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BAKALÁŘSKÁ PRÁCE
BACHELOR THESIS

Alternativní metody využití slunečního záření

Alternative Methods of Sunlight Use

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Zásady pro vypracování:

1. Zpracujte přehled možností výroby solární energie - koncentrací slunečního záření do ohniska pomocí parabolických zrcadel.
2. Posuďte kombinaci solárních zdrojů s využitím fotovoltaických článků apod.
3. Navrhněte aplikaci solárních energií na parní turbíny a nástin úprav parametrů daných turbín.
4. Vypracujte hodnocení využití zdrojů solární energie z geografického hlediska.
5. Proveďte základní technicko-ekonomické hodnocení.

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Abstrakt

Tato bakalářská práce se věnuje metodám využití slunečního záření a popisu technologií, které umožňují přeměnit solární energii na elektřinu. Jejím cílem je navrhnout optimální řešení pro různé typy solárních elektráren s ohledem na jejich spolehlivost. Práce zároveň zvažuje pravděpodobnost budoucí expanze solárních elektráren o nezanedbatelných výkonech, především vežové nebo parkové technologie. Jsou zde také řešeny základní parametry parních turbín využívaných v těchto typech solárních elektráren.

Na základě vlastností již fungujících elektráren fotovoltaického, věžového a parkového typu a na základě výpočtů provedených solárními kalkulačkami byly zhodnoceny a v závěru porovnány dané technologie z hlediska geografického využití, energetického přínosu do přenosových energetických soustav a z hlediska ekonomické návratnosti.

Klíčová slova

solární energie, fotovoltaický jev, koncentrovaná solární energie, věžová solární elektrárna, parková solární elektrárna, parní turbína, geografický, energetický, ekonomický

Abstract

This bachelor thesis is focused on alternative methods of sunlight use and a description of technologies which enable to transform solar energy to electricity. The aim of the thesis is to suggest an optimal solution for various solar power plants with respect to the reliability. The future expansion probability of the cost−effective solar power plants is discussed in this thesis as well, especially the tower and parabolic trough technology. Moreover, the basic features of steam turbines which are utilized in concentrated solar power plants are delineated here. These technologies have been evaluated and compared from the geographical, energetic and economical point of view with respect to the already operational photovoltaic, parabolic trough and tower solar power plants. For the evaluation and comparison the solar calculator and solar maps have been utilized as well.

Keywords

solar energy, photovoltaic phenomenon, concentrated solar power, tower solar power plant, parabolic trough solar power plant, steam turbine, geographical, energetic, economical

Prohlášení

Na závěr studia na Fakultě elektrotechnické Západočeské univerzity v Plzni tímto předkládám k posouzení a obhajobě bakalářskou práci na téma Alternativní metody využití slunečního záření.

Prohlašuji, že jsem bakalářskou práci zpracovala sama s využitím odborné literatury a na základě odborných konzultací s vedoucími pracovníky mezinárodní společnosti Doosan Škoda Power.

V Plzni, 2. června, 2016

Markéta Bulínová

. . . .

Podpis

Poděkování

Tímto bych ráda poděkovala vedoucímu bakalářské práce Ing. Václavu Mužíkovi za cenné rady, metodické vedení a čas strávený konzultacemi.

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List of Symbols

E_g [eV]/[J]	Band gap energy
K	Kelvin
km/s	Kilometer per Second
mA	Miliamper
cm^2	Square Centimeter
mm	Milimeter
μm	Micrometer
mc−Si	Multi−crystalline Silicon
η	Efficiency
MPa	Megapascal
$^\circ C$	Degrees Celsius
kW	Kilowatt

List of Abbreviations

PVE	**P**hoto**v**oltaic **E**nergy
PV	**P**hoto**v**oltaic
PVC	**P**hoto**v**oltaic **C**ell
CIS	**C**opper−**I**ndium−**S**elenium
PVS	**P**hoto**v**oltaic **S**ystem
AC	**A**lternating **C**urrent
CSP	**C**oncentrated **S**olar **P**ower
PM	**P**arabolic **M**irror
TSPP	**T**ower **S**olar **P**ower **P**lant
PT	**P**arabolic **T**rough
PD	**P**arabolic **D**ish
HTF	**H**eat **T**ransfer **F**luid
PTR	**P**arabolic **T**rough **R**eceiver
ST	**S**team **T**urbine
RMS	**R**emote **M**onitoring **S**ystem
NREL	**N**ational **R**enewable **E**nergy **L**aboratory
JRC	**J**oint **R**esearch **C**entre
HP	**H**igh **P**ressure

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Introduction

For last few centuries the development of new technologies and the progress of humankind from the living standard point of view have been increasing rapidly. For keeping this established feature even in the future, main sources which allow us to continue developing and help us to keep our standard of living, must be retained. The solution of this problem is to keep these sources. All modern technologies which have been developed recently and which are considered to be necessary for living in the 21^{st} century would be nothing but empty boxes without one simple thing – electrical energy. But what would happen if there were no sources which enable us to create electricity anymore?

The problem comes with the word $'$non – renewable$'$, because many sources which are utilized for electricity generating are classified in this category. One day, which may not be so far from today, there might be none of these resources available. Now it is the era of renewable resources – sunlight, wind, water and biomass. The largest progress in the group of renewable sources has been happening with the development of solar energy.

In the world of solar energy there are, of course, well–known photovoltaic technologies, but moreover, there are new technologies for creating electricity which have been developed recently. Nowadays, sunlight can be used to run a steam turbine supplying electrical energy of sufficient output which can be distributed to power whole cities. These technologies use the principle of concentrating solar power by variously shaped heliostats into one receiver. Through this receiver a fluid of a convenient quality flows and receives the heat from the reflected sunlight. The absorbed heat can be stored for even tens of hours in thermal storages so that it could be utilized to transform water to water steam which runs a steam turbine even during nights or cloudy days.

In this thesis the photovoltaic and concentrated solar technologies will be described and evaluated in English, because it is the most common business language utilized in the contracting company Doosan Škoda Power. At first, the most suitable materials and manufacturing technologies for photovoltaic panel production will be introduced. After that, some applications using photovoltaic phenomenon or the combination of solar with another energy source will be depicted. Then the introduction of concentrated solar power will be performed, including a description of individual components in the solar plant. Eventually, the economical, geographical and energetic balance of every single technology will be presented.

Chapter 1

Photovoltaic Energy (PVE)

An idea of further solar energy utilization comes with the problems of non−renewable resources decrease. The sun is the most stable source and it is also the main condition of living on the Earth. Its surface temperature is 5 770 K and it is a continuous source of electromagnetic waves with the speed of 300 000 km/s in vacuum. [1] These waves are usually in a heat or light form. From this fact it is clear that the sun does not need to be extracted because the sunlight is everywhere on the Earth. Its service life is calculated to be about 5 million years, so we can consider it as a renewable source. Furthermore, it does not cause any pollution. With these qualities it seems to be a perfect solution.

The qualities of the sun as an energy source and the obvious advantages of solar energy utilization have caused that many researches in this field have been accomplished. These researches led to the discovery of photovoltaic phenomenon which is closely connected with the qualities of semiconductor materials. Its roots reach to 19^{th} century. In 1839 Alexander Edmond Becquerel found out that dropping sunlight at two platinum electrodes separated from each other by a porous wall causes the existence of voltage between these electrodes. This voltage was proofed by connecting a galvanometer to separated electrodes. It was the first time when solar energy was directly converted to electricity, although the reason of voltage existence between these two electrodes had been unknown. In 1904 Albert Einstein explained the photovoltaic phenomenon and in the year of 1921 he was awarded Nobel Prize for it. Albert Einstein and Max Planck came out with a quantum theory which dealt with the form of electromagnetic radiation as a $'stream'$ of energy particles. Einstein found out that these little particles contained in sunlight transmit their energy to electrons in the valance band of a semiconductor material so that the electrons can leap to the conductive band over the band gap. He called these little particles photons and defined them as the smallest and further inseparable amount of solar energy. Photons do not contain any electrical charge and so neither electrical nor magnetic field affects them. [2]

1.1 Physics of Semiconductor Materials

The photovoltaic electrical energy production is based on the technical knowledge of semiconductor physics. [3] As mentioned above the semiconductors have got the ability to convert light to electricity directly. No other technologies which will be described in this thesis are based on direct solar energy–electricity transformation.

1.1.1 Brief Introduction to Physics of Particles

All materials in the world can be divided into smaller particles which are called atoms. Until the 19^{th} century atoms had been considered as the smallest and further indivisible particles, but then in 1897 Joseph J. Thomson changed this conception. He discovered that even smaller particles existed and called them electrons. J.J.Thomson also realized that electrons contained negative charge and atoms, in the standard conditions, were neutral. That led him to an idea that there must be also some positively charged particles – protons. He constructed the first atomic model where protons were spread over the total atom volume and electrons were placed in the protons like 'raisins in pudding'. Thomson also knew that electrons took a very small part in the total atom weight and considering protons as the widespread 'pudding' explained why protons were so heavy. [4, 5]

Nevertheless, Thomson's model was corrected by the discovery of the atom nucleus by Ernest Rutherford in 1911. Rutherford found out that the positive charge was actually located in a very small part of the atom – nucleus, not spread all over the atom volume as Thomson had assumed. Nowadays it is certain that nucleus takes a very small but also the heaviest part of the whole atom. Rutherford introduced the second atomic model – Planetary model. He believed that electrons circle around the nucleus as planets around the sun. [5]

In the year of 1913 Danish physicist Niels Bohr compiled, in that time third, model of atom where electrons circled around the atom nucleus on in advanced defined quantum tracks – orbits. This model was considered as a very sufficient one comparing to the two previous models, which had not described the reality completely. [5, 6]

This is a very short and incomplete description of existing particles we can cooperate with, but the quantum physics is so difficult and extensive, that many theses and discoveries have been accomplished. For the aim of this work the above written description may be sufficient. The Niels Bohr's atomic model is shown in Fig. 1.1.

The most important discovery for photovoltaic systems was the existence of orbits described by Niels Bohr. Orbit is a place, where electrons appear the most probably. These orbits are characterized by energy levels. Each orbit has a different energy level than the others. Electrons in the atom's shell leap between the orbits and cause the energy emission or energy absorption. If electrons leap from an orbit with a higher energetic level to an orbit with a lower energetic level, it leads to electrical energy emission and on the contrary, the energy absorption happens. [4, 7]

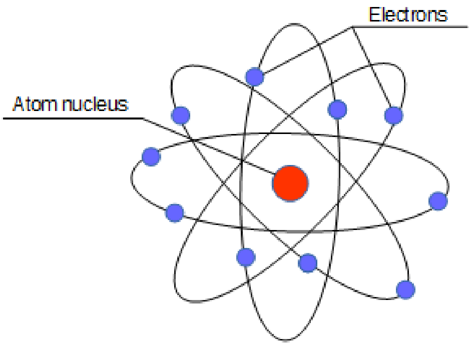

Figure 1.1: Bohr's model of atom [8]

From this rule it is clear that some energy must be absorbed so that electrons could leap to the orbit with a higher energetic level. The amount of needed energy is defined by the width of the band gap of every material. The width of a band gap can be considered as energy E_g needed for introducing a material into a conductive state and is indicated in electron volts (eV). One eV is equal to 1.6×10^{-19} J and it can be also described as an amount of energy needed to move one electron through a potential of one volt. Every material can be described by three various bands - a conductive band, a valence band and as mentioned above the band gap. [7, 9, 10]

With respect to the width of a band gap every material can be divided into one of the following sections – conductive materials, semiconductors and insulating materials. The main structure difference between these materials is shown in Fig. 1.2. [10]

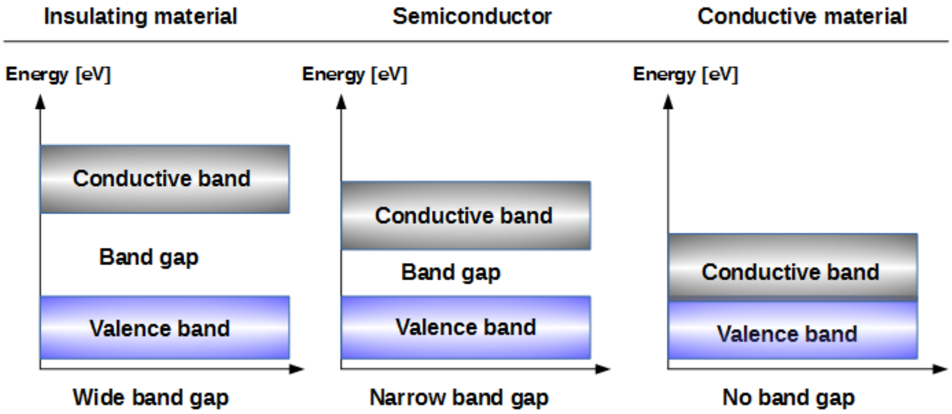

Figure 1.2: Energy bands of various quality materials [10]

Conductors are defined by their ability to lead electrical current. On the contrary, insulating materials do not lead electrical current at all, unless they are destroyed. The semiconductors have got the advantage of ability to create electrical energy only in some specific conditions. The width of a conductor band gap is smaller than 0.1 eV, which means that electrons take place in the conductive band. Insulating material band gap width is bigger than 3 eV, which causes filling the valence band with electrons. Semiconductor materials are defined by the band gap width between 0.1 eV and 3 eV. The band gap width can be also described as binding energy which is an amount of energy that enables to move electrons between various orbits. [4, 9]

When electrons in a valence band gain a sufficient amount of energy, they leap over the band gap to the conductive band. The resistivity of the semiconductor drops exponentially and it gets to a conductive state. Semiconductors can be divided into several groups. The first division is to single element semiconductors and compound semiconductors. Semiconductor materials which are composed of only one single element are for example silicon, germanium, carbon, selenium, tellurium, etc. The composed semiconductors are usually made of two and more elements from various groups of Mendeleev's periodic table of chemical elements. The possible compound semiconductors are Cu_2O, PbS, CdS, $PbTe$ and many others [1].

1.1.2 Materials and Technologies in Photovoltaic (PV) Industry

Photovoltaic cells (PVC) consitute the basic elements for sunlight transformation into electricity. They are large scale semiconductor components with at least one p–n junction. The front part of the PVC is constructed so that it could absorb sunlight effectively. If the dropping solar energy is large enough, the interaction with PVC happens and the binding electrons are released and the couple electron – hole is formed. Then the couple is separated because of the inbuilt electrical field of p–n junction and electrical voltage in the PVC can be measured (only tenths of volts). When the PVC is connected in a closed circuit, an electrical current flows. The amount of current is based on a PVC surface and an intensity of dropping sunlight. The amount of current is at about tens mA/cm^2. [1]

One PVC creates a very small amount of electrical energy, so in practice the photovoltaic cells are connected together in a serial link to create photovoltaic panels/modules. One PV panel is usually made from 33 to 36 photovoltaic cells which are placed in a frame for increasing the mechanical strength and rigidity. The frame is usually produced from aluminium or stainless steel and it also serves as a structural piece for installation on walls, roofs, etc.. The front side of the PVC is protected by glass which may content a small amount of iron. [1, 11]

The first photovoltaic cells were composed of Cu_2O or selenium, but the efficiency of solar energy to electricity conversion was about 1 %. Silicon and other semiconductor materials, such as $CdTe$, $GaAs$, InP, $AlSb$, etc., were used in photovoltaic industry for the first time in 1954 [1].

In Fig. 1.3 there are represented the examples of the most suitable materials for PV industry. [11].

During last few decades many developments in the field of semiconductor materials for photovoltaic applications have been accomplished and various technologies for PV panel manufacturing have been determined for specific materials. The main subject of these researches is to develop new materials and manufacture technologies with the highest efficiency and lowest cost.

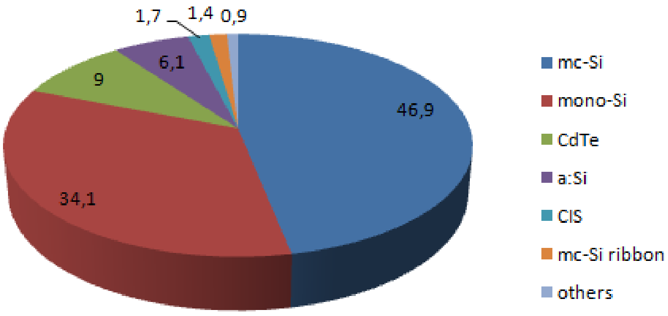

Figure 1.3: Materials for PVC production [11]

It can be seen in Fig. 1.3 that the commanding position in PV industry has got the crystalline silicon currently and semiconductor materials in thin–film condition (such as amorphous silicon, amorphous silicon – germanium), $CdTe$ and materials like CIS – $CuInSe_2$, $CuIn_xGa_{x-1}Se_2$), take the second place. According to literature crystalline silicon was used from 82.4 % for PVC production in 2009. Crystalline silicon can be in a form of mono–crystalline silicon (mono–Si), multi–crystalline silicon (mc–Si) or string ribbon silicon (a type of multi–crystalline silicon). [11]

At the beginning of PVC production mono–crystalline silicon took the biggest part. The cleanliness of this silicon had to be about 99.999 %. Boards with dimensions about 200 * 200 mm were cut from the manufactured mono–crystal, one board matched to one PVC. The semiconductor boards were covered by metal contacts and an anti–reflective layer. [1, 11]

The efficiency of mono–crystalline silicon is around 33 % in ideal (laboratory) conditions. However, the production of mono–crystalline PVC is very expensive and energy challenging, so cheaper technologies have been searched. The first PVC made of multi–crystalline silicon (mc–Si) was created in 1981. The mc–Si PVCs are manufactured by control solidification of melted silicon which is much cheaper than mono–Si manufacture, because there are not so high requirements for the cleanliness of input materials. However, the efficiency drops rapidly due to the losses on the edges of the nucleus. [1, 11]

The thin–film PVC is based on the ability of some materials (amorphous silicon, amorphous silicon - germanium, etc.) to absorb a lot of intensity from the sun even in very thin layers. The thickness of thin–film PVC is in μm. The production technology of thin–film PVC must enable to create very thin layers with high efficiency of photovoltaic energy conversion and high stability of the layer. This technology does not create single cells but entire photovoltaic panels. [11]

The main reason why silicon has got the dominate position in the photovoltaic industry is that its width of a band gap is very narrow. The width of mono – crystalline silicon band gap is only 1.12 eV. The optimal band gap width for a solar spectrum is around 1.4 eV. Due to this advantage a smaller amount of solar energy is needed for electron leaping and the photovoltaic cell becomes more efficient than solar cells made from a different material. Some admixtures can be sometimes added for increasing the regarded qualities. They can for example help to extend the service life of the PVC, increase the conductivity, etc. The service life of mono–crystalline PVC is at about 15 to 20 years. [1]

1.2 Photovoltaic Systems (PVS)

Photovoltaic systems may be divided into three sections – autonomous, hybrid and directly connected to the electrical grid.

The autonomous PVS has got no connection to the electrical grid. Instead of the grid, it uses batteries to store electrical energy. This variation is usually applied in locations where the public distribution grid is not available. The power output must not be too big, so that the capacity of the batteries could store it or so it could be immediately consumed. The produced energy by autonomous PVS might power for example the security and telecommunication systems or it can serve for the water pumping, etc. The block diagram in Fig. 1.4 typifies the autonomous photovoltaic system. [3]

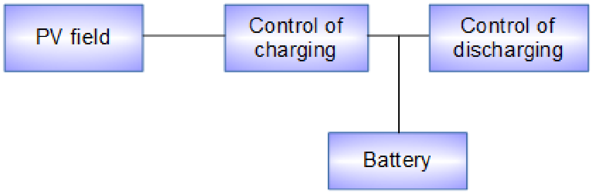

Figure 1.4: Block diagram of autonomous PV system [3]

The hybrid PVS includes the photovoltaic panels, one or more auxiliary generators and one or more batteries. Hybrid systems require more demanding regulators and control features which optimize the complete properties utilization of every single source. Every single feature must be very reliable even in long term working mode. For the block diagram refer to Fig. 1.5. [3]

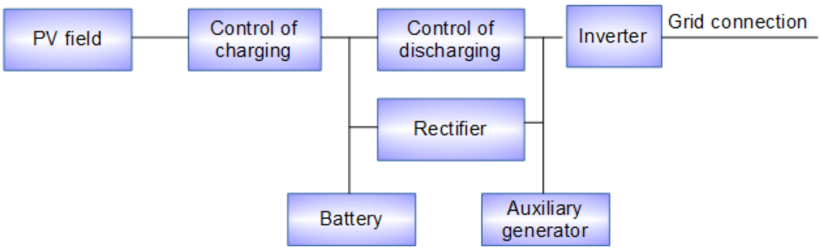

Figure 1.5: Block diagram of hybrid PV system [3]

The direct connection with the electrical grid of the PVS usually does not need the battery because it transmits the surplus electricity to the distribution grid. The voltage inverter must be modified so that it could run in the entire range of voltage provided by the PV panels. The most simple PV system of this modification usually includes only the PV panels and the inverter. The high voltage systems (the AC voltage higher than 230/400 V) must contain a transformer, high–output switches and some security features. There is a high need of harmonic filtration and correction of phases when using the system directly connected to the grid. Refer to Fig. 1.6 for the block diagram. [3]

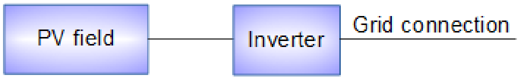

Figure 1.6: Block diagram of direct distribution grid connected PV system [3]

1.3 Applications Using PV Technology

Photovoltaic energy may be utilized in various applications which can exploit from the semiconductor characteristic qualities. The basic and most well–known application of PV technology seems to be the photovoltaic fields and PV panels utilization for powering a house. In these cases the photovoltaic cells create photovoltaic panels which are mounted on a roof (house power application) or at some mechanical assembly which is resistant to the ambient conditions (wind, frost, etc.) and placed at some southern fields. The photovoltaic panels usually take place at some south oriented fields or roofs so that the efficiency would get as high as possible. [3]

The electrical energy produced by the photovoltaic panels is used for water heating very often. [3] The combination of PV technology with another energy source induces the consideration of using PV panels for electrical energy production which could be used for water heating while at the same time the water tank made from a highly absorbing material would be exposed to the solar radiation. Then the thermal energy of the sun would be used for direct heating of water and all at once the green energy could warm the necessary remain.

The hybrid photovoltaic–thermal collectors create electricity by photovoltaic phenomenon and also the redundant heat which is formed by the dropping sunlight on the PV panel is led out of the panel by a cooling medium and this heat may be used for heating water, houses, etc.. The cooling medium may be liquid or gas (air mainly). [12]

The easiest photovoltaic application is to connect the PV cell or panel directly to an appliance. In some cases there may be a little battery placed between the appliance and the PV module, so that the device has some stored energy and can run even when the sunlight amount is not sufficient enough. The appliances which use this technology are for example calculators, children's toys, etc. [4]

Another application where photovoltaic phenomenon might be utilized is an optoelectronic converter. In this case, the dropping sunlight transmits its energy to semiconductor and according to the amount of released electrons the original picture can be reconstructed. The optoelectronic converters are the basic elements of camera systems. The advantage of this application is that only a very small area of photovoltaic material is required. It means that the semiconductor materials such as germanium or gallium might by utilized to increase the efficiency in the case of optoelectronic convertors. Even though these materials are very expensive and there has not been developed any technology which would enable us to manufacture large scale PV panels from these materials yet. [13]

Some applications which use a combination of PV technology and another source or kind of energy are already described above in this chapter, but one more remains. This thesis explains the principle of electrical energy production using concentrated solar power (CSP) technology as well, for the information refer to chapter 2, and it is mentioned many times below that the necessary equipment of the CSP plant, refer to 2.4, causes quite high own electrical consumption of the CSP plant (mainly heliostat field). This problem is sometimes solved by building of photovoltaic fields nearby to the CSP plant. The produced PV energy might be utilized for covering of the electrical losses caused by the big number of necessary heliostat electronics. An example of this solution is Abengoa Solar in Spain which includes the PV and also the heliostat field with a multiple tower solution. For the picture refer to Fig. 1.7. [14]

Figure 1.7: Combination of CSP plant and PV plant [14]

Chapter 2

Concentrated Solar Power (CSP)

As mentioned above solar energy has got a huge potential in the future electrical energy production. Photovoltaic energy is probably the only way how to transform solar energy to electricity directly, but there are other possibilities how solar energy can be useful for humankind.

One of these technologies is called concentrated solar power (CSP). CSP can be realized by variously shaped heliostats which reflect the sun beams to a solar receiver. This method of producing electricity is not direct like in the photovoltaic technology case where electricity is created by the dropping sunlight on the semiconductor, but it can be much more efficient than PV technology. CSP technology can be divided into several variations, but in this thesis only parabolic mirrors (PM) and so called tower solar power plants (TSPP) will be introduced. The parabolic mirrors comprise two various technologies which depend on the shape of heliostats and receivers. First of them is called parabolic troughs (PT) and the second technology is titled as parabolic dishes (PD). [15]

The brief introduction to TSPP and PM will by described in chapters 2.1, 2.2 and 2.3. All these technologies work on the principle of conversion sunlight to thermal energy which is transported and stored in heat transfer fluid(s)(HTF). The acquired heat is used to create steam in a steam generator, then it enters a steam turbine which is mounted to an electrical generator. The generator creates electricity and it is connected to an electrical grid. [15]

The various components which are necessary for building a solar power plant are described in chapter 2.4 and the example of combined tower and PT CSP plant layout is shown in Fig. 2.1 where most of below described components are pictured. [16]

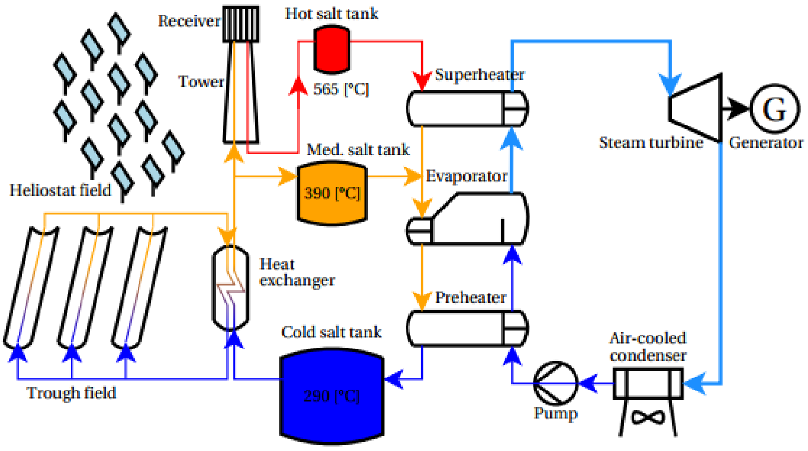

Figure 2.1: Tentative example of CSP plant layout [16]

2.1 Brief Description of Tower Solar Power Plant

Tower solar power plant consists of a heliostat field(s) which focuses the sunshine to a receiver(s). This receiver is situated on a very high tower, so that every heliostat, even the ones which are located in quite a distance from the receiver, could point the sun beams precisely. A HTF flows through the receiver and absorbs the heat from the sun. The HTF is usually stored in cold and hot storages, when there are any, so the sun heat could be used to drive a steam turbine (ST) even at night when no sun shines. The cold storage is located before the HTF enters the receiver and the hot thermal storage is situated after the HTF flows through the receiver. In some cases various HTFs are utilized for absorbing the sun heat in the receiver and for keeping the acquired heat in thermal storages. It leads to necessary utilization of a heat exchanger which is placed in front of the hot thermal storage. The HTF flows from the hot thermal storage to a second heat exchanger (a steam generator) where the HTF transmits its thermal energy to water, so that steam for running a steam turbine could be created. [15]

When the TSPP is considered, the heated condensate in the steam generator can lead up to superheated steam at approximately 565 °C and 125 bar. This steam is utilized to run a reheat steam turbine up to 300 MW. The superheated steam expands in the steam turbine and in the turbine outlet it is led to a condenser, so that it could get to the condensate state again. With such a technology, the circle can repeat again and again. [15, 14, 17]

The efficiency of the total circuit is, besides others, affected by the design of the steam path in the steam turbine with high influence of the inlet parameters as well as the back−pressure at the outlet of the steam turbine which is maintained by the condenser. The back−pressure has the direct impact on the design of the last stage blade of the steam turbine. [14]

In Fig. 2.2 there is shown an example of TSPP in Spain – Abengoa Solar. This is a picture of one tower with its heliostat field from a multiple tower solar power plant.

Figure 2.2: Abengoa Solar in Spain - tower solar power plant [14]

Tower solar power plants may be constructed as a central single or a multiple TSPP. The main difference between the central and multiple tower solar fields is the decomposition of mirrors and the mirror−receiver distance. [15]

For a central solar field with a single solar tower a huge area around the central receiver tower must be occupied by heliostats to achieve sufficient efficiency. The biggest disadvantage of the single solar tower solution is a very long distance between the receiver and the most remote mirrors which causes considerable attenuation and spillage losses. It is also very difficult to handle the right aiming of all heliostats, which are settled in a cylindrical shape around the receiver, to the single fixed point(receiver) from all directions and distances. [14, 15]

An example of the central single tower solar power plant Gemasolar in Andalusia in Spain is demonstrated in picture 2.3. [18].

Multiple tower solar power plants need to follow some assumptions as well. Multiple tower fields consist of two or more central towers with their particular receivers and their heliostat fields around. The main aspects that must be considered are the heliostat field layout and the sunlight concentrating strategy. The thought of a spillage, cosine and attenuation losses reduce and a prevention of adjacent heliostat shading and blocking must be kept. [16]

For an example of a multiple tower solar power plant refer to Fig. 2.4.

Figure 2.3: Central single tower power plant with field of flat heliostats [18]

Figure 2.4: Multiple tower power plant [19]

2.2 Brief Description of Parabolic Trough Power Plant

The parabolic trough technology is also based on the reflection of solar beams to a solar receiver. The name of parabolic troughs is caused by the parabolic−shaped mirror which reflects the sunlight into a parabolic trough receiver (PTR). PTR is a linear focused solar collector which allows to use a single−axis tracking system. Conversely, the tower solar and parabolic dish power plants contain the need of a two−axis tracking system due to the point−focusing mirrors. [15, 16]

A fluid of convenient properties circulates through the parabolic trough's tube and the HTF absorbs the direct solar radiation reflected by parabolic trough mirrors. The PTR is situated into a focal line of the parabola. The shape of these reflecting mirrors affects the final efficiency of the PT very much. The parabolic shape allows the PT reflect the solar radiation onto a thinner surface of the PTR. The main advantage of the parabolic shape is the fact that every part of the parabolic through concentrates the sun beams accurately onto the PTR from a very small distance and the whole surface of the PT is utilized. The working fluid circulating through the PTR absorbs a huge amount of solar energy which is transformed into a thermal energy in the form of heat of the fluid. [15]

This energy can be used in systems depending on thermal energy or it can serve as the working fluid in Clausius-Rankine cycle to produce electricity using a steam turbine in a solar thermal power plant. Nowadays, parabolic troughs can provide useful thermal energy close to 400 °C. [15]

The HTF which is used in this application must be considered very carefully. It must be taken into account that the PTR usually interconnects all of the parabolic troughs in the solar power plant. It means that a very long grid of a pipeline must be constructed. The pipeline materials must be unconditionally resistant to the HTF for a very long time, so that no accident would happen. The problem comes with properties of each of these HTFs, which are described in chapter 2.4.4, because some of them react with various elements in the air or in the pipeline material. [14]

Fig. 2.5 shows how a parabolic trough solar power plant looks like in practise, including the pipeline grid which connects all PT mirrors from the power station, in order that the HTF could flow through it and absorb the sun heat.

Figure 2.5: Parabolic trough mirror with linear focus receiver [14]

2.3 Brief Description of Parabolic Dishes Power Plant

Parabolic dishes (PD) are usually situated similarly like parabolic troughs, but the shape of a heliostat and also the shape of a receiver differ. The biggest difference between these two technologies is that in PD technology every heliostat has its own point receiver. The heliostat is a three dimensional paraboloid with a mounted receiver situated in front of the paraboloid. As mentioned above in chapter 2.2 this feature leads to the requirement of two−axis tracking system, so that the heliostat could reflect the sun rays precisely on the target (receiver). The operating temperatures can reach to 1500 °C. [16]

Dish systems have got the highest optical and overall conversion efficiencies from all possible CSP technologies. It is caused by the full aperture directly towards the sun which they always provide and the zero cosine loss effect. On the other hand, the commercial development is not advanced enough, because the cost of one kW installed can even reach up to $10.000. The cost is the main reason why parabolic dish systems are not built very often, but thanks to the great efficiency the development of PD systems is still running. The main focus in the PD development is to reduce the capital and operating cost of the power plant, so that it could be built also for commercial applications, not just experimental ones. [15]

The main components of a parabolic dish system usually are: a three dimensional parabolic mirror, a tracking system, a solar point receiver and a system control unit. The diameter of dishes can be from 1 to e.g. 25 meters. [15]

The receiver for so called Stirling dish technology, which absorbs the reflected sun beams from the mirror, may be a Stirling engine or a micro−turbine. The generator is usually placed in the receiver of every single dish, which helps to reduce the heat losses. As written many times above, also the Stirling dish technology meets the highest efficiency of all CSP variations, but the problems with the cost reduce remain. Moreover, the storage utilization in Stirling system is very challenging. [20]

An example of a parabolic dish heliostat and a receiver is pictured in Fig. 2.6. The supporting structure of the PD system may be of various constructions, but the basic requirements, such as a prevention of shading, a wind resistance and a mirror tracking ability, must be kept [15].

Figure 2.6: Parabolic dish heliostats with point receivers [21]

2.4 Components of CSP Plant

The main equipment of a concentrated solar power plant consists of heliostats, a solar receiver(s), a heat exchanger(s), a steam generator, a steam turbine and in some cases thermal storages. The components for various technologies differ, but the basic philosophy is similar. For every technology the best facility should be suggested, so that the efficiency of the CSP plant is as high as possible. [15]

There are many subsystems which influence the final efficiency of the whole CSP plant. The definition of each subsystem efficiency can be done very easily by comparison of the input and output energy. The final efficiency of the overall system depends on efficiencies of following features: heliostats, receiver, HTF transport, storages and conversion. This efficiency of overall system can be counted according to the following formula:

$$\eta_{system} = \eta_{heliostats} * \eta_{receiver} * \eta_{transport} * \eta_{storages} * \eta_{conversion} \text{ [15]}$$

A lot of time and money have been devoted to the development of suitable thermal storages, HTF, etc., which could be used in CSP plants and which would make CSP plants comparable to the fossil and nuclear power plants. These researches are still running nowadays even if the present utilization of working fluids and thermal storages is sufficient enough so that the returnable CSP plants could be constructed. [14]

The necessary components which are needed in a CSP plant are described below in the subsection of this chapter with references to the internal knowledge and experiences of the company Doosan Škoda Power and to the literature. [1, 15, 16]

2.4.1 Heliostats

As mentioned in chapter 2 the CSP technology can be divided into three sections – parabolic troughs, parabolic dishes and tower solar power plants with flat heliostats. Although the shape of heliostats and receivers differs, each of these solar power plants is based on a very similar technology, principle and philosophy. Heliostats usually take the largest area from all CSP plant components and this area is normally called a heliostat field. [15]

The heliostat field could be divided in general into two groups – experimental and commercial. At first, in early eighties only experimental heliostat fields were build. Some of these fields served for testing the impact of multiple tower systems, or the impact of various mirror shapes, etc. to the total system efficiency, cost and many others. The first commercial heliostat field was build and put into service in 2007 in Sanlùcar la Mayor in Spain and since then a lot of other facilities of various areas have been realized. [16]

The heliostat field is filled with individually tracking mirrors. The main task of these mirrors is to follow the sun as it moves across the sky, so that the sun beams could drop on the mirror with minimum losses and the dropping sun rays could be reflected to the receiver precisely. Depending on the mutual position of the receiver and the mirror, the movement ability of the facility must be set. For PD and tower technologies two tracking axis, vertical and horizontal, must be performed. For PT technology one tracking axis is enough, because of the linear shape of the receiver. [16]

The exact position of the sun must be calculated over and over again during the day, so that the heliostat could aim the sun rays precisely on the target. For the sun movement during the day there are some specifics that must be known accurately, such as the longitude, latitude, date and exact hour. Conversely to the photovoltaic technology, a heliostat field cannot reflect sun beams which are refracted due to the clouds or other atmospheric effects, but the software which calculates the exact position of the sun should compensate the small refraction errors. These errors may be also caused by the tilt of the pole where the heliostat field is mounted or atmospheric refraction near the horizon. In case of TSPP every single heliostat receives its own commands because each of them is situated in a unique position relatively to the receiver, for PT and PD technology the commands can be the same for a part of the heliostat field. [22]

There has been a tendency to increase the size of heliostats a lot in past several years. The main benefit of building larger heliostats is that the high own auxiliary consumption of heliostats is spread over a larger area and the cost reduces per unit area. As written above, one of the most expensive parts of a CSP plant is the heliostat field itself due to its high own electrical consumption. Although the spillage and sunlight concentration is affected by the dimensions of heliostats a lot, designing larger heliostats is more preferred due to an economical point of view. The lower cost is caused by a smaller number of required controls, actuators, pedestals, etc, for larger units. The enormous own electrical consumption is the main problem in heliostat development. Thus, significant reducing of consumed electrical energy on the heliostat field would lead to great development in solar energy utilization. [15]

The heliostat composition usually follows a requirement of increasing the efficiency as much as possible, which leads to a production of several mirror module panels more often than single large panels. The higher number of mirror module on one panel enable to hit the target more successfully than in a single large mirror case. Each of the individual modules on the heliostat is canted toward the receiver. The reflecting element of a heliostat is usually a thin, low−iron glass mirror. The material of heliostats should be considered very carefully, so that the reflectivity of panels is as high as possible and almost no solar heat absobtion happens. The thin glass mirrors are supported by a substrate backing to form a slightly concave mirror surface. However, when considering so called flat heliostats, which are used in the central tower CSP plant, the concavity of a heliostat is so small that optically this heliostat seems to be flat. [22]

Nevertheless, there has been a huge progress in using CSP during last two decades and heliostat losses have dropped significantly, hence central receiver power plants are getting able to compete with conventional fossil power plants. In some cases the own heliostat consumption is solved by building a photovoltaic field nearby which creates a sufficient amount of electrical energy. The electricity created by the photovoltaic panels can cover and compensate a high amount of electrical energy which is needed for the heliostat movement. This solar technology combination has already been mentioned in chapter 1.3. [14]

2.4.1.1 Flat Heliostats

In case of a tower solar power plant the solar energy concentration and collection are based on the field of individually tracking heliostats which reflect the sun rays to the point receiver at the top of a centrally located tower. Usually 80 to 95 percent of the reflected energy is absorbed by the HTF. There is an effort to develop a HTF which would absorb even more reflected sun heat with the lowest self−consumption of the heliostat field. [14]

The heliostat itself consists of mirror modules, a rack assembly, an elevation drive mechanism, an encoder, electronics, a support pedestal, a power box and foundation. The basic components of the flat heliostat are pictured in Fig. 2.8. [14, 22]

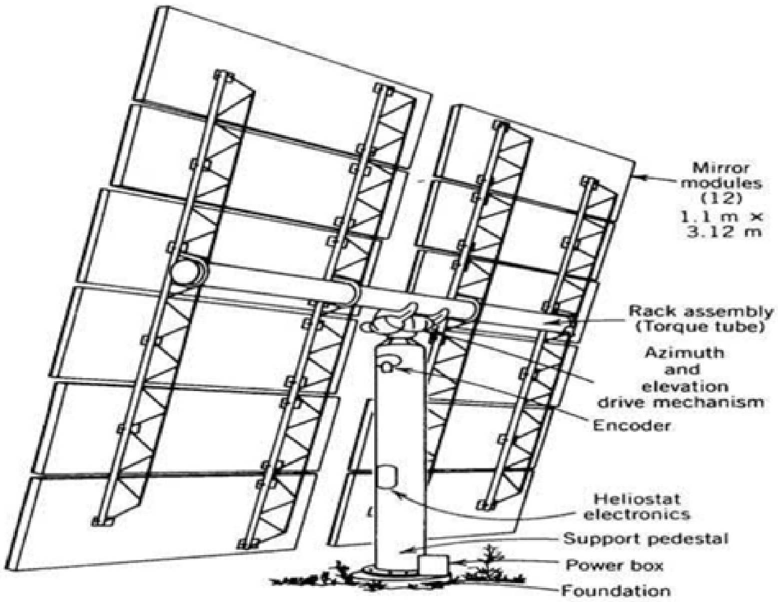

Figure 2.7: Assembly of flat heliostat [22]

2.4.1.2 Parabolic Troughs (PT)

As already mentioned, parabolic trough heliostats require one tracking axis, so that it could follow the sun moves. No other moves caused by a vibration or a wind are required. It leads to very strict demands to the rigidity and strength of the PT assembly. [14, 16]

Since 1980s many researches have been performed so that the best design of the parabolic trough heliostat could have been realized. In 1984 the unit called LS1 designed by a company LUZ International was created. The length of one LS1 unit was 50.2

m and the parabola width of 2.5 m, but in quite a short period of time it became evident that for larger CSP plants with higher electrical output, larger units must be constructed. As a result for example the SKAL-ET design of the parabolic trough mirror was build in ANDASOL−1 solar power plant in Spain in 2008. The dimensions of the PT heliostat nowadays can reach even up to the overall single heliostat length of about 150 m and the width of parabola of almost 6 m for large scale CSP solar power plants. [15]

The structural profile assembly is usually made from steel and it must follow some requirements, such as the overall structural rigidity and low cost. Some designs include a central space frame or a central steel tube, which help to increase the rigidity and prevents torsion. The central space frame provides better performance and rigidity under wind loads in contrast to the central steel tube. On the other hand, the central space frame is more expensive than sentral space tube, because it consists of s higher number of steel profiles with the high−precision assembly requirement. [15]

In some commercial PT power plants, such as the Solargenix and Acciona in Nevada Solar One Plant, the structure of the PT mirror is solved by using a metallic space frame, which provides a good rigidity as well. [15]

2.4.1.3 Parabolic Dishes (PD)

In case of a parabolic dish system the movement ability is required in two axis so that the PD heliostat could always aim to the sun precisely. There are two possible ways how to realize the two axis tracking system of the PD mirror. [15]

First of them is to use an azimuth−elevation tracking. The PD can rotate in a plane which is parallel to the earth azimuth (surface) and around an axis, which is perpendicular to the azimuth, the mirror can track up/down and left/right. The rotational rates around these axis change during the day, but it can be predicted by an applied software. For an example refer to Fig. 2.8. [15]

The second possibility how to build two tracking PD systems is to take an advantage of the polar−equatorial pattern. In this case the mirror rotates around an axis which is situated in parallel to the Earth's rotation axis. The mirror also rotates with the same constant rate as the Earth's rotation rate is. The second rotation axis is perpendicular to the polar axis and is called the declination axis. Refer to Fig. 2.9 for an example. [15]

The tracking system usually consumes quite a huge amount of the electrical energy. It is normally driven by an electrical engine which works by using gearbox units. A tracking algorithm calculates the accurate sun position from the time, date, tilt of the pole, etc., so that the heliostat could reflect the sun beams to the receiver the most precisely. [15]

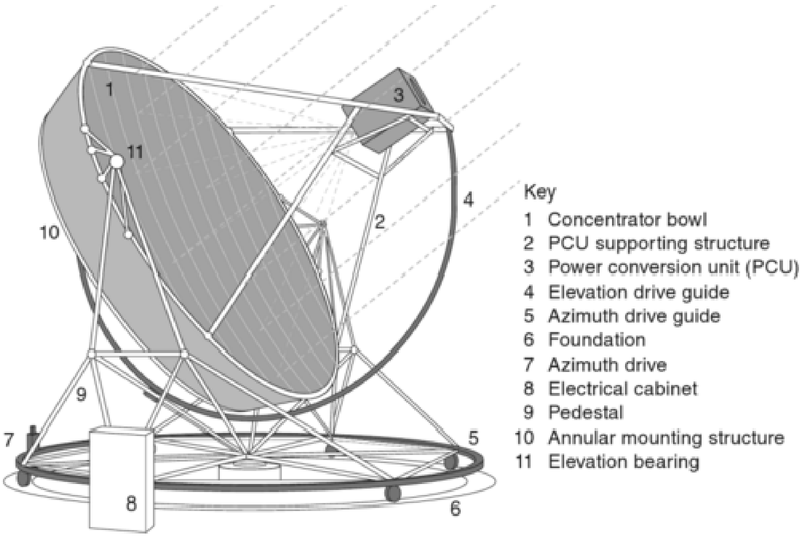

Figure 2.8: An example of the azimuth−elevation tracking assembly [15]

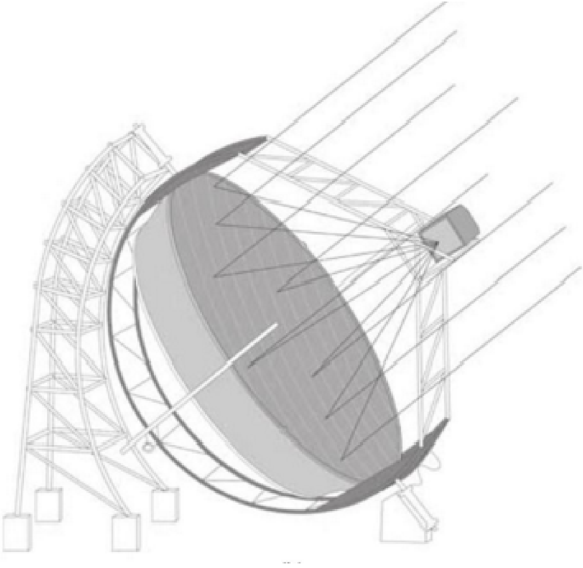

Figure 2.9: An example of the polar−equatorial tracking system [15]

2.4.2 Solar Receiver

The solar receiver is a facility which permits to receive the solar energy. A heat transfer fluid circulates through the receiver and absorbs the heat from the sun. This HTF collects and stores the thermal energy which is used to drive an electrical generator or is used as a process heat. [15, 16]

As explained above, the solar receiver may be of various shapes according to the required application. Parabolic troughs have got a linear shape receiver which is constructed as a pipeline. This pipeline links PT mirrors and a HTF flows through it. On the other hand, parabolic dishes use point receivers, each of them mounted to only one heliostat, and when considering a tower CSP plant, the solar receiver is placed at the top of the tower and every heliostat from the field around the receiver focuses the dropping sun rays to the receiver where the reflected solar energy can be intercepted most efficiently. [15]

Central solar tower receivers are profitable mainly because all the solar energy is converted by the heliostats to a single fixed point (receiver). This allows the receiver to be fixed, more cost−effective investment designed and there is much smaller need for energy transport networks compared to parabolic trough power plants. It is more common to use central receivers to single large systems to power a steam cycle but there are some useful applications to smaller or modular systems employing multiple towers as well. Compared to 3D parabolic shaped mirrors there is a big disadvantage which is based on the fixed position. Heliostats do not point directly at the sun and that means that the amount of collected solar radiation per a unit area of a mirror is reduced. This disadvantage may be compensated by a smaller multiple tower system, which helps to increase the collected solar radiation, thus also the efficiency. [15]

The solar receiver for a central tower and sometimes PD CSP plant can be chosen from two various types described in chapters 2.4.2.1 and 2.4.2.2. The parabolic trough receiver is introduced in chapter 2.4.2.3 and for the parabolic dish receiver refer to chapter 2.4.2.4.

2.4.2.1 External Receiver

An external receiver is a type of receiver which is usually used for TSPPs. The most often, due to its all direction absorbing surface, it is utilized for a single tower solar plant with a large spread heliostat field all around the receiver. External receivers consist of panels with many small vertical tubes. The size of these tubes is usually from 20 to 56 mm and these tubes are welded one next to each other so that a cylinder was created. The disposition of heliostats reflects in the size of an absorbing area which is quite large, because the absorbing surface can be seen from all directions. One of the disadvantages is that the absorbing surface is exposed to the elements, such as wind, rain, hails, dust, etc. Due to these adverse conditions radiation and convection losses happen. [22]

The dimensions of a typical external receiver are usually in ratio of 1:1 to 2:1 when considering the height of the receiver to the diameter. Although the cylindrical shape of the receiver enables to build a heliostat field all around the receiver, the very important condition of the receiver area reduction must be kept. The area of the receiver must be as small as possible, so that the heat losses were reduced to minimum. The dimensions of the receiver are of course limited. The lowest limit is defined by the maximum operating temperature of the tubes and by the abilities of the used HTF, such as the heat removal capability, etc. [22]

For an example of an external receiver refer to Fig. 2.10.

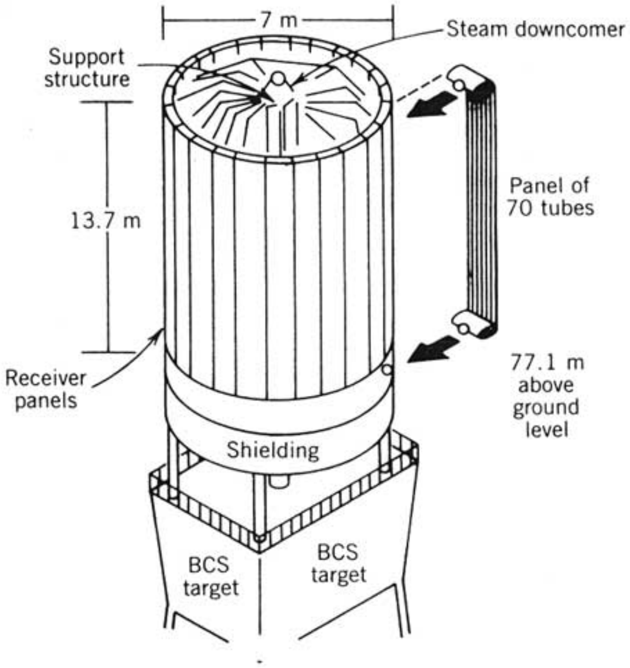

Figure 2.10: External receiver [22]

2.4.2.2 Cavity Receiver

The external receiver suffers from high heat losses caused by the external elements. The problems with the external receivers led to a need of a new receiver development. A cavity receiver is an attempt how the heat losses can be reduced. The cavity receiver works on principle of hiding the flux absorbing surface inside of an insulated cavity and so the convective heat losses are reduced. The number of cavities differ according to a decomposition of the heliostat field and according to the required efficiency. The cavities are placed next to each other on one solar tower and every cavity absorbs solar energy from a different heliostat field or in some cases the aperture may be horizontal. The heliostat fields reflect the sun rays onto the absorbing surfaces through an aperture which is formed by the walls of the cavity. Usually the aperture area is at about one−third to one−half of the internal absorbing surface area. [22]

Obviously the cavity receivers have got some disadvantages as well. For example, an acceptance angle is limited from 60 to 120 degrees. The tower for cavity receivers must be taller than the external receiver tower, so that the same amount of energy could be absorbed. The cavity receiver might be less efficient than external receivers. The cavity receiver utilization is usually limited by the output temperature and the allowed flux density which must be very low. On the other hand, the output temperature must be higher than 1000 K. [22]

The cavity and external receivers can be considered TSPP application as well as at PD systems. An example of cavity receiver with four cavities is shown in picture 2.11.

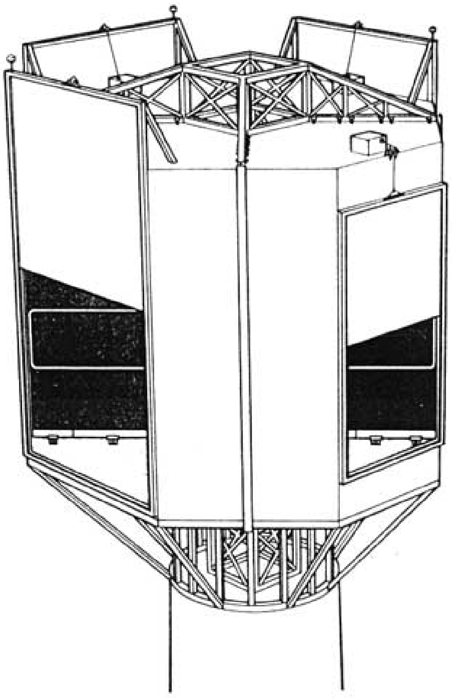

Figure 2.11: Cavity receiver model [22]

2.4.2.3 Tube Receiver for PT

Parabolic trough mirrors are connected all together by a tube receiver which serves as a pipeline between the mirrors. A heat transfer fluid circulates through the linear receiver and absorbs the reflected sun beams. The circulating HTF must follow many requirements which are given by the linear pipeline shape. The pipeline length can be even in tens of kilometres which causes huge heat losses and higher possibility of the HTF leak into the atmosphere. Some HTFs, such as liquid sodium and some others, react with the air elements and it can lead to a very serious accident if an interference happens. [14]

Due to this factor the liquid sodium is not used very often as HTF in a tube parabolic trough receiver and also because of the big amount of HTF which must be utilized there. The liquid sodium is very expensive. On the other hand, the experimental parabolic trough solar power plant in Australia called Vast Solar uses liquid sodium as HTF, but in 2015 an accident happened, when minimum amount of the pure liquid sodium leaked into the atmosphere and reacted with oxygen. It caused a fire and a lot of smoke was created. Many safety measures had to be accomplished there and the research of the CSP was delayed. [23]

A thermal oil is considered as the most suitable HTF which absorbs the reflected sunlight from the PT mirrors nowadays. After that the oil transmits its thermal energy to the molten salts which are used as the working medium in thermal storages. [14]

2.4.2.4 Point Receiver for PD

The parabolic dish technology is a little bit different comparing with the TSPP or PT power plant because every receiver includes a micro−turbine or Stirling engine with generator. Every single parabolic dish unit works as a small power plant then. [14]

The point receiver may be of various types which are described above in chapters 2.4.2.1 and 2.4.2.2. The shape of the receiver depends on a specific application and is selected according to required features. [14]

2.4.3 Thermal Storages

One of the most important aspects for a storage system indication is the way how the solar energy is transferred to the storage material. There are direct and indirect storage systems and according to them the HTF and storage medium are chosen. For direct storage system the HTF, which absorbs the solar radiation, is applied as the storage medium as well, but indirect storage system uses two different fluids as a storage medium and HTF. Then there is a need of a heat exchanger which increases the price a lot.[15]

The storage medium can be in two various substance states − liquid and solid. The liquid storage medium is preferably used in CSP plants in a two-tank concept. [14, 15]

The hot tank may keep the storage medium, which may flow also through the receiver in the direct storage conception, heated at even up to 565 °C. The storage medium transmits its energy to water in a steam generator so that the steam might be produced. Then the steam enters the steam turbine mounted to the electrical generator. The storage medium, which is now on a lower thermal energy level because it has already handed most of its thermal energy during the transformation of water to water steam, is guided to the cold storage. The temperature of the storage medium in the cold storage might be around 260 °C. During the day light it is pushed from the cold storage to the receiver, circulate through the receiver and absorbs the solar energy in the form of heat. This cycle repeats all over again, depending on the length of the day. The storage medium which is utilized the most often are molten salts. [15]

The indirect system is applied in case of lower cost of the storage medium than the HTF (usually molten salts, might be sodium). In this system, two separate loops must be connected by a heat exchanger and the thermal energy of the HTF must be transformed to the heat of the storage medium. [15]

Solid media storage units can be applied to CSP plants as well. The biggest benefit of solid media use for CSP plants is its low cost. The range of cost per unit energy stored is around 10−20 % of the corresponding costs for molten salts in liquid concepts. Another advantage is the fact that no problems with freezing, evaporation and leakages have to be considered. The biggest challenge for solid media storage implementation is the low thermal conductivity. [14, 15]

The reason why thermal storages even come to consideration is that the amount of produced energy during the day is higher than needed, so the surplus can be kept in the thermal storages for future use. The thermal storages enable to the CSP plant to run 24 hours a day 7 days a week with minimal or zero impact on overall system efficiency, lower load and less challenging demands on a steam turbine. [14]

The development of thermal storages is still running, due to the small efficiency it can provide. The ideal thermal storage should not exchange any heat with the surrounding and the elements of the material the thermal storage is made of should not react with the storage medium at all. [14]

2.4.4 Heat Transfer Fluid (HTF)

As mentioned above in chapter 2, the philosophy of electricity production using CSP is based on circulation of working fluid(s), which is able of heat transmission and handover. For recapitulation the whole circuit of the CSP plant described above can be divided into two or three parts according to the number of used HTF. [15]

The first possibility is that only one HTF can be used in the whole circuit. It means that the same fluid flows through the solar receiver, is stored in the thermal storages (if they are utilized) and its heated and vaporous medium is used for running a steam turbine. This method has been used only at the beginning of CSP development where water has been utilized as the only HTF, for example in Ivanpah project. The characteristics of water will be described in chapter 2.1.4.1. [15]

The second opportunity can be realized by two various HTFs. First of them is used for transmitting the heat from the sun flowing through the solar receiver and then for storing the thermal energy in the cold and hot storages. The second HTF fluid is usually water which assumes the thermal energy from the original HTF in a steam generator, where the steam for running a steam turbine is created. [15]

The last option is to utilize one HTF for the receiver, second for storing and the last one for running the steam turbine. [15]

The most suitable working fluid must be chosen very carefully, because it has to accomplish several requirements unconditionally, such as non−toxicity, high specific heat and boiling point, good transfer and storage properties, low cost, low incombustibility, simplicity of system operation and storage concept, etc. [14, 15, 24]

The existing HTFs will be described in chapters 2.4.4.1 to 2.4.4.4. The best solution for variously constructed CSP plants, such as PT power plants, PD power plants and TSPP, will be suggested.

2.4.4.1 Water

Using water as HTF for the complete circuit of a CSP plant has been rejected at the beginning of CSP technology development due to its inability to store thermal energy. Respectively, a direct storage of water steam needed for a steam turbine in high temperatures and pressures is very expensive and non-effective. Moreover, water is not able to assume such an amount of thermal energy which heliostat field is able to provide. [14, 15]

On the other hand, water in its gas stadium (steam) is always utilized for running a steam turbine in parabolic trough, parabolic dishes and tower solar power plants. [15]

2.4.4.2 Pure Liquid Sodium

Pure liquid sodium has got the best heat transfer properties, but it does not fulfil the rest of requirements written in 2.4.4. Pure liquid sodium is very expensive and it is also very difficult to handle due to its high reactivity with water or the atmosphere when interference happens. In some CSP plants such as Vast Solar CSP plant in Australia the pure liquid sodium is used as a HTF, but several safety measures must be implemented there. It can never happen that the pure liquid sodium would leak to the water in the steam generator. [14, 23]

Pure liquid sodium is usually utilized only in one circuit from the three possible circuits described above, most often it is used as the HTF which circulates through the receiver and directly absorbs the heat from the sun. The main reasons why it is not utilized as storage medium is its high cost, which increases with its amount, the high reactivity and the fact that molten salts or thermal oils are still considered as a better solution due to their smaller reactivity. [14]

2.4.4.3 Molten Salts

Molten salts are quite expanded in the CSP technologies nowadays. The NO_3 salt (Na60 %, K40 %) is the most preferred HTF due to its non−toxicity, high specific heat and boiling point, its good transfer and storage properties and the modest cost. The molten salt receiver has got approximately three times higher allowable flux density then using water as HTF and the active area is one−third of the old−type (water) receiver. The storage unit has been modified according to the need of the used HTF. The old−type storage has been replaced and instead of it hot and cold thermal storages (so called salt tanks) are used. The HTF which absorbs heat while flowing through the receiver is utilized in the steam generator to produce water steam. However, liquid sodium still experiences the best heat transfer and heat storage abilities. [14, 24]

2.4.4.4 Oil

An synthetic oil is usually utilized as the working fluid which directly transmits the solar energy from the sun when it circulates through the receiver pipeline in PT solar power plants. The efficiency of solar power plant using a Rankine cycle for thermal−electricity transformation is limited by the thermal stability of the used oil. The thermal stability is closely linked with the ultimate operating temperature of the oil, which is at about 395 °C. An example of the synthetic oil, which can be used in a PT solar power plant, may be a Therminol VP−1. The Therminol VP−1 is a mixture of a biphenyl and a diphenyl−oxide. [24]

2.4.5 Steam Turbine (ST)

The CSP plant in ideal conditions would provide a sufficient amount of solar power in the heat form, the thermal storages would be efficient enough so that the night shut down would not be necessary and the thermal losses in the overall CSP plant circuit would be none. Problem is that there are never the ideal conditions in the world of industry. Many requirements must be followed when the steam turbine for a CSP plant is designed. The thermal capacity of the storages is usually limited so it can keep the necessary heat for at about 7 to 8 hours. However, nowadays there are some running (or under development) solar power plants where the thermal storage capacity can get even up to 18 hours. The short term storages are still more common and from this fact the first assumption comes − the repetitive start−up/shut−down design of the steam turbine is required. [14, 25]

All the technologies described above (PT, PD and TSPP) have achieved sufficient performances, but the highest cycle efficiency is normally expected from the tower concepts. The turbine manufacturing companies usually exploit from their nuclear/fossil supercritical turbine manufacturing experience to design CSP steam turbines. The common temperature which can be achieved by the tower cycle is 565 °C, but the future trend is to increase this temperature as high as possible. The high temperatures have been usually applied on large supercritical turbines (when the nuclear/fossil ST is considered), but the CSP technology requires smaller sized lighter machines, high operational flexibility and ability to run in very unique ambient conditions. [14, 25]

The international company Doosan Škoda Power had to fully understand the complete cycle of the CSP plant, including the detail characteristics of every single equipment of the plant − receiver, heliostat field, thermal storages, heat exchangers, HTFs, etc., to be able to design an appropriate steam turbine for CSP purpose. The company cooperates with the experimental CSP plant in Australia, Vast Solar, to gain all the necessary information. All the below written characteristics of CSP steam turbine comes from the long term and demanding development which Doosan Škoda Power had to accomplish. Nowadays there are steam turbines delivered to CSP plants all around the world manufactured by Doosan Škoda Power from the output 20 MW up to 300 MW. [14]

2.4.5.1 General Characteristics of ST in CSP Plant

The steam turbine size depends on the area of the CSP plant, the dimensions of the heliostat field mainly, and of course the required output. The system efficiency increases with the larger size of the power plant. The heat−electricity conversion efficiency of the cycle is at about 44 % at full load. Of course to increase the efficiency is the main aim of every CSP plant, but there are limits which make the development challenging and which are required to be exceeded. The most specific and demanding requirements are to the inlet parameters, such as the inlet temperatures and pressures, and the output range. [14]

The design and used materials of the steam turbine must follow the needs caused by the high temperatures and pressures which might be for the 250 MW output of the steam turbine at about 560 °C and 14 MPa. The super critical parameters which have been also tested are around 620 °C and 24 MPa. From these numbers it is clear that the steam turbine and also the receiver materials must be adapted to these parameters. The P91 material may be utilized for the inner casing of the high pressure (HP) steam turbine part, for the inner control and emergency stop valves and also the HP rotor may be manufactured from this material. [14]

The required aspects which have to be taken into consideration during design of CSP steam turbines are challenging demands on partial load operations, necessary start−up and shut−down system and last stage blade erosion.

2.4.5.2 Impact of Erosion to the Lifetime of ST

The erosion of blades is a huge problem in the steam turbine industry, because it causes decreasing of the steam turbine lifetime rapidly. The erosion caused by operation of the steam turbine in a wet steam makes the worst conditions possible for the rotor blades. Rotor blades are exposed to an enormous stress and their failure could even lead to the total collapse of the turbo set. The ability to increase the reliability of the turbo set is one of the main requirements given by the customers and the erosion resistance increases the reliability dramatically. [14]

2.4.5.3 Impact of Start−up and Shut−down to the Lifetime of ST

The task of steam turbine in a typical CSP installation is to produce electricity during day light and then through the night storage reserve. It leads to the daily start−ups/shut−downs which cause very dangerous thermal and cyclic stresses. They might be formed by the temperature changes in the steam turbine or corrosion processes caused by the changes of condensate chemical properties. These stresses might also be caused by the reaction of the steam moisture on blades, or when the sealing is not sufficient enough that the oxygen enters inside. The corrosion originated during one start−up/shut−down cycle may influence the whole water−steam cycle and effect the final efficiency seriously. [14]

The impact of thermal and cyclic stresses reduction is the main aim of CSP steam turbine design. The thermal stress levels are carefully measured and evaluated, the last stage blades (its airfoils and root attachements) must be designed to withstand the highest possible number of cycles. [14]

2.4.5.4 The Specific Features Required for CSP Steam Turbine

The specific design of CSP ST has been built on the experience achieved by Doosan Škoda Power from more than 111 years of steam turbine manufacturing. The CSP design leads to the necessity of the particular steam turbine block modification so it could follow the specific requirements. The basic features it has to accomplish are:

- High efficiency
- High reliability
- Rapid starts–up
- Long service time
- High quality
- Flexibility reflected in: casings, last stage blades, flow path, seal design and auxiliary equipment

To achieve the above described demands a long term testing and development of 3D last stage blades, the inner casing, sealing, valves and other critical components of the steam turbine have been implemented. [14]

The local thermal stresses of casings, rotor and blades caused by rapid power changes which lead to an unneclegtable thermal incompatibility of the turbine components. To reduce the thermal mismatch the appropriate component materials must be chosen and in the most critical areas the abradable and retractable seals are applied to ensure the safe turbo set operation. The CSP steam turbine must include the standard vibration control and protection systems to enable the operator assisted fast turbo set start up/shut down. The locations with the sufficient solar irradiation are usually in harsh desert areas with a high seismic activity. The mechanical construction of the steam turbine must follow the possibility of a seismic activity creation in the area which is reflected in the final rotor–dynamics evaluation when taking into consideration the seals, bearing and weight of the structure design. [14]

The CSP power block differs a little when considering the indoor and outdoor application because the outdoor application requires more demanding requests for the seals and glands. In the suitable areas for CSP, as mentioned above, there is a lot of dust, sand, rapidly variable ambient temperatures (often more than 40 °C during the day and temperature below zero at night) and sometimes quite high salinity in the air. Yet the power block must work reliably at any condition. The turbo–generator outdoor enclosure is expected to fulfil the needs of entirety, protection of critical turbo set parts from degradation, simplicity of removal and seismic resistance, but yet it needs to provide sufficient cooling and ventilation system to remove the loss heat so that the electrical equipment, sensors and other electronics, would not get overheated. The example of a double speed 115 MW turbo–generator layout is pictured in Fig. 2.12. [14]

Some additional security systems are applied in the steam turbine to reduce a failure possibility, secure smooth operation, eliminate possible problems and reduce maintenance costs. One of these tools is called Remote Monitoring System (RMS) which allows to control the ST operation online and it collects the operational data for submission of monthly reports. The collected data are analysed and according to them the ST manufacturer can plan the maintenance inspections or in case of troubles they can react immediately. [14]

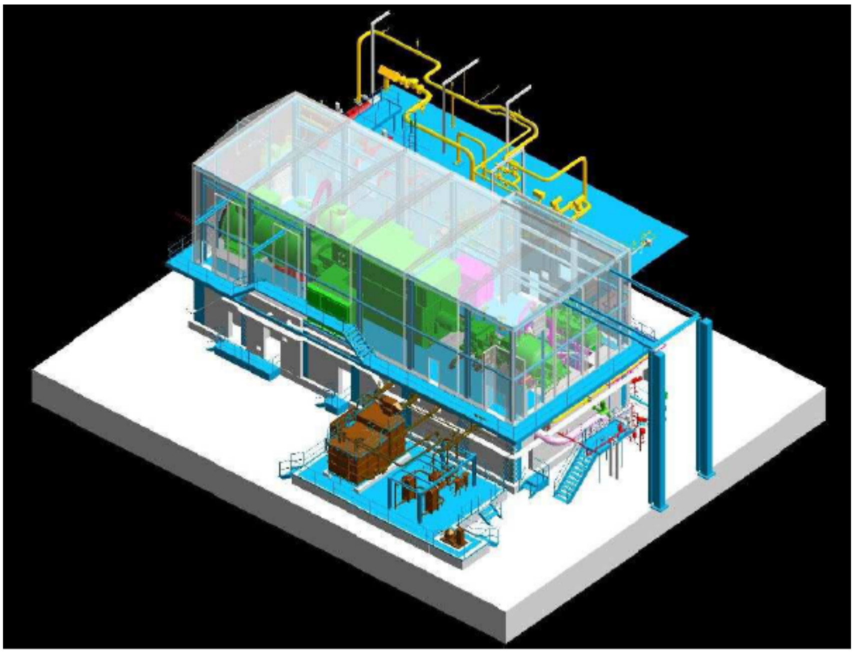

Figure 2.12: Double speed 115 MW turbo−generator layout [14]

Chapter 3

Economical, Geographical and Energetic Balance

The economical, geographical and energetic balance of all the technologies described above will be discussed in this chapter. The most suitable locations for solar power plants can be estimated from the solar map available from the source [26]. Maps like this one usually represent the amount of annual solar irradiation per square meter in colours which change from the vivid yellow, which constitutes the places with the highest solar annual radiation, to the blue colour, which represents the countries with the minimum amount of sunshine per year. [26]

Although both PV and CSP technologies are based on the solar radiation utilization, they are not replaceable. One of the reasons is that PV technology may not achieve such good efficiencies as the CSP technology does. Conversely, the CSP power plant cannot be built at any places where the PV plant can be situated, because the CSP technology requires much higher solar intensity with polarized dispersion of the dropping sunshine. However, the PV panels are able to absorb radiation of larger wave length spectrum. In case of CSP power plants the efficiency may drop rapidly when the sun rays pass through clouds or are dispersed by the horizon, but the photovoltaic modules can embrace even the least amount of solar energy. The only request for PV technology is that the energy is higher than the width of the band gap. This phenomenon has been already mentioned in chapter 1.

It can be deducted which countries are the most suitable ones for solar power plants from the solar irradiation map pictured below in Fig. 3.1.

In this chapter only PV technology, parabolic troughs and tower solar power plants will be evaluated, because parabolic dish technology is not cost−wise enough, so that it could be widely utilized in the world for commercial reasons. Three already operational projects representing each technology will be chosen, so that the possible component combinations could be pictured. From these data the most suitable solution for various applications might be suggested. For the evaluation refer to chapters 3.1, 3.2 and 3.3.

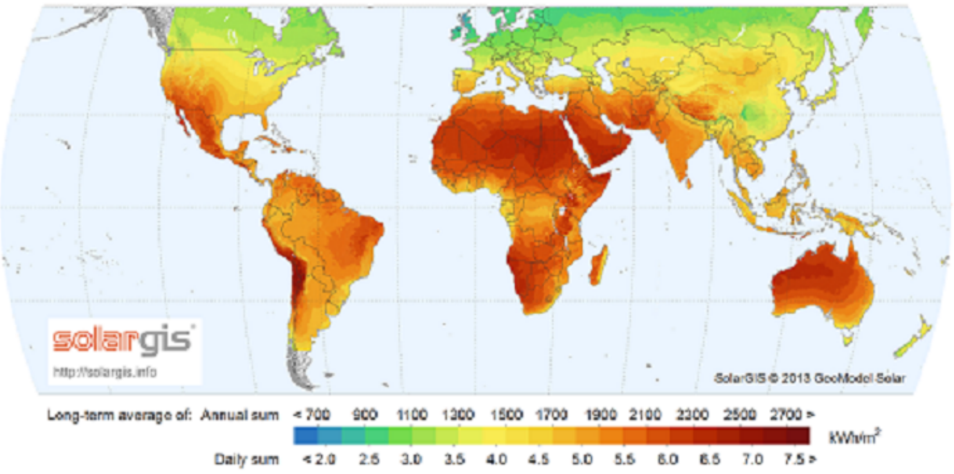

Figure 3.1: The solar irradiation in the world [26]

3.1 Photovoltaic Energy

The map above shows which places boast with the highest solar radiation intensity in the world. The biggest advantage of PV energy is that it does not require much sunlight to produce electricity. For Central Europe, where the Czech Republic is situated, the long−term average of annual energy per unit area sum gets only from 800 to 1300 kWh/m^2. Nevertheless, even in such locations photovoltaic power plants can be constructed. [26]

The various technologies and materials used for PVE production are described in chapter 1.1. The main requirements for the design of PV power plants are: high efficiency, least maintenance, least degradation of panels, high resistance, compactness, light weight and lowest possible cost. These requirements are the same for both field and roof applications. It is not easy to select one solution from all possible options which would accomplish all of the reqirements written above, because no photovolatic material with such properties has been developed yet. At the beginning of every real project, the local boundary conditions, such as layout of the available space, exact location, available location of the panels, measured data of solar irradiation as well as required output of the plant, are usually determined. The appropriate material, number and dimentions of PV panels should be chosen according to this information. [14, 27]

The south oriented installation represents the highest efficiency. The material with the best semiconductor properties is mono−crystalline silicon which may perform the efficiency even up to 20 %, but it is also the most expensive one from all materials which can be used for PV technology. It is caused by the complexity of mono−crystalline panel manufacturing. The most suitable ratio of cost/efficiency presents the multi−crystalline silicon especially when the PV field area is limited. The efficiency of multi−crystalline silicon could be from 15 even up to 17 %. The cheapest materials are based on the thin− film technology (may get to $ 1 per W_{peak}), but their efficiencies are lower than

10 %. The degradation process differs a little from technology to technology as well, but the manufacturers usually guarantee the output drop of only 0.8 % per year for each technology. However, the researches demonstrate that the mono–crystalline silicon degrades slower than the thin–film material which degrades most in the first year of its service life. On the other hand, the thin–film degradation stabilizes after some time. [27]

The Joint Research Centre (JRC), Institute for Energy and Transport, publishes on their website maps which show the photovoltaic solar energy potential all around the world. The JRC also provides data about the average daily/monthly electrical energy production and about the average daily/monthly sum of the global irradiation per square meter received by the modules of the relevant system in any country in the world. The JRC calculator enables us to compare a place with high average solar irradiation, in this case Ghana – location near to capital city of Accra, with the Czech Republic, a location near Pilsen, from the PV solar energy potential point of view. Ghana has been chosen because it boasts with much higher annual solar irradiation than the Czech Republic, so that the comparison will be perceptible. Moreover, there is one fixed purchase price for solar electricity, no matter which solar technology has created it, which has been detected by the company Doosan Škoda Power from verified sources. [28]

The selected 30 MW fixed system modules are made from crystalline silicon, the installed output is 30 MW_p, the orientation is almost perfectly to the south, the modules slope is 33° and the estimated system losses are 14 %. The solar irradiation maps of the Czech Republic and the part of Africa where Accra lies are shown in Fig. 3.2. [28]

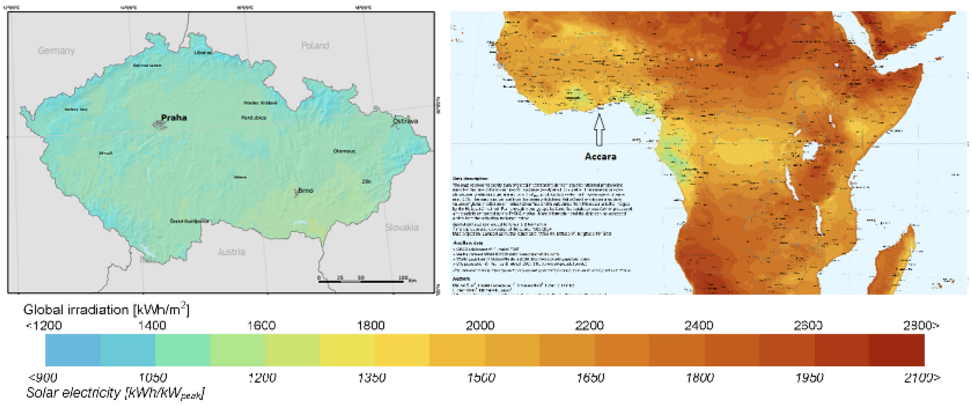

Figure 3.2: The PV solar electricity potential in the Czech Republic and Africa [29, 30, 31]

The results from the JRC online calculator shows the difference between the fixed system with the module slope 33° and orientation −2° and the two–axis system which follows the sun as it moves across the sky. For the generated results refer to Appendix A. The other online calculator, which is available from source [32], has been used so that the rest of necessary data could be evaluated, such as the approximate number of modules for 30 MW PV plant which is 120 000 pieces. For the remain data refer to Tab. 3.1.

Refer to Tab. 3.1 which represents the principal attributes of two largest PV power plants in the world and the largest PV power plant in the Czech Republic for comparison:

Solar Star is located near Rosamond, California, which utilizes 1.7 million of single−axis tracking modules made from mono−crystalline silicon.

Desert Sunlight Solar Farm is situated in Mojave Desert, California, which uses 8.8 million thin−film cadmium telluride modules.

FVE Ralsko Ra1 is placed near Česká Lípa, the Czech Republic, which utilizes combination of various module material and axis tracking.

The data are not accurate, so they should be taken only as tentative. [26, 29, 30, 31, 33, 34, 35]

Table 3.1: Example of operational PV solar power plants

Name	**Output [MW]**	**Solar Irradiation [kWh/m^2]**	**Area [km^2]**	**Approx. Cost [B$]**
Solar Star	579	2400	13	2
Desert Sunlight Solar Farm	550	2400	16	1.4
FVE Ralsko Ra1	38.3	990	0.294	0.189

The average investment return for either Accara located PV power plant or the Czech Republic PV power plant can be calculated from the received data. The additional necessary knowledge for these calculations is the purchase price of solar energy in both countries. The company Doosan Škoda Power achieved the purchase prices for renewable energy technologies in Ghana directly from the Ghana Gazette confirmed by Dr. Emmanuel K. Annan in the year of 2013. The purchase prices of PV energy have been detected for the same year in the Czech Republic, so that the results could be compared. Lets assume that the purchase prices have not changed rapidly since 2013. [28, 36, 37]

Table 3.2: 30 MW PV power plant in Ghana and in the Czech Republic

Country	**Approx. Cost [M$]**	**Purchase Price [$/kWh]**	**Net Electricity [GWh/year]**	**Payback Period [year]**
Ghana	49.2	0.2	47.2	5.2
Czech Republic	49.2	0.1	28.4	17.32

For the average monthly sum of global irradiation per m^2 absorbed by modules of 30 MW PV solar power plant and the total sum of it per year refer to Appendix A. The electricity generated by the modules follows the amount of absorbed solar irradiation. For the brief tentative summary of main differences between Ghana and the Czech Republic located 30 MW PV power plant refer to the Tab. 3.2 which describes purchase prices, invested money, electricity production per year and payback period for the same installation in both countries while considering the fixed module system.

3.2 Parabolic Troughs

There has been a huge boom of concatenated solar power plant construction over the past few years. For the list of all CSP plants all around the world which are operational, under construction or under development refer to [32]. The basic parameters of the CSP plants are described there, such as: technology, location, solar field area, type of HTF, solar field inlet and outlet temperature, turbine capacity, storage type, storage capacity, etc. The map pictured below also shows the CSP output of the plants placed in various locations in the world. [38]

From these data the most suitable solution for CSP power plant may be guessed, but of course the choice of the perfect construction is not easy and it cannot be asserted that only one combination of all the available components is the right one.

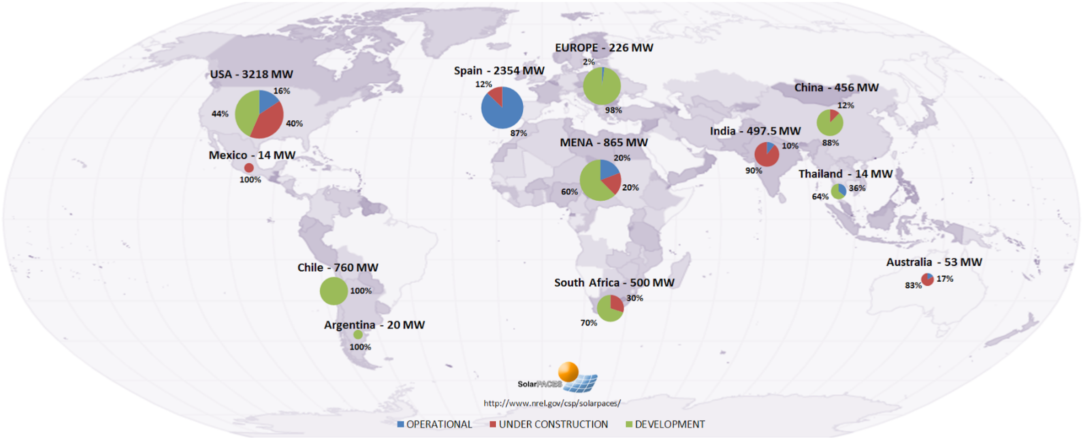

Figure 3.3: The map of CSP plant decomposition from year 2013 [38]

The parabolic trough CSP power plants are probably built the most often all around the world. According to National Renewable Energy Laboratory (NREL) there are already almost 100 operational, under development or under construction PT CSP plants in the world. There are 21 countries in the world which already exploit the solar power using operational CSP plants, such as Algeria, Australia, South Africa, Israel, Mexico, Spain, United Arab Emirates, United States, etc. Three of these PT power plants have been chosen, each of them performs various output and characteristics. [38, 39]

Andasol–3

This PT power plant is located in Andalusía, Spain, and it is one third of the Andasol Solar Power Station which is separated into three power plants – Andasol–1, 2, 3. All of them boast with same output – 50 MW. The Andasol–3 embraces 312 rows of mirrors connected with the HTF (thermal oil) pipelines (90 km long). Molten salts are used as storage medium and the thermal storage capacity is more than 7 hours. For more information refer to Tab. 3.3. [38, 39]

KaXu Solar One

The KaXu Solar One power plant is located in South Africa. The biggest benefit of this location is that the sun shines approximately 350 days a year there. The power plant also uses thermal oil as HTF and molten salts as storage medium. The storage capacity is around 3 hours. [39, 40]

For more information refer to Tab. 3.3.

Solana Generation Station

This PT power plant boasts with the biggest electrical output of all PT power plants in the world and is located in Arizona, United States. On the other hand, two 140 MW steam turbines must be utilized there. Terminol VP−1 is used as HTF and the storage capacity of molten salts is around 6 hours. The natural fossil backup is included in the power plant, so that it could provide electricity continuously. Additional necessary information is available in Tab. 3.3. [38, 39]

Table 3.3: Andasol−3, KaXu Solar One, Solana Generating Statin comparison

Name	Output [MW]	Solar Irradiation [kWh/m^2]	Solar Field Area [km^2]	Approx. Cost [B$]	Net Electricity [GWh/year]
Andasol−3	50	2200	0.5	0.356	175
KaXu SolarOne	100	2400	0.8	0.86	330
Solana Generating Station	280	2400	2.2	2	944

3.3 Tower Solar Plant

The tower CSP technology may be of various modifications, number of towers, number of HTFs in the cycle, type of thermal storages, etc, so it cannot be easily decided what the best solution is. From the data posted by the NREL on their website three various CSP tower plants will be chosen, just like in the PT evaluation case, so that the approximate spread of the tower layout could be visualized. There is a need to take these result numbers only as tentative, because the investment cost and other characteristics of these plants are not accurate and usually the published data, which are available for public, are not precise.

Gemasolar

Gemasolar is the first tower solar power plant introduced in this thesis. This plant is located in Andalucía, Spain. 2,650 flat heliostats which reflect the sun rays to a single receiver placed on the top of an almost 120−metre high tower are spread over an area larger than 0.31 km^2. Molten salts are used as either HTF or storage medium. The storage capacity is around 15 hours. The thermal cycle efficiency is 40 %. The estimated cost differs according to various sources, so it only remains that especially the information about invested money is not accurate and that the data must be taken only as tentative. For more data refer to Tab. 3.4 where the approximate investment cost of Gemasolar follows the data published by Dr. Germain Augsburger in his doctoral thesis. This source has been chosen so that the evaluation of a single tower and multiple tower CSP plant layout of the same output could be realized according to the data measured by Mr. Augsburger. For this comparison refer to Tab. 3.5. [16]

Crescent Dunes Solar Energy Project

This tower power plant is situated in Nevada, United States. The power plant includes 10−hour direct thermal storages. The HTF for circulating through the external cylindrical receiver is the same as the storage fluid, which means that no heat exchanger, apart from the steam generator, is required. Molten salts, as HTF fluid, absorb the heat from the sun and then they can store the thermal energy in the storages for a future use. The height of the tower is around 160 m and the project consists of 10,347 heliostats. [38, 41]

For more information refer to Tab. 3.4.

Ivanpah Solar Electric Generating System

Ivanpah is located in California, United States, and the most interesting fact about this three−tower power plant is that it includes no thermal storages and also there is only one working medium in the whole cycle − water. The HTF (water) is kept in water tanks in the receivers at the top of the towers so that it could be evaporated during the day light. The height of towers is approximately 140 m and they are surrounded by heliostat fields with around 173,500 heliostat assemblies while each heliostat consists of two mirrors. The cycle solar−electricity efficiency is 28.72 %. The low cycle efficiency, comparing to Gemasolar power plant, for example, might be caused by the single working medium in the whole cycle. As mentioned before in chapter 2.4.4.1, water does not achieve such good performances as molten salts or liquid sodium. Ivanpah also includes the fossil backup which is in this case natural gas. [38]

For more information refer to Tab. 3.4. [16, 38, 41]

Table 3.4: Operational tower solar projects

Name	**Output [MW]**	**Solar Irradiation [kWh/m^2]**	**Solar Field Area [km^2]**	**Approx. Cost [B$]**	**Net Electricity [GWh/year]**
Gemasolar	20	2172	0.305	0.1504	87.46
Crescent Dunes	110	2684	1.2	1	500
Ivanpah	392	2717	2.6	2.2	1079.2

Gemasolar – Single vs. Multiple tower layout

According to data measured by Germain Augsburger the single tower power plant Gemasolar might be upgraded by suggestion of some layout differences.

From the Augsburger's charts it is clear that the most suitable solution from the efficiency point of view for Gemasolar layout would be the three–tower decomposition. The annual field efficiency and the annual net electricity do not change distinctly for three, four or five–tower layout. On the other hand, the investment cost for five–tower decomposition is almost M$ 100 higher than the three–tower solution. [16]

For the same number of heliostats (2,650) as in Gamasolar decomposition, the annual field efficiency and the maximal receiver incident power for a three–tower power plant increase rapidly. When the cosine, attention and spillage losses are taken into consideration, the three–tower layout field efficiency increases of more than 14 %. The maximum receiver incident power raises from 138.2 MW_{th} (Gamasolar) up to 179.2 MW_{th} for the three–tower improvement. On the other hand, the total investment cost increases by 70 % especially because of the additional towers – receivers. [16]

In Appendix B there are available some charts depicted by Germain Augsburger. These charts typify the results of measurement of the most suitable tower distance for the three–tower Gemasolar case. For more information refer to Tab. 3.5 or for Appendix B. [16]

Table 3.5: Single vs. three–tower decomposition of 20 MW CSP plant

Layout	**Output [MW]**	**Annual Field Efficiency [-]**	**Approx. Cost [B$]**	**Net Electricity [GWh/year]**	**Cost per 1 $W_{inst.}$ [$/1 W]**
Single Tower	20	45.3	150.4	87.46	7.52
Three Tower	20	59.8	256.6	120	12.83

Conclusion

The main aim of this thesis has been the introduction and comparison of three various technologies – photovoltaic technology, parabolic trough and tower concentrated solar power systems. Moreover, the geographical, energetic and economical evaluation of these technologies has been realized and the steam turbine for CSP power plants has been introduced, but due to the extensive content of the thesis task there has not been much space to follow details and accomplish a sufficient evaluation of each technology separately.

1. The Comparison Issues and Achievements

At first I planned to compare already running projects from either PV or CSP solar power plants. According to them I hoped to suggest a 30 MW solar power plant for each technology so that I could present objective comparable results, but I had to desist from this idea soon, because I realized that this comparison would not be presentable very much. Just for an idea you can refer to Tab. 3.6 in Appendix C where the results of 30 MW solar power plants are represented for all three technologies.

1.1 Photovoltaic Technology Evaluation

The suggestion of a 30 MW PV power plant has been possible, due to the online calculators which allow us to set the parameters we require. On the other hand, these calculators are highly inaccurate. The investment cost is not complete, because solar calculators do not follow the specific requirements which the defined location demands, such as the surface treatment before the own construction, the outlet of surplus heat, the construction costs, etc. For more precise results a supply company should be asked to prepare an accurate offer for the specific project.

Although the data in Tab. 3.2 are not accurate, they enable us to find at least some evaluation. The same fixed system would provide almost 20 $GWh_{electrical}/year$ less in the Czech Republic than in Ghana and the payback period would be more than 12 years longer. In Ghana it would make sense to invest money to more efficient module materials or/and two–axis tracking system which would produce even more electricity per year. On the other hand, the use of cooling system probably should be considered there, due to the high heat losses and material degradation. The most important advantage of PV technology is that it can be built almost anywhere, so the solar energy can be exploit even in locations with lower solar potential.

1.2 Concentrated Solar Power Technology Evaluation

The suggestion of PT or tower CSP solar power plant with the installed output 30 MW has not been easy at all. From chapter 3 it is clear how specific every single project is. The range of possible components is so extensive that it cannot be easily said which combination is the best one. The chapter 3 presents how distinctly every little difference (in the component selection point of view) can influence the final cost and efficiency.

The number of working fluids (which the number of heat exchangers follow) in the cycle effect the final cost a lot, as well as the use/disuse of thermal storages does. The number of towers (in tower system case) are very important, too. It is certain from chapter 3 (Gemasolar – Single vs. Multiple Tower Layout). On the other hand, some things are certain from the literature or the described project. For example, molten salts are used most often as a storage medium and in case of a tower decomposition they are usually utilized as HTF as well. The PT plants usually utilize the thermal oil as HTF instead.

2. Current Trends

The photovoltaic technology does not show much more potential for development, except for the nano–layers which might be considered to increase the efficiency of PV modules. Nevertheless, small photovoltaic power plants are very common all around the world in a roof or a small scale field layout. Although the biggest boom in advanced countries has already passed.

On the other hand, the development of CSP technology is not finished at all. From the countries which already boast with operational CSP plants might be estimated which locations are the most suitable ones for this technology. The largest projects are situated in countries with a stable economical situation and high solar irradiation, such as United States, China, the South African Republic and Spain, but there are already some more projects in other countries in the world, such as Chile, Algeria, Marocco, Saudi Arabia, etc. These places usually have one thing in common – the annual solar irradiation is higher than 2000 kWh/m^2 there.

3. Future Development

I believe that solar energy, especially the CSP technology, has got a huge potential in electricity production. I would say that nowadays the most demanding, and still unfulfilled, requirements are the effective ability of electrical energy storing and the stability of necessary resources for electricity production. If the development of thermal storages and

HTFs is successful enough in next few years, it will be possible to store energy produced by the sun in a heat form, instead of an electrical form, long enough, so we might be able to regulate or even prevent the overload of distribution grid. I think that thermal storages will make the CSP power plants comparable to fossil or nuclear power plants and due to them the solar energy will have a chance to take an important part in the world electricity production.

And when it comes to the decision which technology and which components to choose? One question should be asked. What is the most important requirement – the low investment cost, short payback period or the high annual net electricity which highly depends on the plant efficiency?

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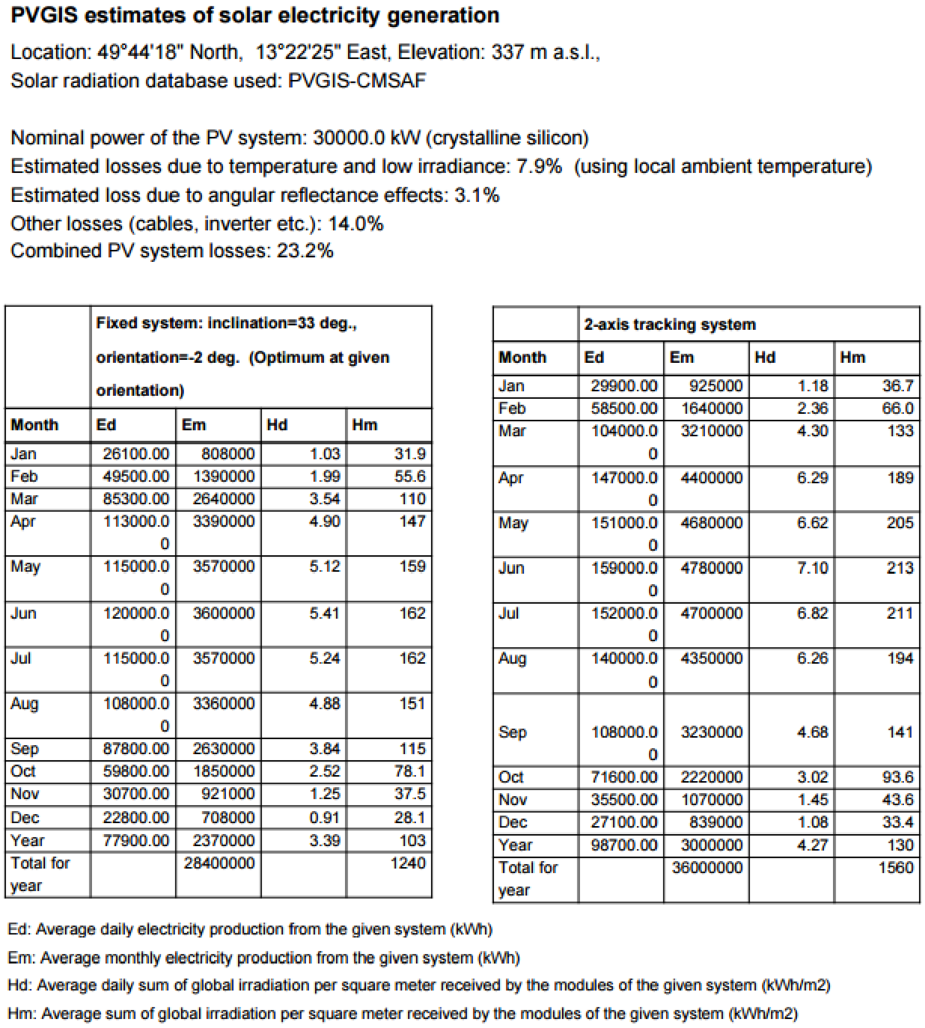
Appendix A

Appendix 1 JRC Calculator Data



PVGIS estimates of solar electricity generation

Location: 49°44'18" North, 13°22'25" East, Elevation: 337 m a.s.l.,
Solar radiation database used: PVGIS-CMSAF

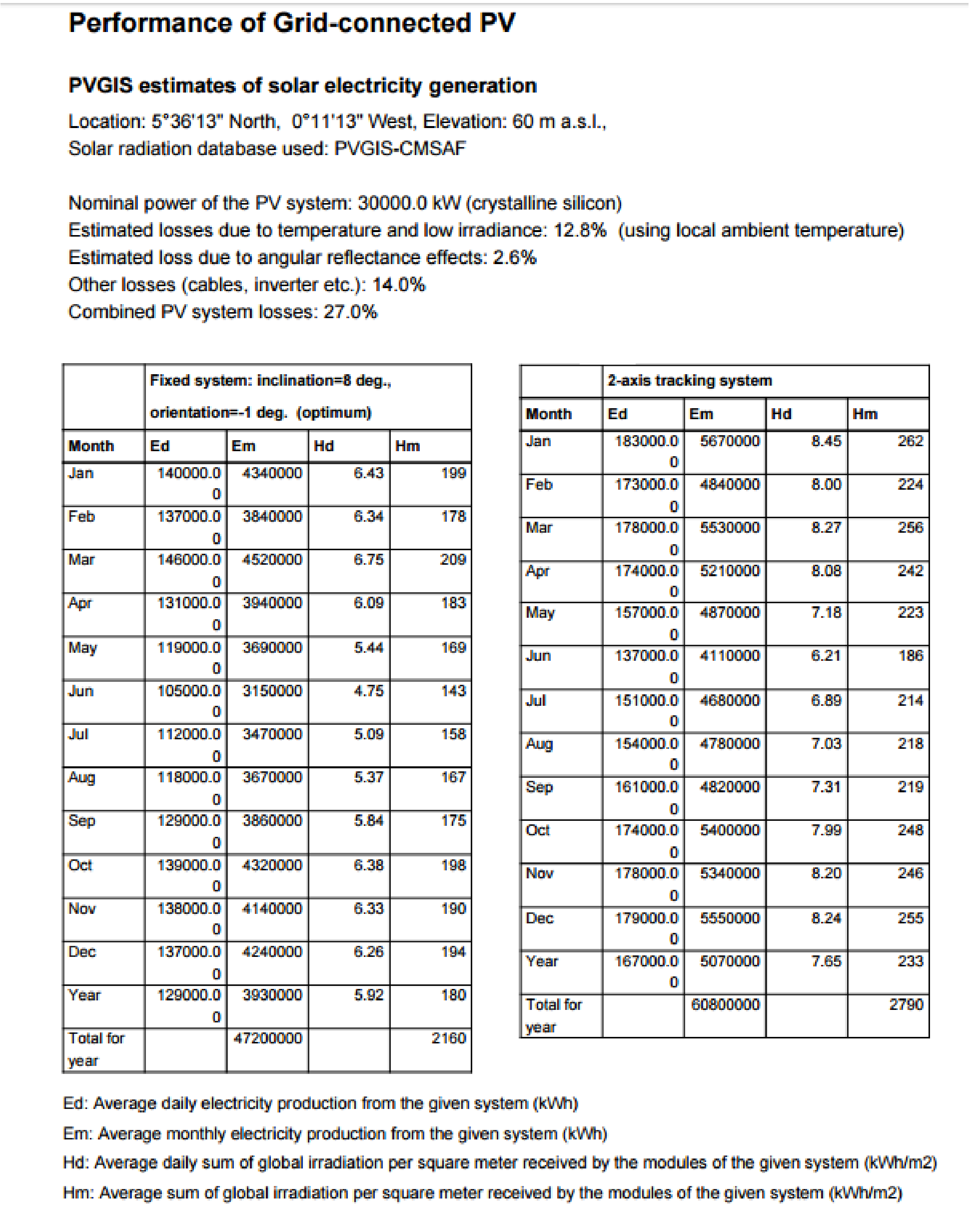
Nominal power of the PV system: 30000.0 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 7.9% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 3.1%
Other losses (cables, inverter etc.): 14.0%
Combined PV system losses: 23.2%

	Fixed system: inclination=33 deg., orientation=-2 deg. (Optimum at given orientation)			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	26100.00	808000	1.03	31.9
Feb	49500.00	1390000	1.99	55.6
Mar	85300.00	2640000	3.54	110
Apr	113000.00	3390000	4.90	147
May	115000.00	3570000	5.12	159
Jun	120000.00	3600000	5.41	162
Jul	115000.00	3570000	5.24	162
Aug	108000.00	3360000	4.88	151
Sep	87800.00	2630000	3.84	115
Oct	59800.00	1850000	2.52	78.1
Nov	30700.00	921000	1.25	37.5
Dec	22800.00	708000	0.91	28.1
Year	77900.00	2370000	3.39	103
Total for year		28400000		1240

	2-axis tracking system			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	29900.00	925000	1.18	36.7
Feb	58500.00	1640000	2.36	66.0
Mar	104000.00	3210000	4.30	133
Apr	147000.00	4400000	6.29	189
May	151000.00	4680000	6.62	205
Jun	159000.00	4780000	7.10	213
Jul	152000.00	4700000	6.82	211
Aug	140000.00	4350000	6.26	194
Sep	108000.00	3230000	4.68	141
Oct	71600.00	2220000	3.02	93.6
Nov	35500.00	1070000	1.45	43.6
Dec	27100.00	839000	1.08	33.4
Year	98700.00	3000000	4.27	130
Total for year		36000000		1560

Ed: Average daily electricity production from the given system (kWh)
Em: Average monthly electricity production from the given system (kWh)
Hd: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2)
Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

Figure A.1: Czech Republic – results of 30 MW PV solar power plant [28]



Performance of Grid-connected PV

PVGIS estimates of solar electricity generation

Location: 5°36'13" North, 0°11'13" West, Elevation: 60 m a.s.l.,
Solar radiation database used: PVGIS-CMSAF

Nominal power of the PV system: 30000.0 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 12.8% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 2.6%
Other losses (cables, inverter etc.): 14.0%
Combined PV system losses: 27.0%

	Fixed system: inclination=8 deg., orientation=-1 deg. (optimum)			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	140000.00	4340000	6.43	199
Feb	137000.00	3840000	6.34	178
Mar	146000.00	4520000	6.75	209
Apr	131000.00	3940000	6.09	183
May	119000.00	3690000	5.44	169
Jun	105000.00	3150000	4.75	143
Jul	112000.00	3470000	5.09	158
Aug	118000.00	3670000	5.37	167
Sep	129000.00	3860000	5.84	175
Oct	139000.00	4320000	6.38	198
Nov	138000.00	4140000	6.33	190
Dec	137000.00	4240000	6.26	194
Year	129000.00	3930000	5.92	180
Total for year		47200000		2160

	2-axis tracking system			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	183000.00	5670000	8.45	262
Feb	173000.00	4840000	8.00	224
Mar	178000.00	5530000	8.27	256
Apr	174000.00	5210000	8.08	242
May	157000.00	4870000	7.18	223
Jun	137000.00	4110000	6.21	186
Jul	151000.00	4680000	6.89	214
Aug	154000.00	4780000	7.03	218
Sep	161000.00	4820000	7.31	219
Oct	174000.00	5400000	7.99	248
Nov	178000.00	5340000	8.20	246
Dec	179000.00	5550000	8.24	255
Year	167000.00	5070000	7.65	233
Total for year		60800000		2790

Ed: Average daily electricity production from the given system (kWh)
Em: Average monthly electricity production from the given system (kWh)
Hd: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2)
Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

Figure A.2: Ghana – results of 30 MW PV solar power plant [28]

Appendix B

Appendix 2 Multiple Tower Evaluation

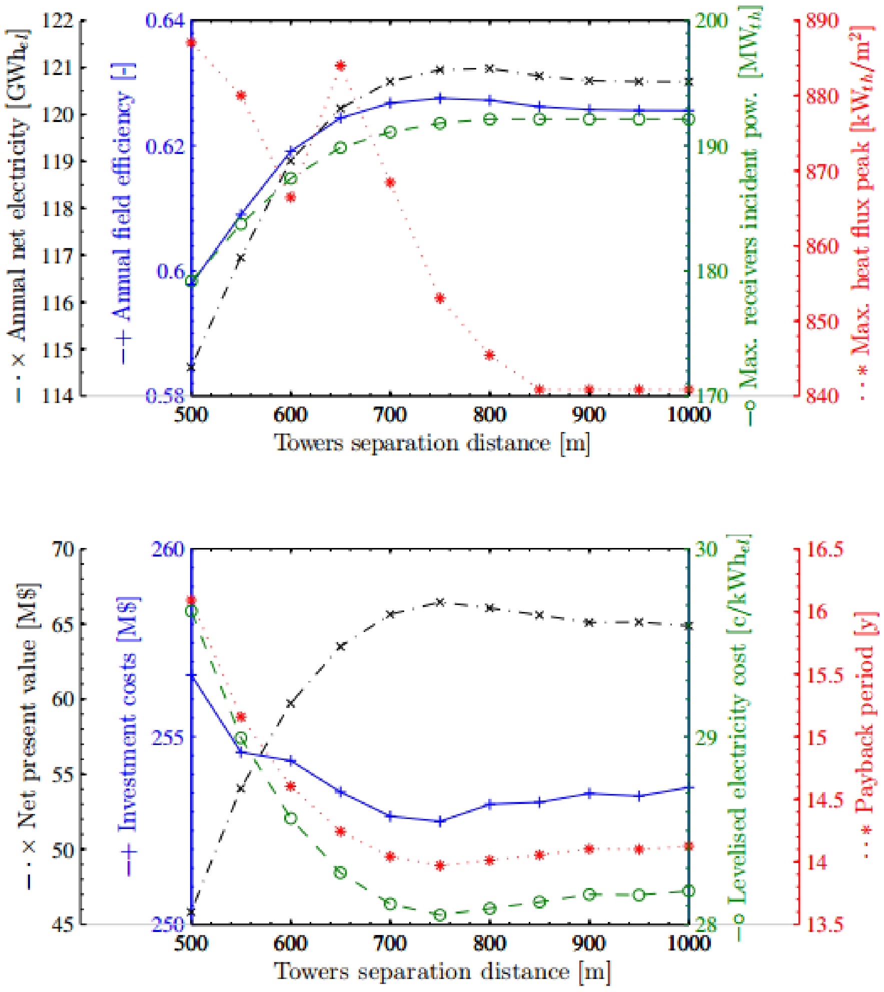


Figure B.1: Energetic and economical performance of multiple tower system [16]

Appendix C

Appendix 3 30 MW Power Plant Suggestion

With references to the chapter 3, where the introduction of 30 MW PV power plant located in Ghana is accomplished and also the Gemasolar and Andasol-3 projects are presented, the approximate data for PT and tower 30 MW CSP plants has been calculated. The approximate cost of each project has been divided by the total installed output. The investment cost per 1 MW has been gained and then it has been multiplied by the number of 30. From this result the approximate cost per 30 MW plant comes. Similarly, the annual net electricity has been calculated. Then the annual earned money has been gained by the multiply of the annual net electricity by the purchase price (the big advantage is, that in Ghana the purchase price for electrical energy does not differ for various solar technologies). The division of the approximate cost and the annual earned money has showed the term of payback period in years.

The PV 30 MW power plant has been suggested by utilization of the online calculators, for more information refer to chapter 3. The Gemasolar and Andasol-3 solar projects have been chosen because the annual solar irradiation per square metre of the locations where they are built is comparable to the annual solar irradiation in Ghana $-$ approximately 2200 kWh/m^2.

Table C.1: 30 MW plants comparison located in Ghana

Technology	Output [MW]	Purchase Price [$/kWh]	Approx. Cost [B$]	Net Electricity [GWh/year]	Payback Period [year]
Photovoltaic	30	0.2	49.2	47.2	5.2
Parabolic Trough	30	0.2	213.6	105	10.17
Tower	30	0.2	225.6	131.2	8.6