Theoretical analysis of issues regarding photovoltaics module placement and application

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Abstract

This article deals with possibilities of photovoltaics usage as an alternative to traditional fossil fuel sources. First part introduces the photovoltaics principle, second part deals with main issues regarding the array placement and the final part deals with photovoltaics and measurements done in our department.

1. Introduction

In present days, due to growing concerns about possibility of global warming, rising fossil fuel prices and the need of improved security is leading more countries to give higher priorities for integrated policies for addressing climate change and energy. The EU set an example to the rest of the world by cutting its greenhouse gas emissions by at least 20% by 2020 and final energy demand should consist from at least 20% from renewable energy sources. In term renewable sources of energy we understand ecologically clean direct or indirect form of solar energy, which can be transformed by suitable technological solution to electrical energy.. Renewable energy sources are available in much higher amount than the whole world needs and their usage is imperative for keeping the ecological equilibrium. Following figure (Fig.1) shows the solar potential of Slovak Republic as well as yearly sum of global irradiation which can be utilized by photovoltaic modules

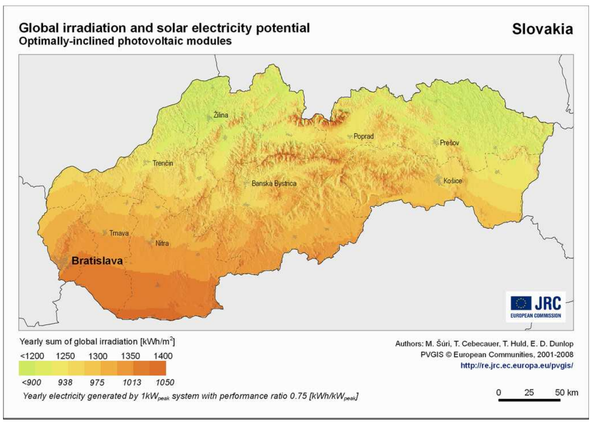

Fig.1 Global Irradiation and Solar Electricity Potential

Following figure (Fig.2) shows the photovoltaic solar electricity potential in European countries. The data was gathered by European Commision Joint Research centre.

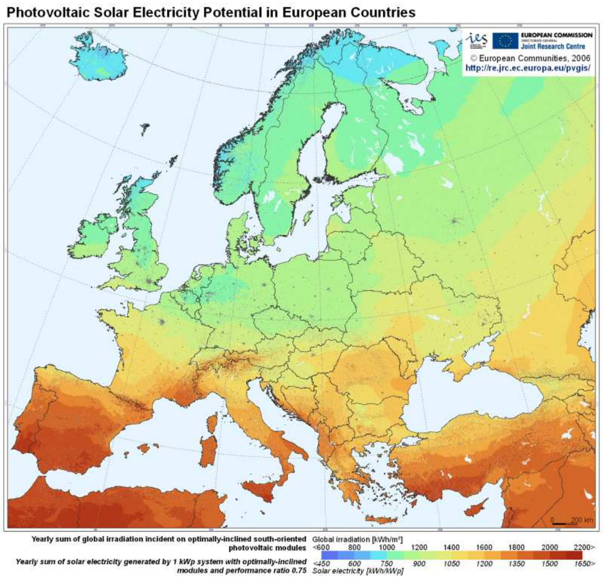

Fig.2 Photovoltaic Solar Electricity Potential in European Countries

2. Photovoltaics principle

Photovoltaic systems use the principle of semiconductors. Semiconductors are elements from IV group of periodic table such as silicon (Si), germanium (Ge), tin (Sn) which have 4 valence electrons on sphere. Semiconductor systems consist of 2 elements, for example III-V semiconductor gallium-arsenic (GaAs) and II-VI semiconductor cadmium-tellurium (CdTe).

Silicon is the most common material in photovoltaics. It is the second most common element in Earth´s crust, but it is not possible to find it in chemically clean form. It is the fundamental semiconductor of IV group of periodic table, therefore it have 4 valence electrons. Because it wants to keep the most stable electron configuration, 2 electrons from neighbouring atoms in crystal lattice form a pair connection.

Such pairing (covalent bond) with 4 neighbouring atoms provides silicon with stable electron configuration similar to rare gas argon (Ar).

From energetical point of view, the valence zone is fully taken and the conductive zone is empty. By providing additional energy, for example from light or heat source electron moves from valence to conductive zone. Electron can freely move on the crystal lattice. When electron leaves the valence zone, the free space is known as the hole, or so called defective electron. Creation of these defective electrons is responsible for inner semiconductors conductivity. Electrons and holes are always in pairs, so in other words there is the same amount of electrons and the holes.(Fig.3)

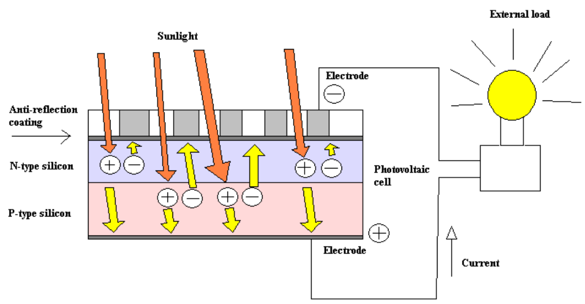

Fig.3 Principle of Photovoltaics Power Cell

Current flowing through PN crossing can be formulated as algebraic sum of balanced heat flows of electric charge carriers. In state of equilibrium is the sum of the heat flows zero. Sums of electron and hole currents passing through the PN crossing are also zero.

Absolute values of electron and hole currents from the N type semiconductor can be marked as I_n^N and I_p^N, from semiconductor type P can be marked as I_n^P and I_p^P.

In equilibrium state:

$$-I_n^N + I_p^N + I_n^P - I_p^P = 0 \quad (1)$$

$$-I_n^N + I_p^N = 0 \quad (2)$$

$$+I_n^P - I_p^P = 0 \quad (3)$$

Illumination will cause the increase in concentration of minority carriers. It will create the I_f current which flows through the PN crossing. When illuminated, Fermi´s level shatters to quasilevels for electrons and holes. Their difference φ resembles the voltage $U_f = \frac{\varphi}{e}$, which was created as the result of illumination.

In stationary state, the current flowing through the PN crossing equals to zero.

$$I_f - I_n^N + I_p^N + I_n^P - I_p^P = 0 \quad (4)$$

Majority carriers currents I_n^N and I_p^P will change because of illumination. Energetic levels are mutually shifted and levels of potential barriers are changed:

$$I_n^N = I_n^P \exp(\frac{\varphi}{kT}) \quad (5)$$

$$I_p^P = I_p^N \exp(\frac{\varphi}{kT}) \quad (6)$$

Using the equations (4), (5), (6) and after adjustments we get:

$$I_f - I_s[\exp(\frac{\varphi}{kT}) - 1] = 0 \quad (7)$$

For photoelectromotoric force:

$$U_f = \frac{\varphi}{e} = \frac{kT}{e}\ln(\frac{I_f}{I_s} + 1) \quad (8)$$

If PN crossing is connected to circuit where current I is flowing, using the (7), (8) equations we get:

$$I_f = I + I_s[\exp(\frac{\varphi}{kT}) -] \quad (9)$$

$$U_f = \frac{kT}{e}\ln(\frac{I_f - I}{I_s} + 1) \quad (10)$$

If PN crossing is connected to resistor $R = \frac{U_f}{I}$, equation (9) will be:

$$I_f = \frac{U_f}{R} + I_s[\exp(\frac{\varphi}{kT}) - 1] \quad (11)$$

In the case of small external resistors when: $I >> Is[\exp(\frac{\varphi}{kT}) - 1]$ we get $I_f \approx I$.

In the case of big external resistors when $I -> 0$, we get: $I_f - I_s[\exp(\frac{\varphi}{kT}) - 1] = 0$

If we connect the source of voltage to PN crossing we get:

$$I_f = \frac{U_f - U}{R} + I_s[\exp(\frac{\varphi}{kT}) - 1] \quad (12)$$

For the solar cell power we use this formula: P=U.I For the maximum output:

$$\frac{d(UI)}{dU} = I_k - I_s + I_s\frac{e}{kT}\exp\frac{eU_m}{kT} = 0 \quad (13)$$

For idle connection:

$$U_0 = \frac{kT}{e}\ln(\frac{I_k}{I_s} + 1) \quad (14)$$

2. Issues regarding the array placement

2.1 Orientation and angle of photovoltaic panel or array

The electricity which is produced by photovoltaic panel is highly affected by its orientation and angle. In ideal state, when direct solar radiation is considered the optimal angle is equal to the latitude of the geographical location. Such prediction is not real, because the major part of the radiation is diffused radiation from other direction than the sun. Because of this, the optimal angle is slightly towards the horizontal. Season of the year must be considered as well, because it is obvious that in winter he sun sun´s elevation is low, so the panel needs higher angle in order to produce more energy and in summer the smaller angle of tilt is needed. The optimal orientation must be determined individually for each application. Local weather conditions such as morning fogs must be taken into account. Following figure shows the percentage of optimal energy production that can be expected from photovoltaic panel at different angles.(Fig.4)

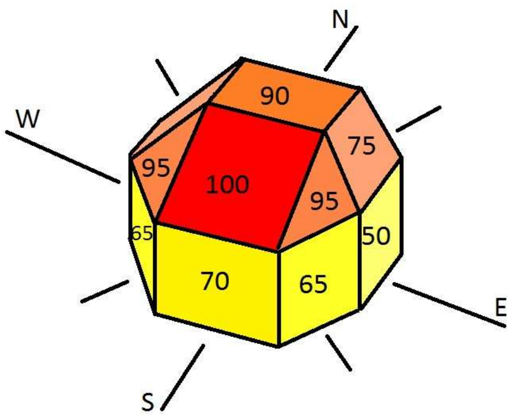

Fig.4 Percentage of Optimal Energy Production at Different Orientations and Angles

2.2 Influence of shading

Possibility of shading is very important factor which must be considered because it can dramatically reduce the generated power output. Even partial shading can reduce the generated power significantly. Shading can be created by trees, buildings, or other objects which may also be the building´s design features Shading varies with the time of the day and the time of the year. It is important to minimize the number of cells which can be shaded. Potential tree obstacles must be taken into account, their height, width, their growth pattern…The building features such as chimneys, satellite dishes, higher parts and such should be designed or at least considered so they are not shading the photovoltaic panels. Considering the aesthetic reasons, dummy photovoltaic models can be installed in permanently shaded areas, just for aesthetic function. Following images shows the shading calculations.

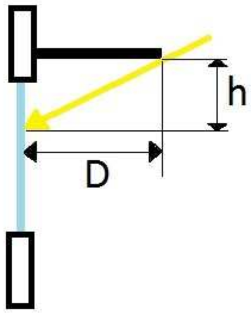

Fig.5 Horizontal Shading

$$h = \frac{D \times \tan \alpha}{\cos(\Phi - \Psi)} \quad (15)$$

Where D is geometry of horizontal shading device, α is sun height, Φ is solar azimuth, Ψ is plane azimuth

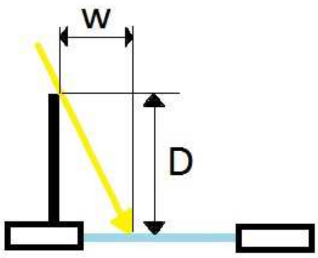

Fig.6 Vertical Shading

$$w = D \times \tan(\Phi - \Psi) \quad (16)$$

Where D is geometry of vertical shading device, Φ is solar azimuth, Ψ is plane azimuth.

Following table shows the power loss due to cell shading.

% of array shaded	Power loss due to shade
13%	44%
11%	47%
9%	54%
6.5%	44%
3%	25%

Tab.1 Power loss due to shading

The interesting thing is that the loss is disproportional. It is caused because the way how individual cells are connected within the solar panel and by the centralized form of performance optimization which is carried by the array inverter.

Mostly, the panels are connected to parallel strings. By strings we mean serial connected cells. The inverter transforms the DC current from these strings to AC current and simultaneously optimizes the array´s power generation. Because the strings are made of serial connected cells, there is a risk of failure when one or more cells underperforms (for instance because of shading).

To prevent such failure, the array is equipped with so called bypass diodes which reroute the current around cells which are underperforming. The problem is, that such rerouting lowers the entire string´s voltage which causes problems to inverter, because basically it has to make a decision either by optimizing the voltage for the underperforming string or it can try to maximize thew energy from the other strings. Mostly the inverter chooses the first option, which results in energy harvest from weakened string to drop near zero.

The energy loss from shading is very hard to predict, because it depends on many things, for example the angle and orientation of the array, connections between cells, and the inverter as well.

2.3 Influence of temperature

The efficiency of photovoltaic modules decreases when the temperature increases. Generally, for crystalline silicon, the efficiency decreases by roughly 0.4% for every degree in temperature rise above its rated output temperature.In most cases such temperature is about 25-30˚C. For modules based on thin-film technology this effect is smaller.

Efficiency of most photovoltaic modules ranges from 15 to 20%. The remaining energy is heat which is not further utilized. Such heat increases the temperature of the panel and decreases its performance.

Photovoltaics module which is exposed to direct sunlight can become considerably hotter than ambient temperature. It is not unusual when the panel is hotter by 50˚C in sunny day, so the performance can drop by more than 25%. This can turn 12kW system to only 8kW system. Such overheating can cause danger to roofing material like melting (especially for bitumen roofs type).

The solutions which can reduce the module´s heat like ventilated air gap at the rear are essential. Such gap can reduce the temperature of the module by at least 10˚C. Air gap should be also between the module and the roof or the facade, so the natural air flow can be used for cooling purposes.

This cooling leads to lowered operating temperature which results in higher system performance and the possibility for using the excessive heat for practical heating purposes.

This principle is now being used in so called SolarWall systems (Fig.7) which cooperate with building´s HVAC (Heat, Ventilation, Air Conditioning) systems wich ducts the heat from back of photovoltaic panels. The circulating air helps to cool the modules and increases their electrical output roughly by 10%. Is is important to leave smal gaps between panels, to prevent the build-up of excessive heat. Panels for balancing the air flow are also used, they serve as a mounting rack for photovoltaic panel as well.

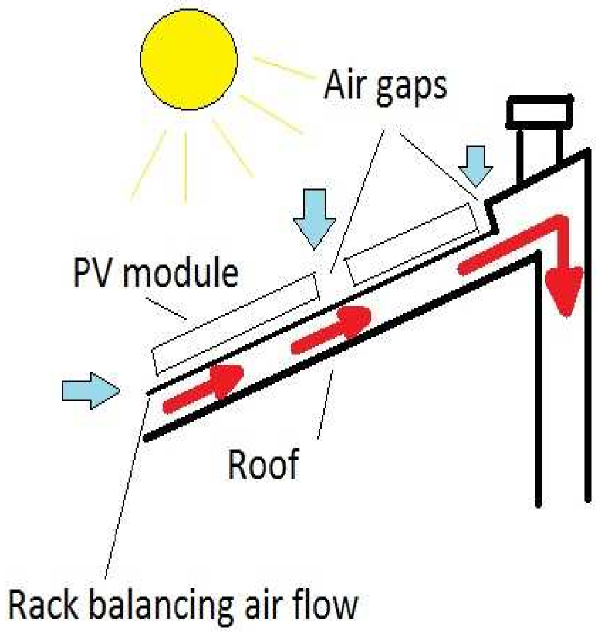

Fig. 7 Photovoltaic Module Ventilation System

2.4 Inverter types and positioning

When choosing the right inverter, there are several possibilities. One possibility is to use larger inverter for complete arrays or sub-arrays, while the other possibility lies in using smaller inverters for each string of modules. However larger systems can need a lot of small inverters. The advantage of smaller inverters is, that they can be used for any system, so the standardized and bulk manufacturing techniques can be used which can lead to reduced prices when compared with large inverters.

When choosing inverter we must consider its efficiency, maintenance and losses caused by wiring.

However, the choice depends largely on operating conditions of the module. If all the cells are receiving equal irradiance, then the single inverter is better option. On the other hand, if the modules have different orientations, or there are issues with shading, the smaller string inverters are better option.

The inverter should be placed as close as possible to the PV array, in order to minimize the wiring loses. For safety reasons it is good to consider the double insulated cable, which on the other can be thick and heavy and difficult to bend, so the long routes are impractical.

Inverters should be placed in some central location in order to ease the maintenance process. It is more convenient than to have inverters scattered all around the place. Inverters should be placed in place where their cooling can be guaranteed. The inverters generate heat (up to 10% of their nominal power) because the overheating lead to lower energy efficiency.

3. Photovoltaics on KTEEM

Automated measurements of power and voltage of photovoltaic panel are performed on KTEEM department. Program (Fig.8) was written for the measurement, which can collect the voltage or current values simultaneously from 4 devices. The results are daily written to *.csv file (fig.9) and are sent to specified ftp server at midnight, where they can be further evaluated.

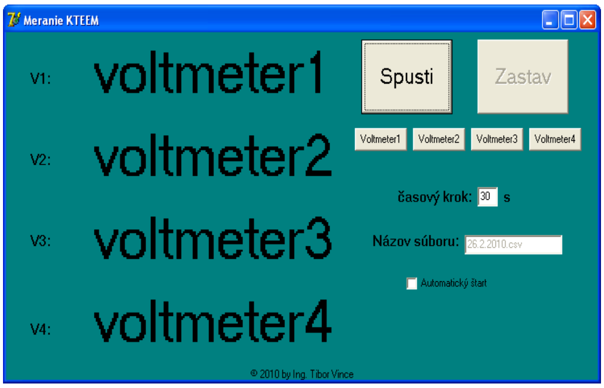

Fig.8 Main Screen of Measuring Program

544	1.3.2010	9:04:01	1,876	V	0,447	V
545	1.3.2010	9:05:01	1,843	V	0,447	V
546	1.3.2010	9:06:01	1,745	V	0,444	V
547	1.3.2010	9:07:01	1,644	V	0,439	V
548	1.3.2010	9:08:01	1,678	V	0,438	V
549	1.3.2010	9:09:01	1,754	V	0,438	V
550	1.3.2010	9:10:01	1,787	V	0,439	V
551	1.3.2010	9:11:01	1,819	V	0,441	V
552	1.3.2010	9:12:01	1,821	V	0,443	V
553	1.3.2010	9:13:01	1,809	V	0,442	V
554	1.3.2010	9:14:01	1,718	V	0,441	V
555	1.3.2010	9:15:01	1,619	V	0,438	V
556	1.3.2010	9:16:01	1,723	V	0,437	V
557	1.3.2010	9:17:01	1,786	V	0,44	V
558	1.3.2010	9:18:01	1,77	V	0,441	V
559	1.3.2010	9:19:01	1,721	V	0,441	V
560	1.3.2010	9:20:01	1,726	V	0,441	V
561	1.3.2010	9:21:01	1,775	V	0,442	V

Fig.9 Example of daily output file

Following figure (Fig.10) shows the resulting graph from output file. Such graph is available for every day of measurement, as well as monthly overview (Fig.11)

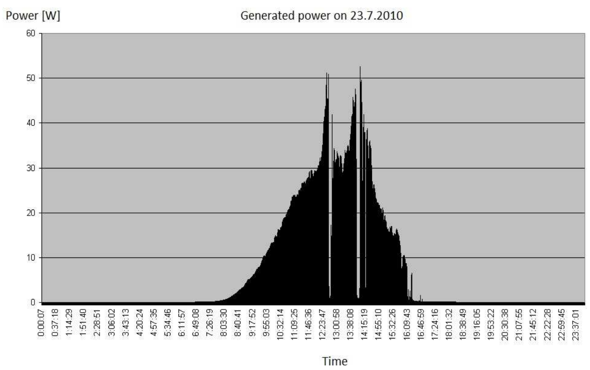

Fig.10 Daily graph of generated power

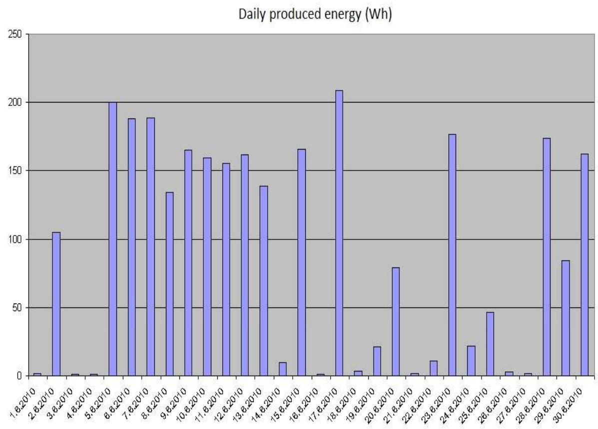

Fig.11 Monthly overview of produced energy

4. Conclusion

Photovoltaics begins to prove that it has the potential to fully substitute traditional fossil fuels as the technology is rapidly evolving. Its potential lies not only in providing energy for household applications, but also in providing energy for vehicles. It is not possible to use photovoltaics in current vehicles, because they are very heavy to be solar powered. However, there are existing projects of light and efficient solar cars which can transport for people, where the solar cells are mainly placed in the roof and front/back horizontal parts of automobile´s body. The realistic approach is the electric vehicle, which uses batteries, which are charged by photovoltaics arrays during day, when people are at work. In case that the sun is not shining, they can be plugged at home for charging. The current research focuses on improvement of such systems to be more efficient and cost effective which will lead to their wider usage. The wider usage of any cars based on electricity is the need of inexpensive and compact energy storage methods. The benefits of the solar cars are obvious, they don´t pollute the environment and their fuel is for free. However, their disadvantage is that they have to be very light in order to PV arrays generate enough energy to operate them and it needs to have enough battery storage to travel for long distances without sunlight. These are the main challenges of current research activities in order to make these cars available for mass production in near future.

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