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## **DEPARTMENT OF FOREIGN LANGUAGES**

ÚSTAV JAZYKŮ

# **ANALYSIS OF A PHOTOVOLTAIC POWER PLANT OPERATION**

ANALÝZA PROVOZU FOTOVOLTAICKÉ ELEKTRÁRNY

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- 1) Mc Evoy, A., et al. (2012). Practical handbook of photovoltaics: Fundamentals and applications. Waltham: Academic Press.
- 2) Poulek, V., & Libra, M. (2006). Solar energy: Photovoltaics - promising trend for today and close future. Prague: CUA.
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## **ABSTRAKT**

Tato práce umožňuje náhled do problematiky fotovoltaických systémů a jejich využití pro výrobu elektrické energie, která hraje v dnešní době důležitou roli. První část je především zaměřena na charakteristiku vybraných fotovoltaických článků. Dále se práce zabývá legislativou v oblasti fotovoltaiky v České republice. Tato kapitola je pak dále rozšířena o kroky potřebné k realizaci fotovoltaické elektrárny. Závěrem je provedena technicko-ekonomická analýza konkrétní fotovoltaické elektrárny.

## **KLÍČOVÁ SLOVA**

Solární energie, fotovoltaický článek, fotovoltaický panel, fotovoltaická elektrárna, doba návratnosti.

## **ABSTRACT**

This paper provides an insight into the issues of photovoltaics and its utilisation, having a significant role to play in today's clean electric energy production. The first part is primarily focused on the characteristics of the common photovoltaic cells known in this field. The work then deals with the legislation related to photovoltaics in the Czech Republic, as well as it is broadened by the steps for a PV plant realization. As regards the last chapter, a technical and economic analysis of a particular ground-mounted photovoltaic power plant is carried out.

## **KEYWORDS**

Solar energy, photovoltaic cell, photovoltaic panel, photovoltaic, power plant, payback period.

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V Brně dne .....

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(podpis autora)

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## **List of Symbols and Abbreviations**

PV – Photovoltaic

TiO<sub>2</sub> – Titanium dioxide

SiO<sub>2</sub> – Silicon oxide

EVA – Ethyl vinyl acetate

CdTe – Cadmium telluride

CIGS – Copper indium gallium diselenide

PECVD – Plasma-enhanced chemical vapour

SWE – Staebler-Wronski Effect

kWh – Kilowatt hour

MWh - Megawatt hour

kWp – Kilowatt peak

DC – Direct current

AC – Alternative current

EUAs – European Union Emission Allowances

DNO - Distribution Network Operator

## **Introduction**

Human beings have not been able to imagine their lives without electric energy since the 19<sup>th</sup> century known as the era of “steam and electricity.” Nowadays, humankind is becoming to be aware of the scourge of using the non-renewable energy sources, such as various fossil fuels: coal, petroleum, gas. The major problem lies in both the reliance on finite supplies of fossil fuels and their negative impact on the environment in the form of undesirable poisonous gases or fly ash, changing the natural concentrations of the atmosphere. The exponential growth of the population equals the exponential consumption of energy. Thus, the usage of alternative energy sources had to be taken into account. As a result, a new challenge emerged in the second half of the 20<sup>th</sup> century that represents a search for new and sustainable energy sources. One of those renewable energy forms is photovoltaics, which is today still quickly growing energetic sector all around the world in spite of a few decades of development.

It is the utilisation of energy from sunlight, which represents an interesting alternative for many people. Energy produced by photovoltaic power plants has many significant advantages, such as an environmentally friendly operation associated with no fuels required, and relatively low operating costs with the possibility to reduce living expenses by covering one’s own electricity consumption. Moreover, electricity provided by photovoltaics is already one of the most effective cost solutions for thousands of people in many parts of the world where there is no access to power grid.

Therefore, the purpose of this paper is to provide a closer look at the possibilities of utilisation of solar radiation for the production of electric energy in the field of photovoltaics and at the technology used as well. The first part deals with the conversion of solar energy into the electric one by describing the principle of photovoltaic effect. Furthermore, the first chapter characterizes particular generations of photovoltaic cells including selected types along with their utilisation. The following chapter is then focused on both the legislation related to photovoltaic power plants and the necessary steps for a PV plant realization. The aim of the last chapter is to carry out the technical and economic analysis of the particular photovoltaic power plant.

# 1 Photovoltaic Cells

In principle, photovoltaic cell is a device that enables direct conversion of energy from the sun into electric energy by using the photovoltaic effect. Individual solar cells typically generate small amounts of electric energy. In order to make the generation even more effective, individual cells are connected in series and in parallel to form a solar module generally known as a solar panel.

## 1.2 Photovoltaic Effect

The photovoltaic effect was first demonstrated by Alexandre-Edmond Becquerel in 1839. He observed that certain materials placed in acidic solution and connected to platinum electrodes were able to produce an electric current when exposed to light.

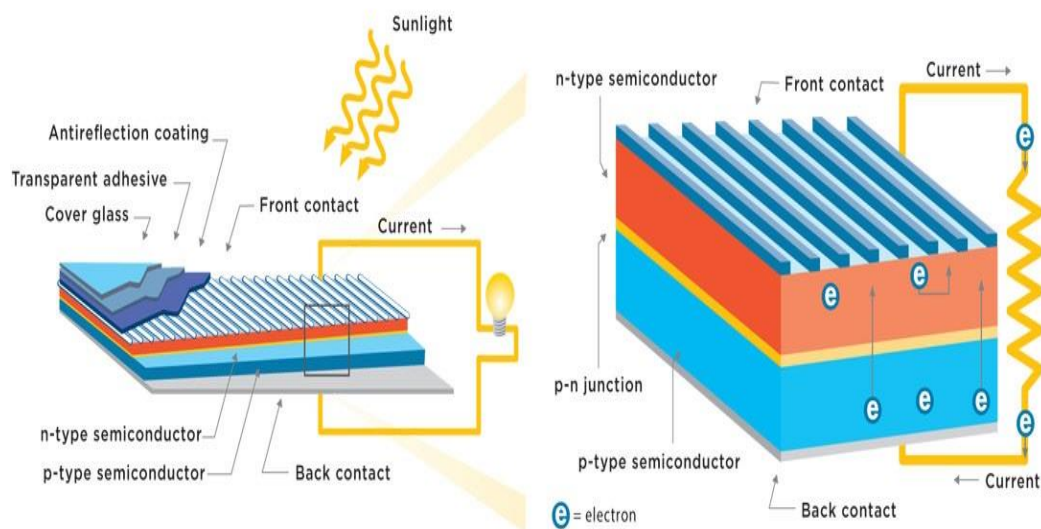
As regards photovoltaics, the most common semi-conductor material used for creation of the photovoltaic cells is silicon, for being the second most widespread element on earth. Generally, semi-conductors are used instead of metals because the goal of reaching as best efficiency as possible is desired.

Light is basically the form of electromagnetic radiation composed of elementary particles called photons. When these particles happen to hit the solar cell, three possibilities may occur. They can be absorbed by the cell, reflected, or they can pass straight through the cell. The electric current is generated only in the case of photon absorption. The more photons (intensity of the light) are absorbed by the photovoltaic cell, the greater the current is generated. Due to the absorption of photons, electrons are knocked from the bond. The positions left by the electrons are named “holes” acting as positive charges. Subsequently, the negatively charged electrons and the locations of positively charged holes are able to move around freely (Boxwell, 2014; Libra & Poulek, 2010). For better understanding of such a process, the internal structure of PV cell must be explained.

In general, photovoltaic cells contain two plates of semiconductor material, which are combined together, both of them with specially added impurities called dopants, for a purpose to modulate their electrical properties. The result is that one region is of N-type, with an excess of electrons, thus being negative, while the other one is of P-type,

in which we can observe positively charged electron holes. This 2-layer structure is called a P-N junction triggering the creation of an internal electric field that acts like a diode, allowing electrons to flow from the P region to the N region, but not the other way round (Boxwell, 2014; Libra & Poulek, 2010).

However, on the condition that photons strike the silicon cell with enough energy, free electrons and holes will be created, and the electric field makes them to move in opposite directions - electrons are driven to the N-type side and holes to the P-type side of the junction. Consequently, the separation of positive and negative charges across the junction results in the accumulation of free electrons in the N region causing a potential difference (Boxwell, 2014; Libra & Poulek, 2010). To allow the electric current to flow, both the front contact usually formed by a transparent conducting oxide and the metal contact at the back side are installed to the layers, and connected with the help of cable enabling mobile electrons to travel through the external circuit, thus electricity is generated (see figure 1).



*Figure 1.* Schematic diagram demonstrating the operation of PV cell (retrieved from ucsusa.org).

Although photovoltaic cells generate most of their electricity from the direct sunlight, certain types are also able to generate it on cloudy days, and some systems are even capable of producing very small amount of electricity on bright moonlit nights.

## **2 Types of PV Cells**

Various kinds of materials and technologies have been used during the last decades within the scope of photovoltaics, as well as the effort to obtain as best efficiency as possible. As far as types of PV cells are concerned, four “generations” of them are distinguished according to their successive development.

### **2.1 The First Generation**

The first generation solar cells are predominately based on silicon structures, such as monocrystalline and polycrystalline ones. Production of these technologies comprises approximately 80 % of the current PV market. Such kind of technology reaches an efficiency of 14-20 %. The major advantages of this category lie in a good performance and long-term power stability. Conversely, they are rigid and require a lot of energy during the production process (Carvalho & Paulino, 2015).

#### **2.1.1 Monocrystalline Cells**

Monocrystalline PV cells belong among the oldest types of PV cells having typically black or iridescent blue colour. First developed in 1950s, they are commonly made from a single crystal ingot of highly pure molten crystalline silicon by using so called Czochralski process. In this case, the method is responsible for a growth of large cylindrical ingots of single-crystal silicon. First, these ingots are sawn into wafers with thickness of approximately 0.3 mm, and then processed into individual cells, and wired together forming a solar panel. Second, cleaning with a chemical agent and etching of the wafers follows in order to remove any impurity from the surface, and add a texture to it as well (see chapter 2.1.3). Eventually, a thin layer of phosphorus of a high temperature is applied to the wafers, leading to creation of the P-N junction (Weller et al., 2010).

Monocrystalline silicon shows predictable, uniform behaviour, however, due to the sophisticated manufacturing processes required, it is simultaneously slightly more expensive. On the contrary, it features higher efficiency of about 15-20 % in comparison with the other types of silicon cells (Weller et al., 2010).

The resulting monocrystalline module is made up of number of cells connected either in parallel or in series to produce higher current and voltage, therefore higher power. Figure 2 demonstrates the monocrystalline module. As we can see, corners of the cell are cut off, making this characteristic shape of octagonal pieces. It is a compromise between the wasted space of the cell material and the effort to reach better surface area for the solar energy absorption.



*Figure 2.* Monocrystalline module (retrieved from solarreviews.com).

### **2.1.2 Polycrystalline Cells**

Polycrystalline cells are one of the most common types. The process of manufacturing is slightly different from the monocrystalline ones. Molten crystalline silicon is first casted into square ingots that are cooled and solidified under meticulously controlled temperature conditions. As a consequence, the distinctive edges and grains are formed within the cell behaving like crystal imperfections (see figure 3), which cause the slight decrease in efficiency of energy conversion compared to the monocrystalline cells. As for the last step, the square ingots are cut into bars, and then into wafers (Weller et al., 2010).

Polycrystalline cells are slowly getting closer to the monocrystalline ones in terms of efficiency, standing at about 15 %. Moreover, since the shape of these cells is rectangular, resulting modules contain less wasted space. It is also important to note that the process of producing polycrystalline cells is much simpler and significantly cheaper unlike the one of other silicon types. That is the main reason why they have become the dominant technology at the global photovoltaic cells market.



*Figure 3.* Polycrystalline module (retrieved from aurinkosahko.net).

### **2.1.3 Structure**

As it has been already mentioned, certain losses of light absorption may occur. Since the silicon is very shiny material, the possibility of reflection of the photons before energizing the electrons arises. In order to minimize these losses, a special antireflection coating is applied to the silicon wafers. Mostly titanium dioxide ( $\text{TiO}_2$ ), silicon oxide ( $\text{SiO}_2$ ) and some other types of materials are utilised for this purpose. For instance, the Sono-Tek Corporation invented an ultrasonic spray suitable for application of thin layers of anti-reflection coating in the manufacturing process (Sono-Tek Corporation, 2016).

Reflection can also be minimized by the means of so called surface “texturing” accomplished in a number of ways. Silicon substrates used in commercial solar cell procedures comprise a near-surface saw-damaged layer which has to be removed. Removal of this layer is usually accomplished by the method of “etching.” It has to be slightly modified when applied to the substrates. Too fast or too prolonged etching may lead to problems with interruptions of metal contacts. This process, as long as conducted under adequate control, produces uniformly distributed pyramids with the height of  $3\text{-}5\mu\text{m}$  that is optimal for the most effective suppression of reflection losses (McEvoy, Markvart & Castañer, 2012).

Another important element related to PV cells bears the name “encapsulant.” It is used to provide adhesion between the top and the rear surfaces of modules. Encapsulant is supposed to maintain stable state even at higher temperatures. The optical transparency and the low thermal resistance are other key features that must be satisfied,

too. EVA (ethyl vinyl acetate) is the most common material used for the purpose of adhesion (Honsberg & Bowden, n.d.).

Lastly, let us skip over to the outside part often composed of a cover plate made of tempered low iron glass, which protects the cell from the external environment. Such a special cover guarantees low cost, good water-resistance and partial self-cleaning properties as well (Honsberg & Bowden, n.d.).

## **2.2 The Second Generation**

The second generation represents thin-film technologies that aim at a lower material consumption of PV cells by using thin layers of semiconductor material. Due to the absence of silicon wafers, the second generation solar cells are characterized by lower material consumption, thereby making the production process simpler - it has been possible to considerably reduce their production costs compared to the first generation. Solar cells of the second generation can even be manufactured in such a way that they feature flexibility to some degree - they might be packaged and utilised as flexible and lightweight building-integrated structures, for example. The three most common thin-film materials are cadmium telluride (CdTe), amorphous silicon and copper indium gallium diselenide (CIGS) with efficiencies ranging between 6 – 10 % (Carvalho & Paulino, 2015).

### **2.2.1 Amorphous Silicon Cells**

One of the most developed and widely known thin-film photovoltaic cells made from thin film silicon of about  $\mu\text{m}$ . Amorphous silicon cells are, at present, predominantly deposited by plasma-enhanced chemical vapour deposition (PECVD), which preferably involves a mixture of silane and hydrogen deposited onto flexible, inexpensive substrates, in most cases made of glass or plastics (Weller et al., 2010).

Owing to the fact that amorphous silicon is not of a crystalline form, it has larger absorption coefficient, and hence requires thinner absorbing layers and less material to be used - the reason for considerably reduced fabrication cost. Furthermore, deposition itself can be processed during very low temperature conditions at about 75 °C (Weller et al., 2010).

Conversely, they suffer from a significant reduction in power output over time, as the sun degrades their performance by affecting the quality of the photoactive layer in the first months of operation. This limitation is called the Staebler-Wronski Effect (SWE) that is widely considered to be a major limitation of amorphous silicon cells. However, the performance degradation can be slightly reduced through already mentioned PECVD (Alchemie Limited Inc., n.d.).

Currently, amorphous silicon PV module conversion efficiencies are in the range of 6 – 9 %. Very small cells at laboratory environment may reach efficiencies of up to 12.5 % (Maehlum, 2013). Due to their flexibility (see figure 4), these modules are perfectly suitable for flat and curved surfaces, such as roofs and facades of various buildings.



*Figure 4.* Amorphous silicon cell (retrieved from modernenviro.com).

### **2.3 The Third Generation**

The third generation contains technology which does not explicitly rely on a traditional P-N junction for separation of the photo-generated charge carriers. It focuses on approaches intended to achieve both high efficiency and lower per watt cost of the electricity generated. PV modules contained in this “generation” primarily include photo-electrochemical cells, cells based on nanowires, and organic solar cells. Ability to directly influence optical and electrical properties is a substantial advantage of these structures (Murtinger et al., 2009). Some of them are being commercialised, but it remains to be seen how successful they will be in taking the market share from existing, widely spread commercial technologies.

### **2.3.1 Organic Cells**

The materials used for organic solar cells are classed as organic semiconductors due to their ability to absorb light and conduct charge either within the molecules (such as conjugated polymers) or through a molecular network. Organic solar cells offer the potential for low-cost and low-temperature preparation methods, opportunity to be produced in arbitrary colours, mechanical flexibility, and the ability to be deposited on a wide variety of substrates, enabling an enlarged range of applications in the field of photovoltaic technology. Despite being inexpensive, such cells do not achieve high efficiencies. However, their success in recent years has been developed mainly by many successful improvements to attempt higher efficiencies. The acceleration in the commercial sector is evident among increasing number of companies, existing materials and manufacturers who have added organic photovoltaics to their range of goods. Besides low cost, the technology uses abundant, non-toxic materials, as well as based on a very scalable production process ensuring high productivity. As a consequence, organic solar cells are becoming a considerable competitor to other PV technologies in some applications in the terms of manufacturing costs that are regularly continuing to decline owing to processes with low consumption of materials and energy (NanoFlex Power Corporation, n.d.; Phys.org, 2014).

In addition to the lower efficiency, there is still a major challenge to reduce their instability over time. Although impressive recent stability results have been achieved in accelerated degradation tests, these cells are not able to achieve lifespans of more than a few thousand hours so far, thus limiting their application to smaller consumer products rather than to larger building-integrated applications. Since organic solar cells feature lightweight and flexibility, it makes them ideal for mobile applications and for fitting to a variety of uneven surfaces (NanoFlex Power Corporation, n.d.; Phys.org, 2014).

### **2.3.2 Nanowire-based Cells**

In recent years, significant researches have been conducted on the materials in the field of nanostructured solar cells towards obtaining an enhanced performance. Scientists from the Ecole Polytechnique Fédérale de Lausanne in Switzerland have proved that nanowires show a great potential in photovoltaic technology, being able to concentrate the sunlight up to 15 times of the normal sunlight intensity, hence predicted to become

one of the most effective materials in the field of solar cells. Since the diameter of a nanowire crystal is smaller than the wavelength of the light coming from the sun, resonances in the intensity of light around and inside the nanowires are triggered. As a consequence, the resonances can generate a concentrated sunlight in which energy is converted, enabling to produce a higher conversion efficiency of the sun's energy (Scoutter, 2014; Phys.org, 2013).

Scientists have recently come up with a relatively cheap and easy way of making nanowires from perovskite, a material composed of calcium titanate, which exhibits very high light-absorption efficiency provided by its atomic structure. It is necessary to create billions of nanowire copies resembling each other like identical twins in order to achieve as best efficiency as possible. With regard to fabrication process, so-called “slip-coating” technique is utilised during which perovskite is inserted between two simple glass coverslips. By means of pressing the liquid material between the coverslips and then sliding them apart, tiny streams of thousands of perovskite nanowires in the form of needle-like structures grow within a few seconds (Scoutter, 2014; Phys.org, 2013). In addition, nanowires are also of great interest in photovoltaics because of the large surface area. Such feature is a major advantage that ensures absorption of a large quantity of the sunlight, and, therefore, these cells operate well on cloudy days or even during rainy conditions. Moreover, based on testing conducted by ČEZ and Elmarco, they are less sensitive to temperature changes (ČEZ, n.d.).

## **2.4 The Fourth Generation**

The fourth generation utilises special composite cells made of various layers of semiconductor material enabling to capture the solar spectrum, meaning that each layer uses a different wavelength. The key to achieve the efficient use of the solar spectrum is that each layer has a higher band gap than the one below, and all of them are mutually interconnected by tunnel diodes. Such cells could reach efficiencies of up to 43 % with upcoming improvements. The only major disadvantage involves increased expenses in terms of manufacturing complexity. Nowadays, the fourth generation technology is quickly emerging mainly in the field of concentrator photovoltaics (McEvoy et al., 2012).

## **3 Photovoltaic Systems**

According to their particular usage, the photovoltaic systems are divided into two main categories: stand-alone (off-grid) and grid-tied (on-grid) PV systems. This chapter will also include the possibilities for power production enhancement of PV modules.

### **3.1 Stand-Alone Systems**

Stand alone, or off-grid systems, are usually used in remote areas where connection to the power grid is not available, and where the price for the realization of the electrical connection would be significantly higher than the expenses on the system itself. Therefore, the most widespread use of stand-alone PV systems can be found in developing countries. In terms of the Czech Republic, it is applied across a variety of separated objects or buildings: sheds in mountains, caravans, radars measuring speed on the roads, lighting applications, a power supply for individual appliances, etc.

Great advantage of such systems is partial energy self-sufficiency - they run independently on the grid, thus providing reliable and free source of electricity, which is, in addition, not affected by a breakdown in the power grid. However, there is a substantial risk of instability of the whole system, especially during cloudy days, evenings and nights. In such cases when the production is minimal or absent, it is necessary to rely on a backup in the form of some other type of generator, or on employment of an energy storage device in order to satisfy the power needs.

### **3.2 Grid-Tied Systems**

As the name implies, this system is connected directly to the power grid, supplying all the electricity produced. Larger PV power plants, rather known as “photovoltaic fields” that are located on vast open spaces are common examples of on-grid systems.

As regards larger buildings and family houses, a combination of grid-tied PV system with extra battery storage, in other words so-called hybrid system, is currently dominating the PV market. In the past, it was possible to sell the excess electricity to the network operator if system happened to produce greater amount of energy than it was

actually consumed. Nevertheless, Czech Republic's legislation has no longer been supporting this action with regard to subsidy reception (see chapter 4.1 for more details). Instead, full consumption of energy is required - the reason why hybrid systems are coming into play. The figure 5 demonstrates a typical scheme of a hybrid PV system with a battery bank.

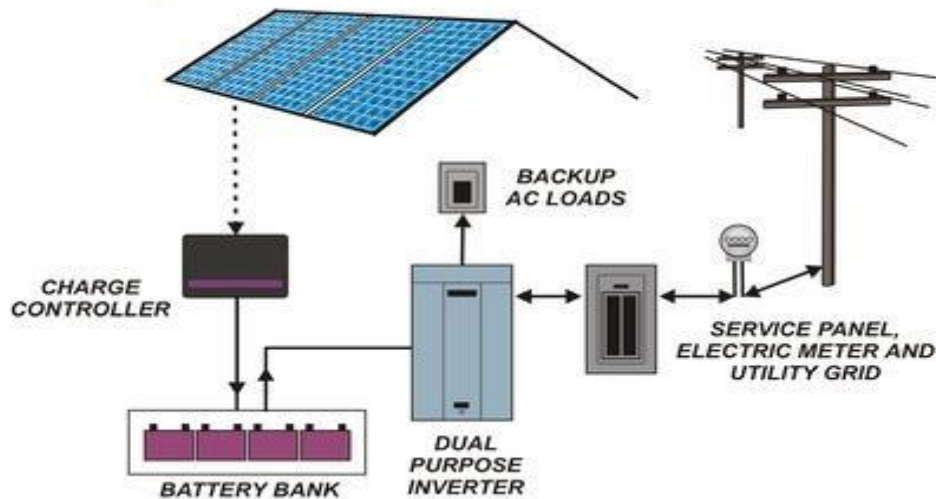


Figure 5. Hybrid PV system (retrieved from aladdinsolar.com)

In this case, the excess electricity which is not consumed is stored in a battery and utilised whenever it is necessary. As soon as there is no electricity available from PV panels, system automatically takes the energy from the grid. This is enabled by a battery-based grid-tie inverter, which is responsible for drawing the electric power from the battery bank by converting it into AC current at the suitable voltage and frequency for supplying domestic loads, as well as for delivering power from the grid to house. However, it must be possible to quickly disconnect a photovoltaic array from the inverter in case of maintenance or troubleshooting. This is provided by disconnect switch, usually installed between the battery bank and the inverter.

Another important element of this system is a battery charge controller, which influences the flow of current being delivered to the battery bank, thus, protecting it from overcharging and ensuring its lifespan maximization. Furthermore, it determines whether the power generated by solar panels runs equipment and lighting in the house immediately or whether batteries will be charged to be used later on (night time or cloudy days, as it has been already mentioned).

### **3.3 Enhancement of Power Production**

Generally, it would appear that conventional solar panels reach a maximum efficiency between 15-30 %. When the whole photovoltaic system is taken into consideration, the overall efficiency is even more decreased - particularly by reflection losses, temperature losses, losses in certain components and wires as well. Therefore, there is a great demand to develop technologies ensuring better efficiency of PV systems in order to enhance the overall operation of entire system. On the following lines, attention will be brought to the issues of concentrators and so-called “trackers.”

#### **3.3.1 Concentrators**

Concentrator is an optical device capable of focusing a solar radiation on the surface of PV cell. The aim of combining cells with concentrators is an attempt to reduce the cost of the electrical energy produced. Concentration has more recently been used as the mean of implementing highly expensive and sophisticated solar cells into the commercial sphere, meaning that significantly enhanced production compensates for higher prices - without the adoption of concentration technology, these extremely expensive cells do not pay off.

A typical PV concentrator usually contains three main elements: an optical collector, cell receiver and a heat sink to avoid any potential damage to the cell. The collector is either in the form of specific mirrors and lens or a combination of both. The individual wires attached to the cell must be of sufficient thickness to carry the large currents generated.

PV module must be directed towards the sun so that the light beam is focused properly on the receiver. The only disadvantage is that concentrator systems cannot collect diffuse radiation, but this drawback might be offset by combination with mechanically driven structures (tracking technologies) that will be described in the following chapter, directing the orientation of the collector towards the sun at all times.

#### **3.3.2 Systems with tracking stand**

Solar systems with tracking stand, in other words so-called “solar trackers,” are devices capable of adjusting the orientation of the panel according to the movement of the sun through a rotation from east to west throughout the day. Owing to such feature, solar

trackers are estimated to increase the output of solar modules by up to 40 % compared to the fixed installations, thus improving the economic side of a facility.

The issues of tracking stands appropriate for solar energy modules have been focused more attention on over the past years because of considerable improvements in the efficiency of solar systems associated with increased energy output, which results in decreasing price of energy produced. Nowadays, concentrator systems, which were mentioned in the previous chapter, are usually connected in combination with trackers to ensure that the sunlight is directed precisely at the focal point of the reflectors or lens. The reason for this is that solar trackers do not produce intended amount of energy unless pointed correctly towards the sun. On the other hand, this technology is not related to concentrated applications only, as solar tracking is exploited in other numerous applications.

Despite offering great energy production, there are also a couple of disadvantages of solar trackers. They are slightly more expensive than their stationary counterparts with regard to more complex technology and moving parts that are essential for proper operation. Hence, an acquisition of the solar tracking system leads to more equipment required. For instance, moving parts and gears must undergo a regular maintenance. Solar tracker is also more prone to be damaged in storm unlike the stationary structures, and comes with a 10-year warranty solely.

Solar trackers are divided into two basic categories: single and dual axis. The single axis trackers are based on the rotation on either a horizontal or a vertical axis, moving back and forth in a single direction. The horizontal type is used in tropical regions where the days are short and the sun gets very high at noon. The vertical ones are rather installed at high latitudes where the sun does not go very high, but summer days are longer.

Dual axis trackers are more sophisticated since they simultaneously make use of both horizontal and vertical axis. Such function enables tracking the motion of the sun virtually everywhere in the world. In most traditional PV applications, two-axis trackers are positioned in a way that they keep photovoltaic panels in a direct perpendicular position to sunlight for as many hours per day as possible.

## 4 Legislation

Fundamentals of the photovoltaics support can be found in the European Union Directive 2001/77/ES on the promotion of electricity produced from renewable energy sources in the internal electricity market. It was later amended and subsequently substituted by the Directive 2009/28/ES on the promotion of the use of energy from renewable sources, complexly covering the support adjustments and the usage of all kinds of renewable energy sources. The purpose of such a directive is to increase the share in production of electricity from renewable energy sources in the internal electricity market and create a basis for the future community framework as well (Kerebel & Stoerring, 2016).

Under the terms of the EU Renewable Energy Directive 2009/28/EC, general plan upon the whole EU was set, through which there is a necessity to reach at least 20 % of the final renewable energy consumption including the mandatory target of 10 % for the transport sector by 2020. However, the conditions of this plan differ from each EU Member State. As far as the Czech Republic is concerned, the European Commission has committed it to a legally binding target of sourcing 13 % of its final renewable energy consumption with the limit of 10 % regarding the transport sector (Kerebel & Stoerring, 2016).

In addition to the Directive 2009/28/EC, another law must be mentioned. As the Ministry of Industry and Trade of the Czech Republic (2016) states on its official website, the Act no. 165/2012 Coll. comprises National Renewable Energy Action Plan, which is being regularly updated. On 25 January 2016, the government of the Czech Republic confirmed a document assuming that the Czech Republic shall be able to achieve an objective in the form of 15.3 % share in the final renewable energy consumption and 10 % share in the transport sector by the end of 2020.

In response to the Directive 2001/77/ES, the Czech Republic implemented the support of electricity from renewable energy sources by means of the Act no. 180/2005 Coll. on the promotion of electricity produced from renewable energy sources and amendments to certain laws (since 1 January 2013, it has been replaced by the already mentioned Act no. 165/2012 Coll. on supported energy sources). The objective was to implement above mentioned EU directive to the national law.

However, not only the conditions, but also the level of financial support had to be changed over the couple of years as a response to a large increment in an installed power due to the favourable grants, as well as a rapid decrease in costs of photovoltaic technology mainly in the years 2009 – 2010 triggered by a mass manufacturing of PV panels (Vobořil, 2015; Divišová, 2013). It is proved by the figure 6 below. The red line indicates an installed power, whereas the blue one shows a number of the photovoltaic power plants.

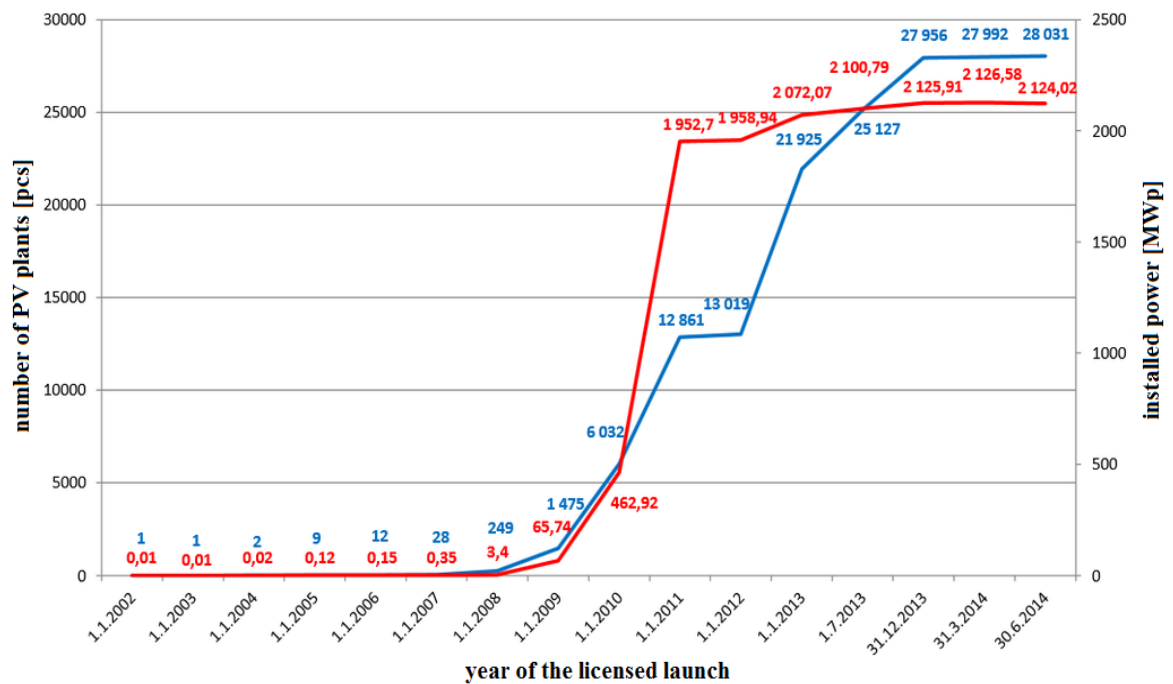


Figure 6. Gradual increase of the installed power capacity by 30 June 2014 (retrieved from oze.tzb-info.cz).

#### 4.1 Support of electricity from solar energy

Support of a photovoltaic power plant operation was, until recently, associated with so-called feed-in tariffs and a fixed green bonus. However, there was solely one possibility to choose from, meaning that the combination of both at once was impossible. As a result of the already mentioned “solar boom”, it has not been allowed for all kinds of oncoming photovoltaic power plants to exploit these forms of support since 1 January 2014. Nevertheless, the PV plants launched by 31 December 2013 are still utilising one of above-mentioned operating aid forms. Hence, they will be introduced and described in the chapter in more detail.

In terms of the Czech Republic, a significant adjustment related to the support of photovoltaic power plants was introduced with Act no. 165/2012 Coll. on supported energy sources and amendments to certain laws. The option of the so-called hourly green bonus was added and restrictions for newly connected sources were also issued. Concerning PV sources launched from 1. 1. 2013 to 31. 12. 2013, support of electricity produced from solar energy is only accepted for plants with the maximum installed capacity of up to 30 kWp that are placed on buildings (roof structures, perimeter walls, etc.).

Depending on the selected form of support, the payment scheme and entities involved vary. The selection of funding was regulated by the already mentioned Act no. 165/2012 Coll. As in the case of support in the form of feed-in tariffs or green bonuses, it was necessary to register them with the local Distribution Network Operator.

#### **4.1.1 Feed-in Tariffs**

As for feed-in tariffs, all the electricity produced by the manufacturer is compulsorily purchased by the company which is an electricity trader designated by the Ministry of Industry and Trade for a certain area. If the ministry did not designate anyone, this duty was taken over by the relevant energy supplier according to the location of the plant (ČEZ Prodej, s.r.o., EON Energie, a. s., Pražská energetika, a. s.). The price of purchased electricity with the feed-in tariff is set by the Energy Regulatory Office and valid in the year the plant was put into operation with the 20-year purchase guarantee - for this is estimated service life. Feed-in tariffs are invoiced directly to the purchaser after entering the amount of production into the OTE (market operator) system. Unlike the green bonuses, the feed-in tariffs are billed with VAT (value-added tax). The Law also contains the annual increase in feed-in tariff by the price index of industrial producers (industrial inflation) for about 2 - 4 %, meaning that the feed-in tariff valid in the year the PV plant was put into operation will be annually increased by at least 2 %, but not more than 4 %. Thus, it used to be an appropriate choice rather for power plants of larger installed capacities, delivering entire electricity production to the distribution network (Energetický regulační úřad, n.d.; Energie ČS, n.d.).

### **4.1.2 Green Bonus**

In the case of green bonuses, the manufacturer provides electricity for the purchaser under the concluded contract. It was generally advisable to use part of the generated electricity for one's own consumption and negotiate a contract for the supply of the unused energy surpluses with a trader. The green bonus is paid to the manufacturer by the market operator on the basis of the measured values of the electricity produced. The overall price consists of both an item for which the manufacturer sells the electricity to the customer and the green bonus. Like the feed-in tariffs, the green bonus is applied for the entire lifespan of the project, however, its value is guaranteed for one year solely (Energetický regulační úřad, n.d.; Energie ČS, n.d.).

## **4.2 Subsidy Programmes**

Due to the fact that the operation support for photovoltaics in the form of feed-in tariffs and green bonuses has been cancelled since the beginning of 2014, future investments in this field would be therefore hardly profitable without any other means of an additional support. For this purpose, a few subsidy programmes has been established in the Czech Republic, thanks to which the contemporary photovoltaic roof installations still represent an interesting alternative for many people.

### **4.2.1 Operational Programme Environment 2014 – 2020**

The Operational Programme Environment on energy savings was approved of by the European Commission on 30 April 2015. Currently, it is being funded by the European Regional Development Fund. The main objective of this programme is to support the transition to a low-carbon economy in all sectors by promoting energy efficiency (reducing final energy consumption), smart energy systems, and increase the use of renewable energy for electricity generation in public infrastructures, such as public buildings, universities, schools or non-profit organisations. For these purposes, The Operational Programme Environment has prepared the funding of EUR 529 million from the European Regional Development Fund and the Cohesion Fund. Funding is provided in the form of a soft loan or non-returnable grant to cover a maximum of 40 % of all necessary expenditures. However, private buildings are not included in this programme (Státní fond životního prostředí ČR, 2016).

#### **4.2.2 EFEKT**

EFEKT is the subsidy programme, which was established in 1998 on the promotion of energy savings and utilisation of renewable and secondary energy sources. Education of general public and practitioners, assistance upon energetic management implementations in cities and countries, promotion of activities with direct energy savings especially for cities and municipalities or smaller business projects are the main objectives of the programme. Compared to other subsidies regarding renewable energy sources, EFEKT does not have a significant budget. Annually, the amount of CZK 80 million is reserved. Despite of this fact, it has an important role to play in regions where EU funds cannot be applied (Ministry of Industry and Trade, 2016).

#### **4.2.3 New Green Savings Programme**

This programme focuses on energy saving reconstructions of family houses as well as apartment blocks, replacement of inconvenient heating sources, and promotion of using renewable energy sources (Státní fond životního prostředí ČR, n.d.). There are two possibilities to choose from: either a photovoltaic water heating (subsidy of CZK 35 thousand), during which DC current produced by PV panels can be directly used for heating of a heater in a boiler, or self-consumption of electric energy through smaller photovoltaic power plants on the roofs, provided in two variants. In the first case, so-called energy surpluses from PV panels are utilised for other necessary purposes, such as space heating or the already mentioned water heating. Otherwise, the energy surpluses are stored in batteries in order to preserve the possibility of exploiting the electricity from solar energy even after the sunset (SolarniStavebnice.cz, 2016).

Funding of the whole programme is carried out by the national budget of the Czech Republic owing to the European Union Emission Allowances (EUAs) sale (Státní fond životního prostředí ČR, n.d.). Only electronic applications are accepted, based on time-limited calls. Subsidy limit depends on very simple principle: the more energy performance of a building is reduced, the higher the financial support might be given. However, this fund holds for photovoltaic systems with an installed power not exceeding 10 kWp. The highest possible limit was set to be of CZK 100 thousand - this value includes applications for a hybrid photovoltaic system using an accumulator on

the condition that the total energy consumption of 3000 kWh per year is exceeded (SolarniStavebnice.cz, 2016).

In the case of all subsidised projects, some kind of monitoring device capable of measuring the relevant state of electricity consumed and produced is required. The measures performed by companies from the List of Qualified Suppliers using the high-quality materials and technologies from the List of Products and Technologies are approved solely. Moreover, consumption of at least 70 % of the photovoltaic system's theoretical profit is another important aspect that must be satisfied with respect to the New Green Savings Programme (SolarniStavebnice.cz, 2016).

### **4.3 Taxes related to Photovoltaics**

Three important areas will be a subject matter of this chapter, which concerns taxes related to photovoltaics:

- income tax of individuals and legal entities;
- property tax;
- electricity tax (solar tax).

#### **4.3.1 Income Tax of Individuals and Legal Entities**

According to the Act no. 458/2000 Coll., The Energy Act, both natural and legal persons are allowed to run a business under the license granted by the Energy Regulatory Office. Nevertheless, from 1 January 2016, a photovoltaic power plant with an output of up to 10 kWp can be run without the license, provided that the entire amount of electricity is to be self-consumed; thus, the ownership of roof-installed PV plant is not, according to the law, considered as a form of business (AION CS, n.d.)

The issues of income tax are governed by the Act no. 586/1992 Coll., which administrates and regulates conditions of the income tax concerning both natural persons and legal entities. The scope of tax liability itself differs for legal persons and depends on whether a legal entity has a permanent residential address on the territory of the Czech Republic. If this condition is fulfilled, a tax is payable from income received both in the Czech Republic and abroad. As far as a legal person with a seat outside the territory of the Czech Republic is concerned, the tax is derived from the income received from sources in the Czech Republic (AION CS, n.d.).

Photovoltaic power plants were exempt from the income tax of legal and natural persons until 31. 12. 2010 - this exemption was applied to all renewable energy sources and lasted for five years since the plant was put into operation. This exception was subsequently abolished even for plants built before 2010. However, in March 2016, an amendment to the Act on income tax was approved. As a result, incomes from the sale of energy surpluses produced by PV plants that are not required to operate with the license (up to 10 kWp) have been included in § 10, indicating so-called *other incomes*, which become tax-free unless the income of CZK 30 000 per year is exceeded. However, under the present market circumstances, the sale of any energy surpluses is completely unfavourable (Solární Experti, 2016).

### **4.3.2 Property Tax**

As soon as a photovoltaic power plant is placed on a building, it is not seen as a separate building; therefore, the property tax is applied to the building in a common way, according to its type and usage.

Regarding a plant situated in an open space, a structure consisting of galvanized steel profiles, which are longitudinally connected with aluminium profiles, is usually utilised for mounting of solar panels. This structural frame can be connected with stud bolts or galvanized profiles installed under the ground, or the anchoring is solved by heavy pre-cast concrete blocks placed on the ground. Although these types of supporting structures are deemed to be solid, their detachable placing enables relatively easy removal or relocation of the entire structure, which is thus not regarded as an immovable construction; therefore, it cannot be a subject to the property tax (Vychopeň, 2011).

### **4.3.3 Solar Tax**

From 1 January 2011 to 31 December 2013, as a response to a large increment in an installed power in 2010, the legislative measure was implemented in the form of “special” tax on PV plants with an installed capacity of more than 30 kWp which were put into operation from 1 January 2009 to 31 December 2010. It was necessary to pay 26 % solar tax in case of feed-in tariffs and 28 % tax was charged in case of the green bonus (Admio, 2015).

This restriction was slightly modified in 1 January 2014, on the basis of the amended Act. Thenceforth, it applies solely to plants with an installed capacity exceeding 30 kWp, which have been put in operation from 1 January 2010 to 31 December 2010. The limitation is valid for as long as the plant has the possibility to sell the electricity based on the advantageous purchase price. Since 1 January 2014, the solar tax rate has decreased to 10 % for feed-in tariffs and to 11 % for green bonuses (Admio, 2015).

Since 1 January 2016, it has become mandatory for operators of other plants whose installed electrical capacity exceeds 30 kWp to register at the Customs Administration, as well as to submit a tax return and pay the sum of CZK 28.30 / MWh (Helion.cz, n.d.).

## **4.4 Realization of a Photovoltaic Power Plant**

This chapter contains the pieces of information about a few administrative steps that must be fulfilled in order to make the realization of such a system possible.

### **4.4.1 Project Assessment**

As for the initial action, it is necessary to assess what kind of PV system is desired. As it has been already discussed in previous chapters, the newly accepted purchase price of electric energy do not play a positive role in favour of selling some portion of energy to the power grid, which has become economically unfavourable. Current conditions rather allow for a full self-consumption of electric energy produced in building with regard to the fact that the benefits in the form of feed-in tariffs and green bonuses are no longer available. Thus, it is better to direct more attention to the construction of PV systems on buildings rather than the realization of larger open-space plants.

Firstly, the type of structure should be taken into consideration. The optimal conditions are fulfilled when energy consumption of the structure is required throughout the entire day, for instance, in the case of schools, production halls or administrative buildings. As far as the family houses are concerned, things get a little bit complicated since the highest energy consumption is more likely to be in the morning and then in the late afternoon or evening hours. This problem may be solved by installation of hybrid

photovoltaic power plant (see chapter 3.2) using electric energy accumulation that can be made use of afterwards.

#### **4.4.2 Technical Requirements**

In order to reach as best efficiency as possible, appropriate setting of technical requirements including total power output is important. It may be calculated on the basis of available area suitable for panel placement. However, roof type must also be taken into account – whether it is slant, flat or possibly shadowed by surrounding buildings or trees.

The orientation of panels has a significant role to play in this process. In the ideal case, a power plant needs direct sunlight all day long; therefore, the most convenient option is placing the panels to face the south in order to exploit the maximum advantage of the sun's potential energy. As regards local environment, an ideal inclination of installed panels is about 33°. It is a compromise between two situations - the sunlight passes near the horizon in winter, whereas it is higher in the sky during summer.

As it has been already mentioned, there are two types of systems used for panel installation, i.e. fixed and so-called trackers. Even though the solar trackers are more efficient, fixed systems are primarily used on family houses, since trackers might cause complications through reliability, significantly higher price, higher expenditures for regular service and a necessity for a larger space. Except all the things mentioned above, one should also consider the distance to the point where a connection to the distribution network is located.

#### **4.4.3 Connection to the Distribution Network**

When the technical requirements are specified, the next step is to request a connection to the network provided by the local Distribution Network Operator (DNO). This request is free of charge and DNO is subject to response within 30 days. In general, electricity providers may set the specific terms related to the connection, but, they are obliged to connect the customers under the condition that the distribution network is not overloaded.

The application form can be sent to the particular Distribution Network Operator (E.ON, ČEZ, PRE) according to the region they cover, which can be seen in the figure of the Czech Republic below.



Figure 7. Territorial layout of DNOs in the Czech Republic (retrieved from energie2.cz)

#### 4.4.4 Building Authority

It is essential for a photovoltaic power plant realization to request a building permit at the Building Authority Department. As in the case of connection to the distribution network, the application is free of charge as well, and the office should reply within 10 days. Furthermore, in some cases, the ownership document and the cadastral map frame might be requested. However, there is no need for the building permit unless an installed power of the plant exceeds 20 kW. The same holds for the situation when panels are supposed to be situated on the roof of some building (Solární asociace, n.d.; VR OZE systems, n.d.).

#### **4.4.5 Construction**

There are usually two possibilities how to deal with the construction of a photovoltaic power plant.

The first way is the so-called turnkey solution. In this case, supplier delivers and installs all required components, inclusive of necessary measurements and revision reports. Certain companies even take responsibility for all related administrative procedures, such as various permits, requests and contracts. The turnkey solution is appropriate for those who do not have much experience in this field, as well as for installations on bigger buildings like halls, schools, a block of flats, etc.

The second solution lies in the building kit delivery. The company provides all the components to the customer. The delivery contains photovoltaic panels, inverter, junction box, cabling, wiring diagram, and the papers for DNO. The customer then mounts panels on the roof by himself, saving a considerable amount of money.

#### **4.4.6 Revision**

Revision is an essential procedure of every newly realized photovoltaic power plant. ČSN 33 1500 Standard has established a duty to make regular revisions in the outdoor environment in the period of every 4 years. However, the date of the next periodic revision depends on the decision of inspection technician. The revision is usually free of charge if the turnkey solution is selected, otherwise, it may be up to CZK 3000 - the price always depends on the power output of particular PV plant and whether the additional analysis of PV panels is included. If the revision shall be carried out, PV plant operators must submit a previous audit report, project documentation, and a data sheet of PV panels used (ALL4EL service, n.d.)

#### **4.4.7 Licence**

When the installation of the photovoltaic power plant is completed, the application for a licence at Energy Regulatory Office must be issued, enabling to run a business in this field. The electricity production licence is valid for 25 years. In the case of a power plant with an installed power below 1 MWp, a fee of CZK 1000 is charged. If the power is over this limit, the sum of CZK 10 thousand must be paid. As regards the licence for

electricity trading, it is valid for 5 years at a price of CZK 100 thousand (Energetický regulační úřad, 2016).

When you are interested in the system whose power is greater than 20 kWh, the paper of electrical engineering qualifications is demanded, requiring the applicant to be educated in electrical engineering, as well as there is a need for practice in this field. If such requirements are not met, it is essential to name a liable person who fulfills all the criteria.

Each application shall be accompanied by Certificate of Incorporation or Trade Register, The Criminal Record, excerpt from The Cadastre of Real Estate, and the cadastral map with indicated position of the power plant.

The new regulation has been implemented since 1 January 2016, enabling to run a PV plant with a power of up to 10 kW without a need of any licence or Trade Certificate. The only requirement is a self-consumption of the entire amount of energy produced (see chapter 4.3.1).

#### **4.4.8 Contract with DNO**

The request for the conclusion of the contract dealing with the connection of the plant to the electricity distribution system shall be accompanied by a paper confirming valid inspection of the electrical equipment of the plant, a valid inspection of the electrical connection including the documentation of the actual realization, then a protocol on the protection settings, a building permit and, in some cases, certificate of tax registration (Solarmont, n.d.).

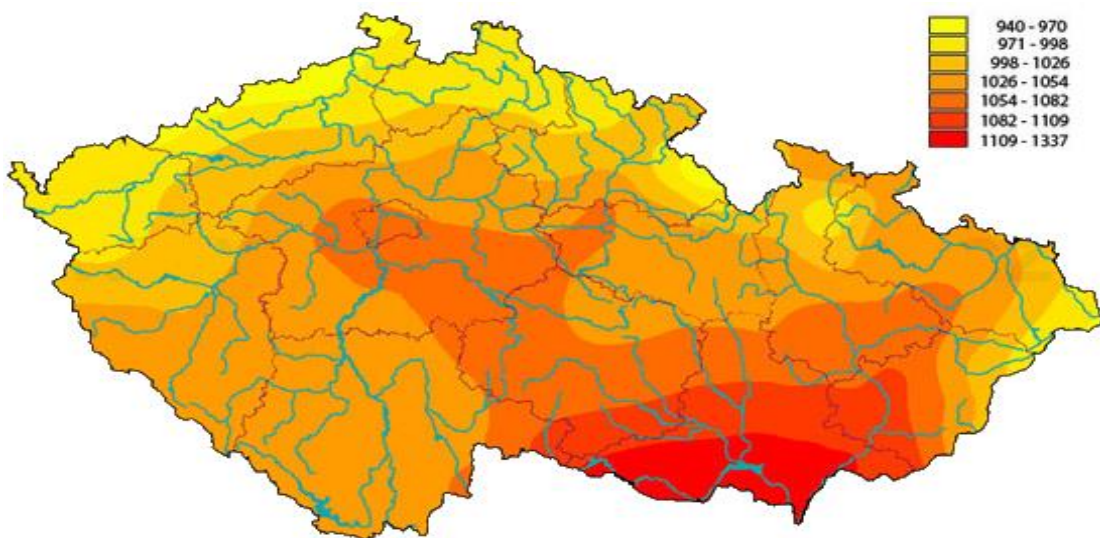
#### **4.4.9 OTE**

The final stage comprises a registration (clients might use the electronical one) at OTE, which stands for The Czech Electricity and Gas Market Operator. Since 1 January 2013, the operator has been obliged to register and be responsible for all the PV market participants. Its principal responsibilities are associated with billing and paying out the support for electricity, in accordance with the law, in the form of green bonuses on client's accounts. On the contrary, feed-in tariffs are paid by companies exploiting the energy produced by particular plants on the basis of the concluded contract with their owners (OTE, n.d.).

## 5 Photovoltaic Power Plant

In this chapter, a larger photovoltaic power plant will be analysed. As it was not permitted by company which provided necessary materials to specify the particular position, we can only say that the photovoltaic power plant is located in the Eastern Moravia. As far as weather conditions related to generation of electricity in terms of Czech Republic are concerned, the region of Eastern Moravia offers relatively favourable possibilities for photovoltaic system establishment. In general, there are certain differences among particular regions depending on a geographic location. According to the figure 8, it can be seen that approximately 1054 – 1082 kWh/m<sup>2</sup> of energy annually hit the surface of the Eastern Moravia. Along with the Southern Moravia, this area is also characterized by comparatively large number of sunny days throughout the whole year.

Launched at the end of 2010, this structure covers an area of about 18 720 m<sup>2</sup> with 3870 pieces of PV panels integrated. In total, installed power of this PV plant is 909 kWp. The power is provided for the local Distribution Network Operator: E.ON.



*Figure 8.* Annual average value of the solar radiation in the Czech Republic [kWh/m<sup>2</sup>] (retrieved from [isofenenergy.cz](http://isofenenergy.cz)).

## 5.1 Overview of Connection

As it has been already mentioned, 3870 pieces of monocrystalline PV panels Trina TSM-235PC05 were assembled to form the total installed power of 909 kWp. They are suitable not only for large-scale installations, particularly ground-mounted, but also for commercial rooftop systems. According to the manufacturer, these panels come with a 25-year performance guarantee of 80 % power production, meaning that their efficiency shall gradually decrease by approximately 0.8 % a year. Technical parameters of this particular kind of PV panel are shown in the table 1 below.

*Table 1.* Technical parameters of TRINA TSM-235PC05 module

<b>Type:</b>	<b>TRINA TSM-235PC05</b>
<b>Peak Power:</b>	235 Wp
<b>Maximum Power Voltage:</b>	30.1 V
<b>Maximum Power Current:</b>	7.81 A
<b>Open Circuit Voltage:</b>	37.1 V
<b>Short Circuit Current:</b>	8.31 A
<b>Operating temperature:</b>	- 40 ~ + 85 °C
<b>Weight:</b>	19.5 kg

The solar modules are mounted on a steel structure and positioned in vertical rows at the angle of 30°; they are installed into 87 mechanical blocks in total. The supporting part of the structure consists of 6 stands which are inserted and attached to the ground with screws. The typical screwing depth is approximately 130 cm. The structures also carry DC/AC converters and the boxes of DC cabling; they are attached to a profile bar mounted on a mechanic block between the stands. The aisle between panel rows is approximately 5.3 m wide. This selection of distance prevents the panels from potential mutual shadowing, as the position of the sun varies between particular season periods.

Three blocks consist of two parallel combinations, each of them with 15 pieces of solar modules connected in series; thus, each of the blocks contains 30 individual PV

panels. A designated junction box is a part of the triplet of blocks. Other blocks consist of 3 parallel combinations, particularly with 15 pieces of PV panels that are connected in series; therefore, each of the blocks carries 45 modules. These blocks are in pairs connected to other junction boxes. The outputs from the series connections of PV modules are brought to the junction boxes via cables installed on the structures or inside a cable conduit in the ground. The outputs from the junction boxes are made by means of cables connected into individual inverters. Power from the inverters is subsequently run through a cable harness to an AC box that contains a circuit breaker for each converter, the main breaker and surge protection. Three inverters are always brought to the AC boxes. Power is subsequently driven by means of three-phase cables, buried under the ground, to 5 plastic junction boxes. Their respective output cables are connected to a transformer station which converts low voltage into high voltage (and vice versa) in order to subsequently deliver the power from PV plant to the distribution network.

## **5.2 Transformer Station**

In the electrical grid, a transformer station is a group of electrical equipment serving the purpose of:

- Transforming power into various voltage levels and forwarding it further into the electrical grids. Transformation is possible from the higher voltage side and vice versa.
- Protecting the cables, transformers and other devices from failures in the electrical grid, such as undesired transients in the grid or phase asymmetry.
- Measuring and regulating voltage, current, power, and other electrical quantities.

Each transformer station houses the following compartments:

- HV substation – contains a HV switchboard that separates the outer grid from the transformer. These switchboards are typically designed in combination with the sulphur hexafluoride (SF6) serving as a fire extinguisher. In the past few years, SF6 has spread to HV switchboards all over the world, outperforming other fire extinguishing media mainly due to its perfect chemical properties. In addition, dielectric carpet is typically placed in front of the switchboard.

- Transformer chamber – contains the transformer that converts electrical energy to the desired voltage levels.
- LV substation – its principal component is the LV switchboard containing the circuit breakers and other protection devices.

### **5.2.1 Transformer Site**

The transformer is a stationary, non-rotating electrical machine that allows for the transition of electric power from one circuit to another using mutual electromagnetic induction. It is typically used to transform AC voltage into the desired voltage level. In this case, the oil transformer 1000 kVA 22/04 kV was used. For each oil transformer over 1000 kVA, a separate site must be realized. In case the transformer is filled with a dielectric material different from oil, the properties of that material must be taken into account and the site adjusted accordingly.

The transformer site must be also designed so as to ensure the requisite conditions for transformer cooling system - thus, it has to be carried out with regard to the operation in summer months, and so the fire safety requirements must be adhered to in this process. The reason is simple - if the heat is not dissipated properly, the temperature of the transformer will rise continually, causing damage in paper insulation and liquid insulation medium of the transformer. Therefore, it is essential to control the temperature within the permissible limit so that both the thermal degradation of transformer's insulation system and its long lifespan are ensured. In addition, the transformer chamber is usually provided with a natural or forced-air circulation. The intake port for cold air is typically placed in the lower half of the north wall of the room, whereas the outlet port for hot air shall be placed in the upper half of the opposite wall.

All transformers filled with oil which are considered as dangerous to the health, to the fire safety, to the environment, and represent a risk of environmental pollution or contamination of surface and ground waters, must be equipped with an oil sump. A sump is not required in the sites for transformers up to 1000 kVA with the maximum of 1000 litres of oil. If such transformers and other equipment in the site do not use forced oil circulation, they are placed in welded containers preventing the leak of the oil and protected with fuses or other similar protective devices precluding the potential short circuit occurrence.

### **5.3 Inverters**

All photovoltaic modules generate DC current. In order to process the generated power further, the DC current must be changed to AC and the voltage must be modified so that it corresponds to the system voltage of the distribution network. Therefore, the inverters in a photovoltaic power plant provide the DC/AC current transformation from the solar modules, which is subsequently forwarded to the transformer station for a further step-up in voltage to reach the AC grid voltage level. Inverters are primarily arranged in string configurations - the modern, high-quality ones offer an efficiency rating of approximately 97 %.

Inverters can also perform a number of functions to maximise the output of the plant. These range from optimising the voltage across the strings and monitoring string performance to protection and isolation insurance in case of irregularities in the grid or within the PV modules.

Recent advancements in power semiconductor technology were associated with the improvement in their reliability, offering gradual increase in the number of transformerless inverters. As these inverters do not have any galvanic separation of the input and output circuits due to the absence of a transformer, they are subject to increased requirements for safe operation - thus, the additional protection devices must be used, such as DC circuit breakers or protection from the live parts. On the other hand, these inverters benefit from higher efficiency, reduced weight and size, and lower manufacturing costs as a result of smaller number of components included within the device.

### **5.4 Cabling**

There are two general cable types distinguished in terms of photovoltaic systems; cables for the modules and module strings (DC) and AC cables which are designed to provide a safe and cost effective means of transmitting power from the inverters to the transformer station and beyond. Depending on the installed power, one or two-conductor cables with a cross section of 2.5–16 mm<sup>2</sup> and typical nominal voltage of 0.6-1 kW are used for connection between the inverters and the PV arrays.

Cables must be resilient to changing weather conditions, high temperature and UV radiation. Due to such properties, the cables can be used outdoors and in damp environment as well. Cables are usually halogen-free with dual insulation and reach lifespans of up to 30 years. In specific situations, they can be protected with stainless-steel shielding against damage from rodents.

The main LV cable routes are installed in underground cable channels as required by corresponding Czech Technical Standards. Cables connecting the particular modules and junction boxes are laid down mostly in a protective tube. Junction boxes together with the inverters are connected by a cord placed under the ground, so as the installed data cables used for data transmission. Above-the-ground cabling is fixed by UV-resistant cable binders in flexible electrical installation tubes situated on the mechanical structures holding the solar modules.

As far as HV cabling is concerned, the cables must have a spacing of no less than 20 cm when installed in buildings or dry environment - there should be a mechanically durable, fire-resistant barrier (a concrete slab, bricks, etc.) for individual cables separation. Underground cabling must be installed in channels no less than 1.2 m deep. The channel width and its arrangement depend on the number of cables and it is governed by technical standard related to material consumption for cabling installations. In all channels and conduits, cables must bear identification labels throughout their length. The labels are typically attached to the cable by using plastic binders with 3-metre spacing, showing the month, year, installation type with the cross-section area, voltage, and the number indicating particular cables.

## **5.5 Monitoring System**

Monitoring system is an essential part of each PV plant. It is designed to control functionality as well as maximum energy yield through automatic data collection from individual strings, invoicing meters of electric power in the output and input, and comparison with theoretical calculations and warnings on a daily basis to quickly find out if there is a performance deficit; therefore, faults are detected and repaired before having a substantial effect on production. The system is also used for a data acquisition from weather station in the form of array irradiance measuring, module and ambient

temperature, global horizontal irradiance, humidity and wind speed. The monitoring system offers to process historic and current data, various statistics and charts including data export into tables. In our case, the system processes all the data on a 15-minute basis - thus, the operators are notified as soon as the given problem occurs. The most common failures related to a photovoltaic power plant operation are:

- inverter failure - as long as an inverter fails and does not restart automatically within one hour, the situation is considered as a failure;
- string defect - defects occurring in particular strings may result in plant's overall power yield reduction;
- junction box defect - the common cause is that fuses within junction boxes might have burnt out;
- power outage of HV area;
- power supply outage of secondary resources.

Upon detecting a defect in the monitoring system, the dispatcher contacts a local service technician who receives information about the defect. The technician is thereby directed to the respective inverter, junction box, string or switchboard, confirms the defect occurrence and secures the restoring of operation consequently. Should their qualification or skill level be inadequate to repair the defect, they have the obligation of contacting a sub-service partner specialising in the corresponding segment of the power plant. Therefore, monitoring technology is necessary during the plant's operational phase in order to maintain a high level of performance, reduce potential downtime and ensure rapid fault detection.

Mentioning the monitoring technology, object's security system is an additional functionality. The PV plant is secured by using a vibration detection system. A detection cable is installed along the entire perimeter of the land to sense the vibration of a fence. Moreover, the entire area is fitted with a CCTV (closed-circuit television - monitoring by cameras placed in various parts of the object) as well as an activation of emergency lighting system in the event of alarm at night-time.

## **5.6 Earthing and Surge Protection**

Earthing should be provided as a means of protection against potential electric shock, fire hazard or lightning. By connecting to the earth, charge accumulation in the system during an electric storm is prevented. For this purpose, there is a continuous earth path throughout every PV array with earthing conductor connected to the mechanical construction by individual terminals and laid down alongside the LV cables.

Whenever a lightning strikes, a risk of surging in the grid occurs within few-kilometre radius from the impact. The protection against this situation requires that the danger to the object containing expensive technology cannot be underestimated. These measures must comply with the requirements of ČSN EN 62305-1 through 4. Surge protection is primarily designed to prevent damage in electric and electronic devices caused by extremely high voltage levels. In the event of overload, relevant surge protection technology components equalize the potential between the connected conductors - this prevents the voltage peaks from destroying the connected devices. In case of internal surge protection, there is made use of surge arrestors, which are of different type depending on the application either in HV or LV side, installed in switchboards.

## **5.7 Operation and Maintenance**

Compared to other power generating technologies, PV installations require quite inexpensive maintenance and service requirements. However, a proper maintenance is essential to maximise both energy production and the plant's lifespan - it shall strike a balance between maximising production and minimising costs.

It is common practice on solar PV projects that all aspects related to operation and maintenance are carried out by a responsible contractor, including any of the works performed by subcontractors engaged to deliver specialist services, such as a required periodical inspection of the electrical installations by a revision technician, inverter servicing (and replacement after 10 years), security, and module cleaning - cleanliness of the modules is quite important aspect, since they are being very often covered with fallen foliage, bird droppings, dust or snow, which might result in energy yield reduction of up to several percent. It is important that the modules should solely be

washed with water without any cleaning products. Water is usually being sprayed on the panel surface by using brush trolleys, dust brooms or smaller crane that move among PV arrays (principally used for cleaning of large solar trackers). The frequency of module cleaning is dependent on the local area conditions and the time of the year. The first thing to remember at all times is that the solar modules cannot be cleaned dry, as the mechanical cleaning might damage the top glass layer.

In addition, tasks consisting of periodical ground-keeping of the surroundings in the form of grass mowing or painting of the fence must be also taken into account. As I have already mentioned, the entire installation is also monitored with a CCTV system connected to a central office of the security agency, which has the obligation to arrive at the place within few minutes in the event of vandalism or theft. The entire object is furthermore covered by all-risk insurance policy that includes natural disasters, theft or operation outage.

## **5.8 Ecological Aspect**

Energy from a PV power plant can be referred to as “environmentally friendly” since no harmful substances are released through its operation. For example, in case of 1 kWh production, it is capable of saving up to 1 kg of carbon dioxide compared to energy coming from a traditional coal power plant. Furthermore, PV plant’s operation is noiseless, and there is no need for fossil fuels that would pollute the environment.

The reason for a lot of negativism coming from the general public in the recent years was the change of agriculture land into “fields with solar modules” where a number of such projects were erected in the “solar boom” period. On the other hand, it is necessary to look at the size of the area which plants of different technology occupy. For example, a coal power plants or large nuclear power plants with all the necessary components cover a considerably large area itself; needless to say that the vast amount of coal and uranium that must be stored under the ground is required for operation. Moreover, the restoration of devastated countryside left after coal mines that we can see in North Bohemia or in the Ostrava region, which takes many years and requires tremendous sum of money, must be also taken into account. From this perspective, coal plants cannot be compared with PV systems that can be easily dismantled in a few days

at the end of their service life, leaving the land hardly changed and available for its original purpose.

### 5.8.1 Recycling of Panels

The growth in the solar energy over the past decade has been associated with vast number of materials required for PV module manufacturing, and it is expected to continue claiming an even greater share. It must be noted that the lifespan of panels is limited (estimated at 20-25 years) - thus, they will need to be recycled. Deriving from estimated lifespan of panels, they are expected to be recycled after 2030 in large amounts. In the meantime, the disposal aspect will apply mainly to modules damaged during transport and assembly, or with manufacturing defects, which usually occur within the period of couple of months since commissioning. Solar modules contain a number of valuable materials which, when recycled, can be utilised for other purposes, including the manufacturing of new solar modules contributing to successful growth of environmental sustainability. A problematic point is that it is currently difficult to estimate disassembly and future recycling costs because of uncertainty about the future price of the materials retrieved from recycling process, therefore, it is equally difficult to estimate the potential profit from the sale of these materials. However, some components, such as glass, or aluminium frame can be reprocessed, since their recycling rate amounts to nearly 100 %. Other materials, such as copper, reach a recycling rate of 80 %; in case of silicon, certain recycling process types reach efficiencies of more than 85 %. This is proved by table 2 based on the data taken from the article on the “tzb-info.cz” web portal (Bechník, 2011).

Table 2. Composition of PV crystalline panels

Material	Quantity contained [kg/kWp]	Proportion [%]	Efficiency [%]
<b>Glass</b>	60	67	>95
<b>Aluminium</b>	16	18	100
<b>Plastics</b>	10	11	-
<b>Silicon</b>	3	3	85
<b>Copper</b>	1	1	80

Thermal recycling is currently considered as the most advanced recycling method. Although it is demanding in terms of energy and labour, up to 85 % of the materials the modules contain can be reprocessed. The second most widely used recycling process is the mechanical method. Compared to the thermal recycling, it requires a lower portion of labour. However, the only result is crushed material. The method is more appropriate especially for thin-film cells where semiconductor materials cannot be obtained in any other way.

The future disposal of solar modules at the end of the service life was initiated by EU Directive in 2012. At the end of 2012, the Ministry of the Environment of the Czech Republic introduced the obligation applying to PV operators whose plants were put into operation before 1 January 2013 to pay contribution for future recycling of solar modules. The contribution must be sent to the bank account of a selected collective system that specialises in recovery and recycling of solar modules in equally distributed instalments from 2014 to 2018 based on the concluded contract. The obligation to pay contribution for the disposal of solar modules is regulated by the Waste Act no. 185/2001 Coll. as well as by the corresponding amendment to Decree no. 352/2005 Coll. issued by competent state administration authorities. The minimal amount has been determined at CZK 8.50 per 1 kg, which is supposed to cover all costs related to recycling, administration, and transport. However, according to certain calculations, the actual price should be about CZK 5.17. On the contrary, responsibility for recycling of panels in terms of plants launched after 1 January 2013 has been taken over by the manufacturer. Thus, the recycling fee is automatically included in the price of the modules (REsolar, n.d.).

## **5.9 Estimated vs. Real Energy Production**

So-called energy audit, in other words, assessment of the anticipated energy yields and resulting financial returns, is a key phase for future analysis of almost every PV project. For this purpose, companies utilise very expensive, complex simulation models providing very accurate calculations of estimated energy production, which are dependent on the amount of solar radiation determined by local geographical conditions, temperature, installed power of the system, losses associated with particular

components within the system (transformers, cables, inverters), as well as by slope of the modules. Unfortunately, such complex software is very expensive and thus not available for general public. However, Murtinger (2009) mentions a programme called PVGIS (Photovoltaic Geographical Information System - see the link <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php>) which is supposed to calculate a desired PV potential since it is based on satellite and ground measurements of geographical and climatic data from 1998 to mid-2010 in every place throughout the Europe.

The parameters of the PV plant were entered to the system, including a concrete location of the plant, installed power, material which the PV panels are made of, slope of the panels (30°), and total losses within the system - estimated to be (5.3 %). PVGIS automatically takes the local weather conditions into account and includes them in the calculation. The resulting output energy estimation will consequently be compared with the real values of production in particular months during the first year of operation (the plant was put into operation at the end of 2010, but, it will be counted with the year 2011 to make the comparison and following calculations more manageable) demonstrated in the figure 9. The exact values of production can be seen in the table 3.

*Table 3. Values of estimated and real production*

Month	Real production [MWh]	PVGIS estimation [MWh]
January	33.240	29.100
February	58.473	48.300
March	108.624	92.800
April	122.562	122.000
May	147.414	127.000
June	124.312	124.000
July	127.803	126.000
August	135.099	122.000
September	103.122	95.900
October	67.021	69.300
November	25.888	36.700
December	23.114	24.900
<b>Total for year</b>	<b>1076.272</b>	<b>1018.000</b>

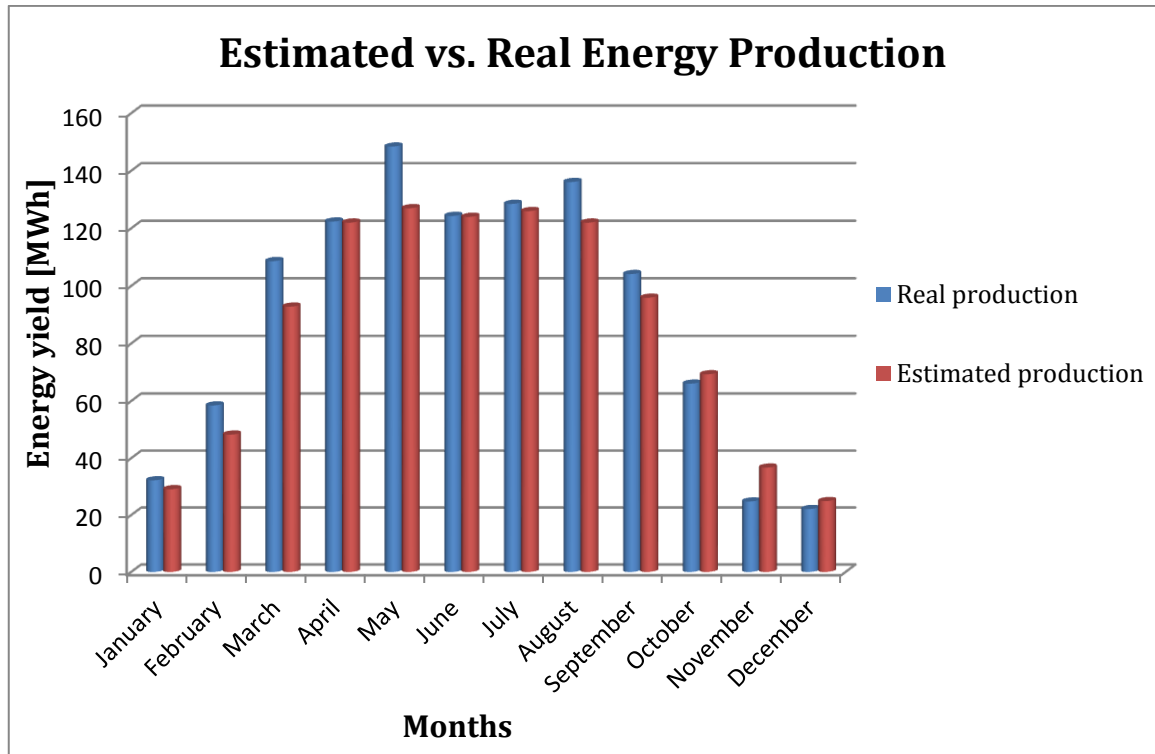


Figure 9. Estimated vs. real energy production

As is evident from the figure, at the start of the year the energy yield was considerably higher than in case of estimated values. During the month of February there was a difference of approximately 10 MWh, while virtually 16 MWh in March. The better climatic conditions in that particular period of the year compared to the statistical data evaluated by PVGIS were apparently the reason for such difference. As far as winter months are concerned, the most productive one was February - in all likelihood, it must have been characteristic of higher number of sunny days and absence of snowfalls. On the contrary, the lowest production in terms of energy yield was recorded in December, when it is presupposed that the panels could have been covered by snow for several days.

The production reached its peak in May with 147.414 MWh; in general, however, no significant difference between spring and summer months can be noticed. Even though one could think of summer as the most appropriate period for photovoltaics, it is, in fact, the wrong assumption. Since the sun is high in the sky in summer, its rays strike the surface of modules at higher angle, and thus decreasing the maximum values

of incident radiation. As a result, we can see the highest energy yield in May. On the contrary, the months belonging to autumn are, except September, associated with higher number of cloudy and rainy days that appear to contribute to lower production.

It is clear that the PVGIS cannot achieve 100 % accuracy of prediction since it is impossible to predict changeable weather conditions for the whole year in advance, however, according to the results compared there is, apart from few exceptions, no significant difference among the values. With regard to the fact that this programme is free of charge and available for general public, the final results are relatively satisfying.

## **5.10 Payback Period**

This chapter is going to deal with the rough estimation of project's payback, which is the length of time it takes the project to pay up for itself through the sale of electricity. Firstly, let us focus on the aspect of project's financing. Considering plants of larger installed capacities, most of the investors usually conclude medium-term loans in order to cover a larger proportion of the financial expenses related to project's realization instead of covering the project with company's own financial sources, which is quite common in case of most roof installations.

The plant's acquisition price was estimated to be CZK 89 900 000. Let us consider the project will be financed with a loan granted at an interest rate of 7 % covering 80 % of the acquisition price, thus amounting to CZK 71 920 000 with a maximum maturity of 10 years paid in quarterly instalments. Back in 2010, the high price of feed-in tariffs guaranteed for 20 years ensured that the loan of similar conditions could have been concluded without any greater difficulty. Table 4 shows an annual amortization schedule of the loan that corresponds to the amount of interest associated with each payment until the loan is paid off at the end of its term. As can be seen from the table, the total price was increased by CZK 28 687 706 due to the loan interests.

Table 4. Annual amortization schedule of the loan

Year	Annual payment [CZK]	Interest [CZK]	Principle [CZK]	Loan balance [CZK]
0	X	X	X	71 920 000
1	10 060 771	4 900 912	5 159 859	66 760 141
2	10 060 771	4 530 123	5 530 648	61 229 493
3	10 060 771	4 132 703	5 928 069	55 301 424
4	10 060 771	3 706 717	6 354 054	48 947 370
5	10 060 771	3 250 121	6 810 650	42 136 720
6	10 060 771	2 760 715	7 300 057	34 836 664
7	10 060 771	2 236 140	7 824 632	27 012 032
8	10 060 771	1 673 869	8 386 902	18 625 130
9	10 060 771	1 071 194	8 989 577	9 635 553
10	10 060 771	425 212	9 635 553	0
<b>Sum</b>	<b>100 607 712</b>	<b>28 687 712</b>	<b>71 920 000</b>	<b>X</b>

Apart from the loan, the additional costs for recycling of the panels must also be taken into account. The REsolar is one of the companies dealing with panel's recycling, and through the calculator, which can be found on the [www.resolar.cz/cs](http://www.resolar.cz/cs) website, the price for this process can be determined once the value of total installed power is entered. The price was estimated at CZK 849 915. According to the law, this charge must be paid in equally distributed instalments from 2014 to 2018 based on the concluded contract (see 5.8.1) - this equals to CZK 169 983 for each year, which will be reflected in the estimation of payback time as an additional sum to operation and maintenance costs during that period.

Other aspects of payback calculation are the annual decrease of panel's efficiency at the rate of 0.8 %, the annual operation and maintenance costs (estimated to be of CZK 900 000; this value will be increased by 2.5 % every year, which complies with the inflation over time), the withholding tax on plant's revenues (see chapter 4.3.3 in which all the details related to 'solar tax' have been discussed), and eventually the energy yield (see tab. 3) along with the purchase price of feed in tariffs (since 2018, it will be calculated with the increase by the price index of industrial inflation rate at 2 %) for PV facilities realized in 2010 and exceeding the installed power of 30 kWp,

according to which the annual revenues can be specified. In addition to operation costs, the value of CZK 420 000 represent the average annual price of investments in inverter replacement - as it is in case of all conventional energy audits due to the fact that inverter failures cannot be predicted, and it would be a wrong assumption to include, for example, one specific year during which all the inverters are to be replaced.

Table 5. Calculation of payback period

Year	Feed-in tariff [CZK/MWh]	Energy yield [MWh]	Revenues [CZK]	Tax rate	Loan interest [CZK]	Operation costs [CZK]	Inverter replacement [CZK]	Balance [CZK]
2011	12 400	1076.272	13 345 773	26 %	4 900 912	900 000	420 000	4 142 145
2012	12 650	1067.662	13 505 922	26 %	4 530 123	922 500	420 000	8 263 904
2013	12 903	1059.121	13 665 832	26 %	4 132 703	945 563	420 000	12 878 355
2014	13 161	1050.648	13 827 573	10 %	3 706 717	1 139 185	420 000	20 057 268
2015	13 424	1042.242	13 991 062	10 %	3 250 121	1 163 415	420 000	27 815 688
2016	13 692	1033.904	14 156 220	10 %	2 760 715	1 188 250	420 000	36 187 321
2017	13 966	1025.633	14 323 993	10 %	2 236 140	1 213 707	420 000	45 209 069
2018	14 245	1017.428	14 493 264	10 %	1 673 869	1 239 800	420 000	54 919 337
2019	14 530	1009.289	14 664 965	10 %	1 071 194	1 096 563	420 000	65 530 048
2020	14 820	1001.214	14 837 998	10 %	425 212	1 123 977	420 000	76 915 057
2021	15 116	993.205	15 013 282	10 %	X	1 152 076	420 000	88 854 935

According to the table 5 it can be seen that the investment in this facility will be paid up at the beginning of the twelfth year of plant operation, i.e. 2022. However, the calculation is not 100 % accurate since it does not take, for example, the income tax into consideration, which would certainly prolong the entire payback period; unfortunately, calculations related to the income tax are beyond the scope of this paper.

## **Conclusion**

This paper enables to immerse in the issues of photovoltaics. The first part is mainly concentrated on the conversion of solar energy into the electricity. Since photovoltaic panels are one of the most important components in every photovoltaic system, the individual generations of photovoltaic cells and their selected types were also described. The commercial types, such as monocrystalline and polycrystalline cells have been the most common types for many years. However, there are other different types with great potential, namely quickly emerging organic and nanowire-based ones, but, it remains to be seen how successful they will be in taking the market share from existing, widely spread commercial technologies.

Legislation with regard to the field of photovoltaics is a topic of the fourth chapter. The implementation of the Act no. 180/2005 Coll., on supporting generation of energy from renewable sources, was the fundamental step towards the major development of renewable energy sources in the Czech Republic including photovoltaics. The photovoltaic power plant projects did not initially appear as a prudent investment, especially due to the significantly high price of the modules. However, the mass manufacturing of PV panels primarily in Europe and China resulted in the gradual reduction of price of the modules, which led to a corresponding drop of the overall price of photovoltaic projects. Henceforth, a large number of investors immediately responded to the trend through building and connecting a large number of photovoltaic power plants to the power grid primarily in the years 2009 and 2010, during which investors could draw on favourable subsidies. These aspects triggered the increase in the final price of electric energy that had to be paid by general public; as a result, the entire photovoltaic industry received notable mediation in the Czech Republic and received somewhat negative connotation in the eye of most people.

Over time, however, the amount of operation support would adjust to the gradually decreasing costs of components used in photovoltaics, and the number of successive installations was reduced considerably. As the conditions changed, today's installations appear merely on roof structures and their installed power has been gradually limited to 30 kWp. However, there have been several programmes established in the Czech

Republic, such as the New Green Savings Programme, whose purpose is to support rooftop PV installations in order to prevent economic unprofitability of the photovoltaic projects (since the support of electricity for PV facilities in the form of feed-in tariffs and green bonuses was abrogated in 2014), as well as to maintain the future investments in the this industry. Maintaining future investments has also significant role to play because of to the regulation set by the European Commission, regarding its ecological politics by which the Czech Republic is obliged to accomplish the target of increasing the share in the renewable energy consumption by 2020.

As regards the last chapter, the particular ground-mounted photovoltaic power plant which was launched in the period of so called ‘solar boom’ has been introduced. In order to carry out the analysis, we were given very helpful pieces of advice and the necessary materials, especially the data about the energy production for the first year of operation, according to which the comparison with relatively accurate prediction based on the publicly available PVGIS programme was realized, but, most importantly, it allowed for the rough estimation of project’s payback period. In the first place, the loan covering most of the acquisition price was considered since it is common procedure in case of all larger PV facilities. Calculation then comprises necessary aspects, such as gradual decrease of panel’s efficiency, contribution to future recycling of the panels, annual operation costs, and the ‘solar’ tax that is supposed to compensate for the favourable support of electricity back in 2010; hence, being the subject of many discussions. It was concluded that the initial investment shall be recovered at the beginning of the twelfth year of operation. However, the income tax is not included and with respect to, for instance, the value of money over time, the payback period should be considerably longer under the real conditions.

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