commercially produced. The silicon was produced by the Czochlarski process which gave an extremely pure structure. However as monocrystalline silicon is widely used in electronics and also the process to create such high quality silicon is lengthy and requires skilled work the photovoltaic cells made from this material are expensive.

Polycrystalline silicon does not have a perfect lattice structure such as monocrystalline silicon. It basically has parts of monocrystalline silicon which are randomly packed. The technology used to produce polycrystalline silicon is cheaper and simpler than monocrystalline silicon [1]. However efficiency is still in favour of monocrystalline technology as can be seen in Fig.3.13 [19].

A silicon ribbon is merely polycrystalline silicon but the manufacturing process is different, creating very thin strips of polycrystalline silicon instead. Due to the ability to control the width of the thin ribbon of silicon and therefore being able to approximate the dimensions needed this process does not have as much waste as the previous two processes do. The other two processes require the sawing of the silicon ingots into the desired shapes which creates waste. This process is again cheaper than normal polycrystalline production but suffers with lower efficiency.

Gallium arsenide monocrystalline photovoltaic cells are very expensive as the components are not as readily available as silicon [1]. However these photovoltaics have better efficiencies than single junction silicon based photovoltaics, as well as having better behaviour under high temperatures which could degrade the efficiency [1],[19]. This combined with its high cost makes gallium arsenide photovoltaics very well suited for space applications, concentrating photovoltaics, which will discussed later, and multi-junction photovoltaics, which will also be discussed later.

3.9 Second generation of PV cells (Thin films)

One of the first types of thin film photovoltaic cells developed was the so called amorphous silicon photovoltaic cell. This type of cell does not have a crystal structure such as in the first generation cells, which means that atoms are not covalently bonded into lattices. However, the manufacturing process involves a gas 'Silane' mixed with hydrogen which bonds with the atoms instead. This mixture is doped and then applied onto a suitable substrate. The thickness of the mixture applied is usually in the range of nanometres or micrometres. However these cells have relatively low efficiency and they tend to degrade after a couple of months of use.

Other notable thin film technologies are the Cadmium telluride (CdTe) and the Copper indium gallium selenide (CIGS) PV cells. CdTe cells are the most prevalent of thin film technologies having 5% of the total world's capacity of photovoltaic cells [20]. These cells also have a comparable efficiency to the that of the polycrystalline silicon PV cells as can be seen in Fig 3.13. Due to stigma of having a toxic and non-green (cadmium) element make up these cells they aren't received well with the public.

The CIGS cells exhibit the best efficiency of all the thin film cells. This type of cells has 2% of total world's capacity of photovoltaic cells.

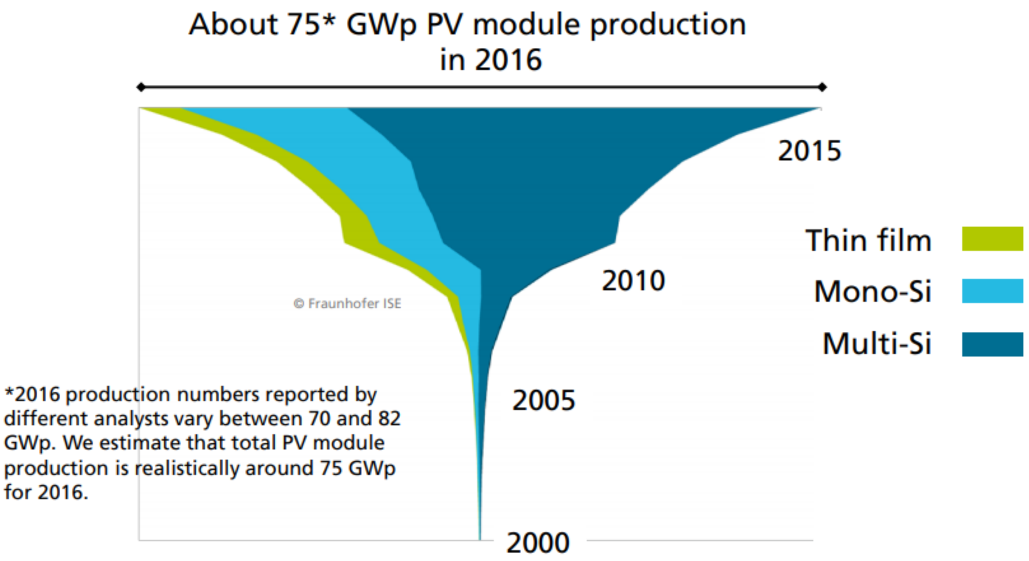


Fig 3.12. Annual PV production by technology worldwide (in GWp) [20].

3.10 Third generation of PV cells (upcoming technologies)

All the other developments in PV cells have been lumped together into the 3rd generation of PV cells; therefore the list of all the different types of technologies is quite long. The most prevalent technologies nowadays are the multi-junction and the concentrator cells. These technologies have been developing for quite some time now and commercial production has been already under way for some years now unlike the emerging PV cells in Fig 3.13.

Multi-junction cells are cells made from technologies already discussed in the previous two sections, such as amorphous silicon cells and gallium arsenide cells. The crucial difference between these technologies is that in multi-junction cells there are multiple PN or PiN junctions stacked on one another. Each different junction is calibrated in such a way to absorb a particular range of light while the next junction would be calibrated for a different range of light waves. This inceases overall efficiencies of PV cells by considerable amounts as can be seen in Fig 3.13. The way to calibrate the different junctions for different light wave frequencies is done by changing the dopants in such a way that changes the band gaps of the material [1].

Concentrating PV cells concentrate the incoming light radiation using mirrors and lenses onto smaller cells. Usually multi-junction cells are used as the small cells due to the high efficiencies. This type of photovoltaic cell has no production regarding residential purposes such as rooftop PV cells, but instead the main focus is on independent solar power plants [1]. Due to high light radiation concentrations the concentrating PV cells require cooling, usually in the form of passive heat sinks as active cooling systems would drastically decrease its efficiency. Another aspect of concentrating PV cells is that very little of diffuse light is able to produce electricity therefore tracking systems are needed as well as regular lens cleaning. This also affects the areas where concentrating PV cells are economically viable to be used. Only regions where high levels of direct radiation are commonplace is this type of PV cell viable (similar to the solar power towers).

Other emerging PV cell technologies such as organic, dye-sensitized, perovskite, CZTS and quantum dot cells are being researched and developed however without commercial production yet. The closest of these technologies for commercial production is the perovskite cells which have seen a huge increase in efficiency in the last several years.

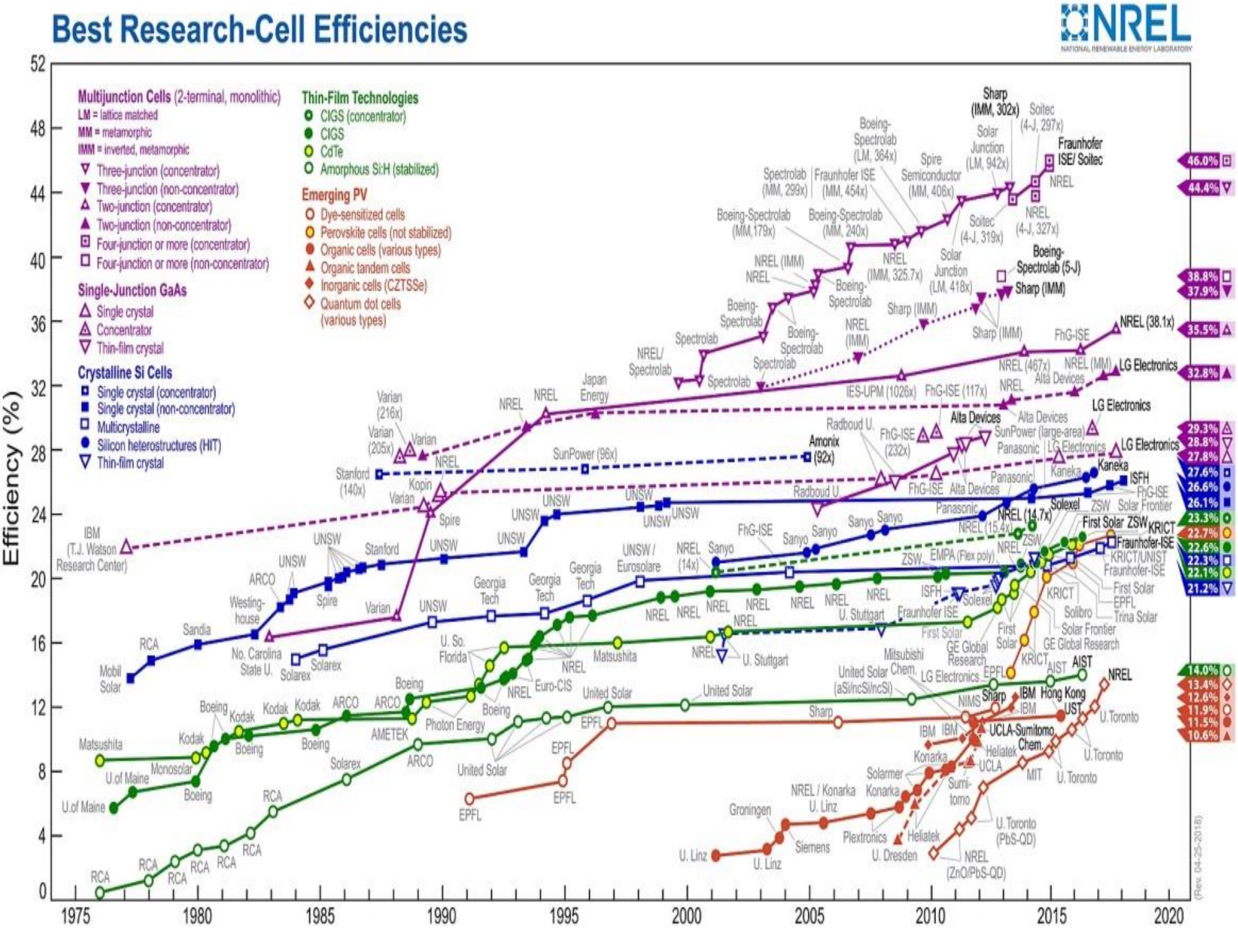


Fig 3.13. Efficiencies of different PV technologies [19].

3.11 Electrical characteristics of silicon PV cells

A conventional PV cell has an intrinsic voltage created by the PN junction which is usually around 0.5 volts. However current produced by the cell is related to the light radiation which varies during the day and with weather. This means that there is a maximal and a minimal current possible. When testing how the current affects the power and voltage a graph of the I-V characteristics is plotted as can be seen in Fig 3.14. This graph is plotted by varying the resistance a PV cell is under from 0 to infinity. From the graph it is easily shown where the point of maximal power is.

It is crucial for the efficiency of the cell to track this point of maximal power as current changes. Systems that enable this power tracking are usually done by DC to DC converters [7].

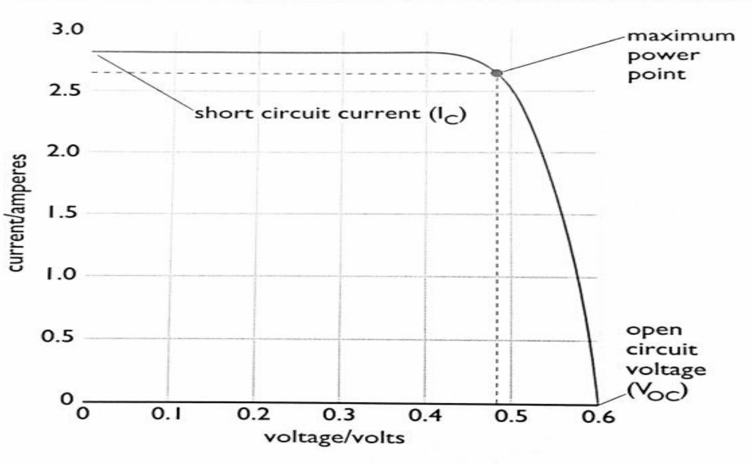


Fig 3.14. Estimated I-V characteristic of a PV cell [1]. Pg 84

3.12 Environmental impact

Photovoltaic systems of today have arguably the smallest environmental impact of any electricity producing plants regardless whether they are renewable or not. Very few of the photovoltaic arrays contain any toxic materials except the aforementioned CIGS and CdTe cells which would require a fire to release their toxins in any case. PV cells also have no moving parts which create no noise and are also relatively safe even for small animals. Sun tracking systems are moving much too slow to harm animals. The appearance of solar panels might be a cause for discussion however this is a subjective matter and varies from individual to individual. Some PV panels have been used as noise dampeners on railways and highways and therefore arguably decreasing the overall effect of the environmental impact [1].

Solar thermal systems have a larger effect on their environment, especially plants like the solar power towers. The amount of heat created by the mirrors may affect wildlife such as birds and insects. A bird has once been reported to have been killed in air as it flew in direct path of the reflecting mirrors.

Reports of this kind have been rare. Another consideration that must be taken into account is the potential interference with planes as well as interference with radio signals.

Both of the different solar systems require wide flat areas for operation. PV systems to supply power larger than 1000 megawatts usually require plants with sizes upwards of 20 kilometres squared.

As mentioned previously some high end solar panels are made of some rare and or toxic materials. This means that appropriate disposal of cells is quite important regards to not using up the finite rare materials and causing them to become more expensive as well as not harming the environment by realising toxic materials. The EU has conducted a thorough study of waste management back in 2011 and one can review his study in reference number [21]. The study concluded that it was necessary to have policies that regulate the recycle and waste management of solar cells. The EU directive WEEE has put the solar panel producers responsible for the recycling and waste management of solar cells.

3.13 Grid influence

It is a known issue with solar panels that it is an intermittent source, which means that they do not produce electricity at a stable rate. The time of day and weather affects the production. A popular theory for minimizing the effect this would have on the grid system is the geographical distribution of the solar panels so that weather in one area would be different than another as can be seen in Fig 3.15 below.

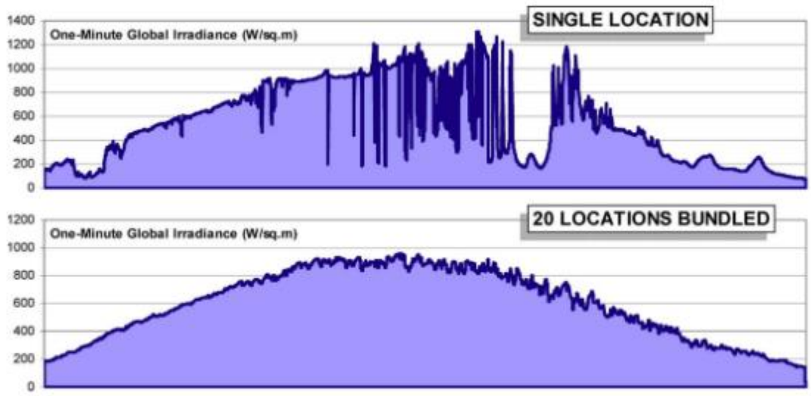


Fig 3.15. Solar irradiance over a single location vs 20 using the ARM (atmosphere radiation measurement program) [23].

Another viable option is the tracking of weather forecasts on a detailed scale using large amount of small data readers scattered around the desired area. This could help predict when production of electricity will peak and when it will decline giving other sources the chance to turn up or down their production.

Solar powered electricity production also has the ingrained disadvantage that when the sun is shining that’s the least time power is required. Clearly storage will play a crucial role to best utilize this energy in the time that there is requirement for it. The most prevalent storage options so far are lithium ion battery packs used mostly in PV systems or wind turbines while molten salt is used in solar thermal plants. Lithium ion battery packs are however quite expensive and their capacity is quite low. Molten salt can hold temperatures for a really long time; this means that power plants can produce electricity even when the sun isn’t shining. The amount of time depends on the amount of molten salt storage; it can vary from a couple of hours to all night production. Other technologies as hydrogen generation through electrolysis have seen a comeback in the recent few years. Hydrogen production is an attractive technology as it is pretty simple to divert excess electrical production as well as hydrogen being a fuel in itself. This means that a small hydrogen production chamber can be implemented in a residential property, such as the solar house in Freiburg Germany [24], while also having the option of large plants simply devoted to the production of hydrogen and using this as fuel.

In a milestone achievement solar power technology was the biggest power production technology to be installed in 2016 [22]. The total installed capacity for photovoltaic installations reached 303 gigawatts, increasing the installed capacity from 228 gigawatts in 2015. Solar thermal technology has seen small rise having only a total installed capacity of 4.8 gigawatts at the end of 2016 [22]. Solar PV systems have produced 1.5% of the world’s total demand in 2016 with China currently leading the way with 125 gigawatts of installed capacity.

In 2001 a report done by the European PV industry association and Greenpeace estimated that by 2020 the total PV installed capacity would be just over 200 gigawatts [1]. As today’s figures show this milestone has already been achieved with over a 33% larger margin and 2020 is still 2 years away. This goes to show the improvement this technology has benefitted from simply from the public movement for a greener future. Evidence of improvement of renewables can also be seen in Fig.3.16 below, as the production of additional plants using fossil fuels start slowing down.

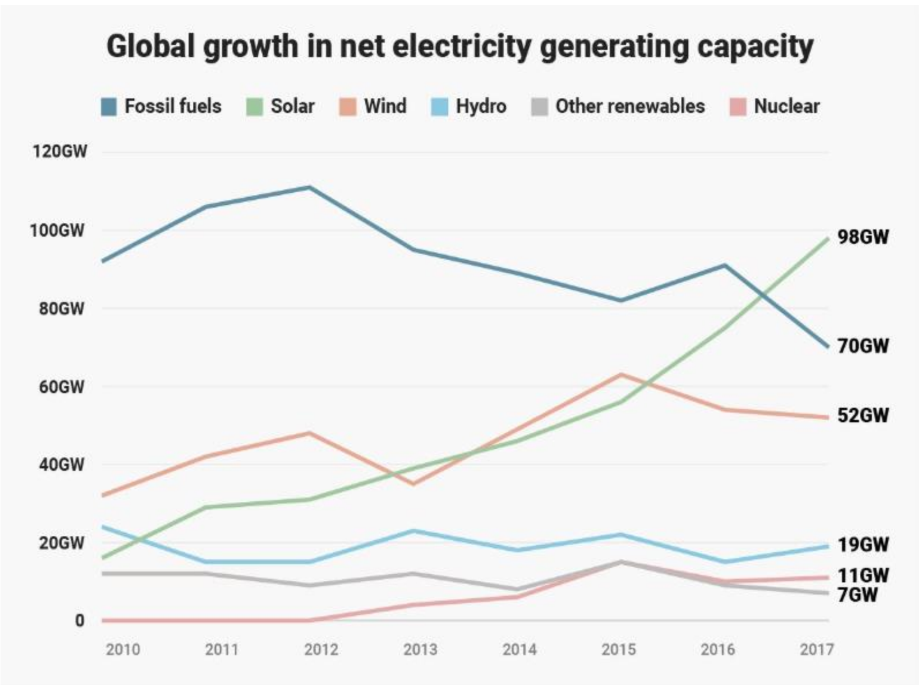


Fig 3.16. Global growth of different power sources [22], [27]. [28].

Chapter 4

Case study

4.1 Introduction

The case study involved the simulation of photovoltaic systems on a low voltage (0.4 kV) distribution line mixed in with consumers. This simulation tried to copy a real life scenario where some normal residential properties owned photovoltaic systems. The scenario involved a new block of residential homes on the outskirts of the city Nymburk in Czechia as shown in Fig.4.1 and Fig.4.2.

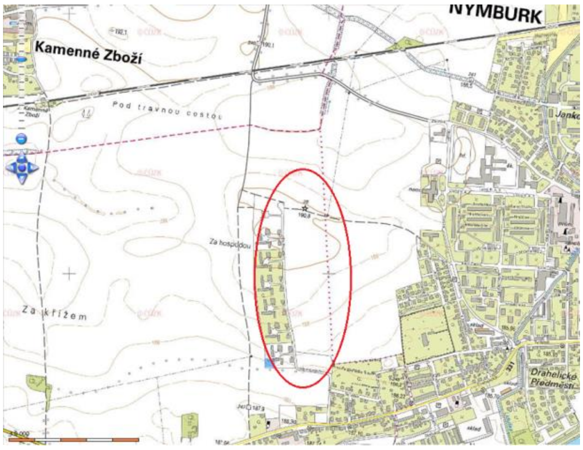


Fig.4.1 Outskirts of Nymburk

Fig.4.2. Plots for each consumer

The application used for the simulation was eVlivy. This application was best suited for our purpose as it had in its database equipment which is currently being used in the Czech Republic.

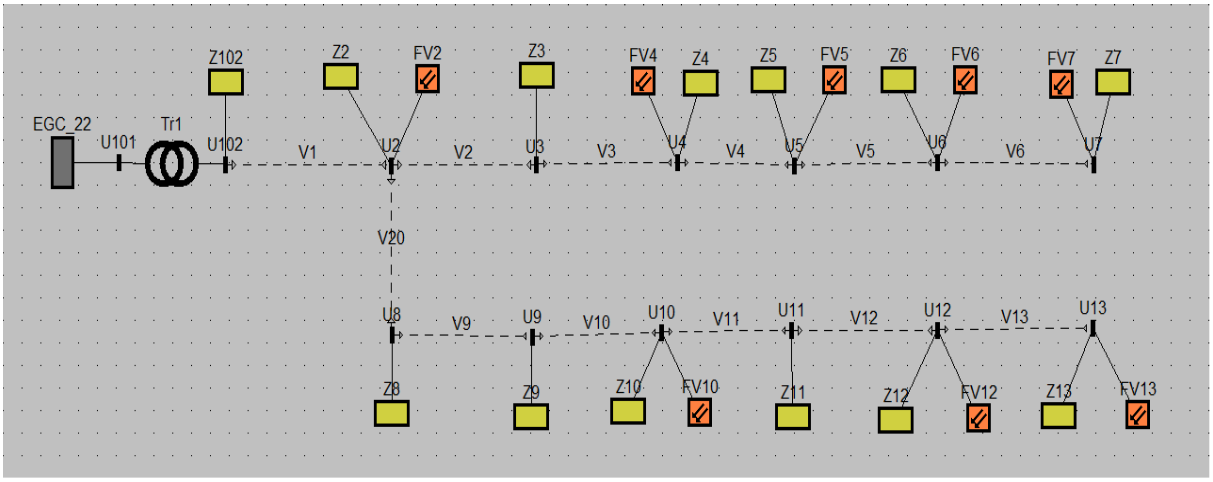


Fig 4.3. Outline of the low voltage line simulation

4.2 Criteria for grid connection by CEZ

There are many criteria for the connection of an electricity generating plant to the distribution grid. However most are out of the scope of our simulation and only the necessary ones will be mentioned. The main criteria for low voltage level distribution grids are the fluctuations in the voltage levels, namely the percentile difference in voltages throughout the day.

The difference between the nominal voltage and actual voltage at any point along the distribution line, at any time, must be within 10% of the nominal voltage. This criterion is specified by the EU CSN 50 160 standard. Nominal voltage in this case study is 400 V therefore the allowed voltage levels are +/- 10% of this voltage, which are 440 V and 360 V respectively.

$$10\% = +/- 40\ V$$

Another crucial criterion is the difference in voltage when switching electricity generating plants on and off. This criterion is specified by the Czech distribution grid code. This happens gradually with solar panels however disconnection or sudden coverage of the panel could still occur. This criterion is set to allow 3% difference in the nominal voltage between peak production and lowest production. In this case study the nominal is set as 400 V therefore the 3% difference would translate to a 16 V difference.

$$3\% = 16\ V$$

Other criteria such as long term flicker effects and current harmonics were not considered as generally they are not regarded as issues with small scale photovoltaic cells as their effects are minimal.

4.3 Properties of the tested simulation

Table 4.1. Parameters of lines V2-V13, V1:

Name of line	Nominal voltage. U_n[kV]	Cross-section [mm^2]	Max current [A]	R [Ω/km]	X [Ω /km]	B[µS/km]
50AYKY50	0.4	50	147	0.619	0.077	1

Table 4.2 Parameters of line V1

Name of line	Nominal voltage. U_n[kV]	Cross-section [mm^2]	Max current [A]	R [Ω /km]	X [Ω s/km]	B[µS/km]

120AYKY70	0.4	120	245	0.258	0.069	1

Distances of lines:

- V2,V3,V4,V5,V6,V7,V8,V9,V11,V12,V13 = 25 m.
- V20 = 100 m
- V1 = 50 m

Table 4.3. Parameters of transformer:

Name on schematic	Primary voltage, U_n1 [kV]	Secondary voltage, U_n2 [kV]	Power, S [MVA]	Pk [kW]	uk [%]
Tr1	22	0.4	0.4	4.6	4

4.4 Parameters of the different modes of operation

The goal of this case study was to conclude whether or not the simulation of a possible real life distribution connection would satisfy the criteria set by the Czech utility providers CEZ. Therefore the two worst case scenarios must be considered, which are: the excessive production of electricity with little to no consumption and the case of no production by the panels but high consumption rates. These cases would translate to real life scenarios of production at noon when little electricity is needed and night time when no production by the solar panels is generated. The results will be shown in tables 4.5 and 4.6.

To understand best the different cases a control simulation must first be tried out. This means that electricity production would perfectly equal the consumption and therefore creating an ideal balance. The results are shown in the table 4.4.

*note: Z102 represents other residential blocks connected to the same transformer.

Table 4.4. Ideal consumption vs production:

Name of consumer on schematic	S [kVA]	Name of photovoltaic cell on schematic	S [kVA]
Z102	30		
Z2	3	FV2	3
Z3	2		
Z4	4	FV4	4
Z5	5	FV5	5
Z6	5	FV6	5
Z7	4.5	FV7	4.5
Z8	5		
Z9	3		
Z10	4	FV10	4
Z11	2		
Z12	4	FV12	4
Z13	3	FV13	3

Table 4.5. No PV production and large consumption:

Name of consumer on schematic	S [kVA]	Name of photovoltaic cell on schematic	S [kVA]
Z102	100		
Z2	5	FV2	0
Z3	6		
Z4	4	FV4	0
Z5	6	FV5	0
Z6	6	FV6	0
Z7	8	FV7	0
Z8	5		
Z9	6		
Z10	6	FV10	0
Z11	4		
Z12	5	FV12	0
Z13	7	FV13	0

Table 4.6. Excessive PV production and little to no consumption:

Name of consumer on schematic	S [kVA]	Name of photovoltaic cell on schematic	S [kVA]
Z102	10		
Z2	0.25	FV2	5
Z3	0.15		
Z4	0.3	FV4	6
Z5	0.1	FV5	8
Z6	0.2	FV6	6
Z7	0.1	FV7	7
Z8	0.4		
Z9	0.3		
Z10	0.1	FV10	6
Z11	0.2		
Z12	0.4	FV12	6
Z13	0.3	FV13	8

4.5 Simulation results and conclusions

Table 4.7. Case of ideal consumption:

Name of node on schematic	U [kV]	Difference between nominal and actual voltage [%]
U101	22.987	
U102	0.418	4.5
U2	0.418	4.5
U3	0.417	4.25
U4	0.417	4.25
U5	0.417	4.25
U6	0.417	4.25
U7	0.417	4.25
U8	0.417	4.25
U9	0.417	4.25

U10	0.417	4.25
U11	0.417	4.25
U12	0.417	4.25
U13	0.417	4.25

Table 4.8. Case of no PV production and large consumption (evening):

Name of node on schematic	U [kV]	Difference between nominal and actual voltage [%]
U101	22.948	
U102	0.415	3.75
U2	0.413	3.25
U3	0.412	3
U4	0.411	2.75
U5	0.41	2.5
U6	0.41	2.5
U7	0.41	2.5
U8	0.408	2
U9	0.407	1.75
U10	0.406	1.5
U11	0.406	1.5
U12	0.405	1.25
U13	0.405	1.25

Table 4.9. Case of too much PV production and little consumption (noon):

Name of node on schematic	U [kV]	Difference between nominal and actual voltage [%]
U101	23.011	
U102	0.419	4.75
U2	0.42	5
U3	0.421	5.25
U4	0.422	5.5

U5	0.423	5.75
U6	0.423	5.75
U7	0.424	6
U8	0.423	5.75
U9	0.424	6
U10	0.424	6
U11	0.425	6.25
U12	0.425	6.25
U13	0.426	6.5

Table 4.10. Percentile difference between evening and noon:

Name of node on schematic	Difference between nominal and actual voltage [%]
U101	
U102	1
U2	1.75
U3	2.25
U4	2.75
U5	3.25
U6	3.25
U7	3.5
U8	3.75
U9	4.25
U10	4.5
U11	4.75
U12	5
U13	5.25

The resulting graphs of voltages from tables 4.8 and 4.9:

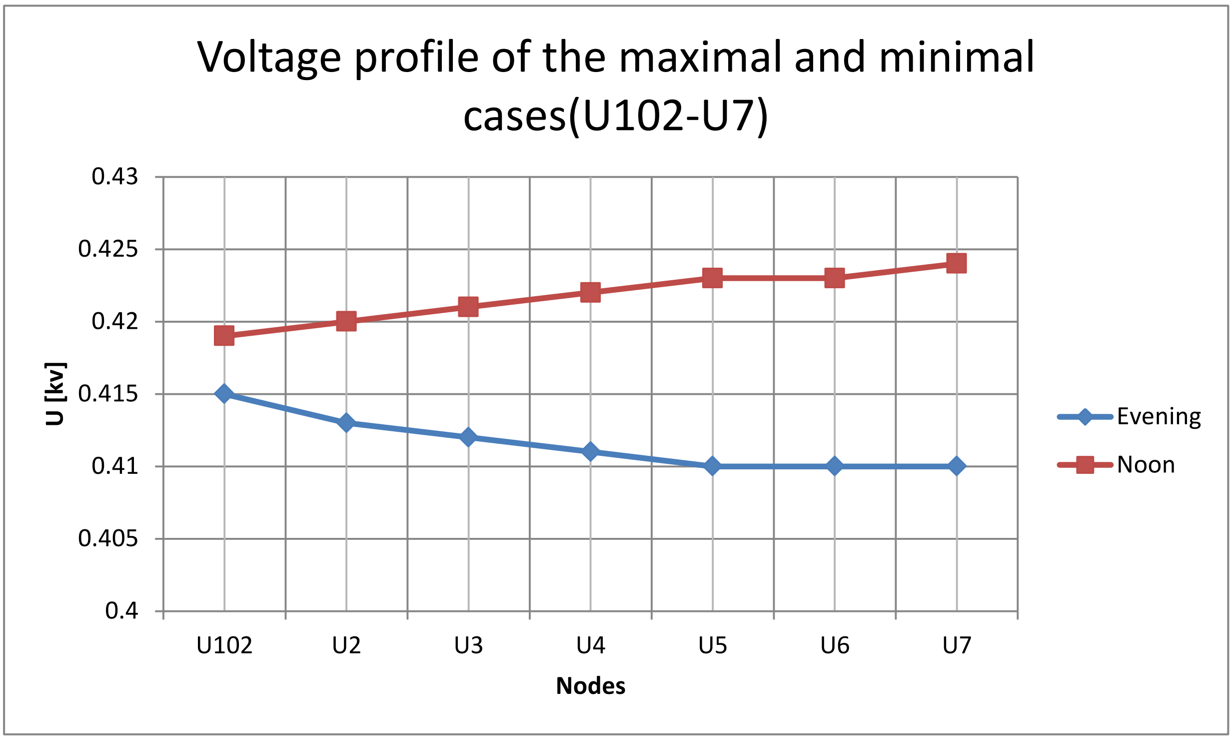


Fig 4.4. Voltage profile graph (U102-U7)

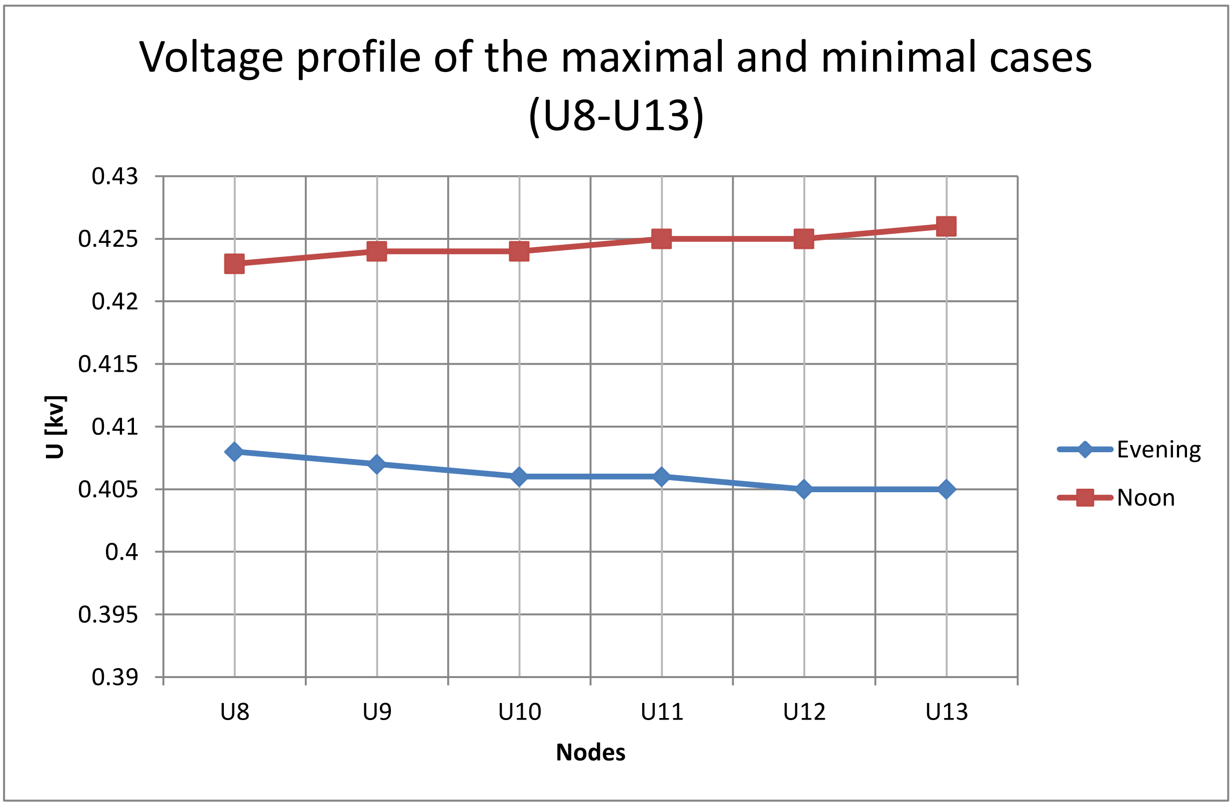


Fig 4.5. Voltage profile graph (U8-U13)

Discussion on results:

As can be seen in Fig.4.4, and the corresponding tables, the simulated scenario did hold to one criterion but failed to meet the other. The voltage levels in any node never went 10% above or below the nominal voltage according to the standard EU CSN 50 160, however the voltage levels in some nodes between the two cases of noon and evening have a difference in voltage larger than 3%, according to the Czech distribution grid code.

This result would have had an even larger margin if the consumer Z102 also had photovoltaic cells that produced power, instead of simply averaging the consumption. The fact that our simulation did not hold within the criteria set by the utility distributor CEZ gives reason for research into other technologies which could resolve the issues.

Auto regulating transformers may resolve the issues posed in this simulation. FITformer® REG by the company Siemens is a transformer which reads the voltage levels of the lines and adjusts the voltage difference automatically [25]. The company Maschinenfabrik Reinhausen also developed products such as the ECOTAP VPD which is a tap-charger used as an add-on for a fixed transformer to convert it to an auto regulating transformer [26].

Chapter 5

Conclusions

The presented thesis had 4 guidelines:

1. General overview of renewable energy sources
2. Focus on solar applications
3. Integration of renewable energy sources to distribution network
4. A case study for connection of the photovoltaics power plants to distribution network

The three renewable sources of wind, solar and hydro power were chosen for having the biggest penetration on the grid globally and having the biggest increase in capacity over the last few years. These renewable sources were described from a technical point of view as well as describing the physics behind them in detail. Environmental impact and impact on the grid was covered for every renewable energy source. Great detail has been given to solar power applications as this technology has seen the largest growth in the last few years as well as being the main point in the case study. Renewable technologies have seen a great increase of investment in the last few years and the trend does not seem like it is stopping any time soon. The EU is especially driven to increase the amount of renewables to decrease pollution and become independent from fossil fuels.

In the Czech Republic subsidies for small photovoltaic cells are available, however there are certain restrictions as the PV cells must be combined with other measures such as improving the overall energy output of a building or company [29]. The reason for only small subsidies is connected with the Czech Republic already reaching its intended national goal of PV installed capacity of 1695 MW in 2010. Since then the PV market has seen slow progress. Total PV capacity in 2016 in the Czech Republic was 2.08 GW [30].

With pressure from the EU and its policies to encourage renewable energies Czech Republic might eventually give larger subsidies. In every country so far, in the EU, that has established subsidies for small PV plants the amount of PV systems grew exponentially. If that is the case a good understanding of the behaviour of such generation is required in order not to destabilize the grid and/or damage it.

The case study sought to recreate a real life scenario and to study the effects of what many renewable energy sceptics are afraid of, the intermittent nature of the renewables causing issues for the grid. The case study was limited to studying only one block of houses and a multi block case study would give much clearer results. It was also discussed the possibility to control the issues created by the intermittent nature of photovoltaics by having auto regulating transformers and having better cabling.

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