Usage of photovoltaic systems issue

Bělík Milan, Škorpil Jan

Department of electrical power engineering and ecology, Faculty of electrical engineering, University of West Bohemia, Pilsen, Czech Republic

Abstract

The use of renewable energy sources is very fashionable nowadays. But is it really the best way to solve the growing lack of energy? Are thermosolar and photovoltaic systems pleasant for our environment? These and similar questions must be seriously examined and the public must be correctly informed. This paper presents some fundamental and advanced experiment performed on real systems in real conditions.

Keywords: Solar energy; Photovoltaic system; Basic values; Service conditions; Efficiency; Influence on supply network

Introduction

Continuous reduction of reserves of classic energy sources such as coal, oil, gas on one hand and increasing power consumption around the all world on the other hand has lead to a lack of energy. This issue is going to become a serious problem in the near future. Humankind needs to solve this problem before it will grow into real recession. So-called renewable energy sources are very fashionable nowadays and seem (at least particular solution) to solve this issue. These renewable sources could be basically divided into 4 separate categories:

1. solar energy
2. wind energy
3. water energy
4. biomass.

But, in fact, they should be summarized into only one large set of different sources, because the primary energy source is in all cases the Sun. Direct use of solar energy will be described separately. Photons emitted by Sun warm the Earth and it causes vaporization of water and its circulation, what we can use as kinetic and/or potencial water energy. The same principle causes movement of atmospheric masses, what we observe as wind and use as kinetic wind energy. Next the sunlight is necessary for life of plants and the energy of photons captured by chlorophyll in leaves cells is stored as chemical energy in organic substances. By the way – the chemical energy stored in coal has the same origin. So, in fact almost all energy (except nuclear and thermal) is only some stage of solar energy.

The direct use of solar energy can also be split into some categories. Natural use of sunlight for lighting means only distribution using solar tubes, solar windows, Fresnell lenses etc. The energy of photons can be further converted into thermal energy via thermal collectors or using special “solar” architecture. Likewise some experiments about the use of solar energy for chemical processes (so called synthetic photosynthesis) are in progress. Probably the most dynamically developed field explores the direct conversion of energy of solar radiance into electricity. Some issues of this research will be explained in following paragraphs.

If we consider that the density of solar radiation on the Earth’s surface is approximately $1000 W/m^2$, we can easily imagine that use of this energy could be a very significant power source (in any way as mentioned above).

Theoretical basics

The principle of conversion of sunlight into electricity lies in the ability of specially doped semiconductors to absorb photons while emitting electrons. At present the most widely used semiconductor is doped monocrystalline silicon. From a historical point of view this was the first technogy developed and practically tested. The very first applications of this technology were solar cellls mounted on the first space explorers. This technology is best elaborated, gives the best efficiency and is the mainly used, but is also the most expensive, because we need a large monocrystal of silicon to be grown. Bearing in mind that a typical PV cell is 10x10cm square.

A cheaper possibility is cutting the base plates from fused polycrystalline silicon. This technology is much cheaper but gives less efficiency of the conversion. Intensive development is performed to enhance the technology.

The cheapest way is the use of amorphous silicon, but the cells degrade very fast and also the efficiency is very low. Compared to previously described technologies this degradation is 7 – 10 times faster. The power of typical monocrystalline cell falls in 20 or 25 years to 95% of nominal value. Analogical degradation of produced amorphous cells is in approximately 3 years.

Of course, other technologies of usage of “non classic “ semiconductors or organic materials are in evolution and seem very interesting for the future, but detailed description of them exceeds the range of this article.

Not depending on the technology the cells are connected in parallel and/or serial way into photovoltaic panels and arrays.

These panels can be operated separately or connected to a public grid.

Island operated photovoltaic systems

A very easy and useful way to use solar energy is usage of self-standing solar panels. This means that separate panel is connected directly or via inverter to operated equipment. Typical application consists of solar array, accumulator and controlled charger. The voltage level is typically 12V or 24V DC. An accumulator is used for storage of electricity in peaks and for further usage in dips. Charger – so called solar charger is controlled per V-A characteristic of the solar panel and accumulator.

This system is mostly operated separately from supply network - typically in inaccessible places in the wilderness, in mobile traffic signs while roadwork and during expeditions to deserted countryside. This is very often used to power low-power halogen lamps (12V), portable battery chargers, laptops, hand TVs and refrigerators etc. These equipment should be designed to be operated at voltage level 12V DC, or we must use special inverter for conversion to 240V AC. This conversion and the second conversion in the equipment decrees the final efficiency of the whole equipment chain.

Output power of similar system can be typically about 100W- that means approximately 1m^2 large PV panel. Of course this power is reachable only in good conditions! Finally this is the limitation of these systems to power strong power circuit devices such as circular saws, electrical tools, cookers, pumps etc. One possible solution is usage of parallel diesel generator to power these heavy equipment.

PV systems connected to network

The second frequent usage of solar systems is their cooperation with public supply network. Photovoltaic panel is typically much larger than in previous case and is connected via DC/AC inverter to a grid. This solution solves problems with low-power load of the system, time distribution of the output, need of diesel generator for power applications, but raises other issues.

While connecting any equipment to public supply network we must comply to connecting rules and standards. These “Connection rules” partially depend on local electricity distribution company and can vary in some details. But simply said, our equipment must not disturb any other device connected to the grid in any way.

The disturbance can be caused by low voltage oscillation, phase voltage unbalance, fast voltage oscillation (flicker), emission of harmonic and non-harmonic frequencies etc. The limitations of a disturbance are very rigorous, but description and explanation of their details is beyond the scope of this paper.

Service conditions of PV systems

Instead of classical energy sources the service of a photovoltaic system is almost unpredictable. This issue is caused by the character of the “power source” – the sunlight.

The spectrum of the radiation emitted by the Sun is close to that of a black body at a temperature of 5,900K. About 8% of the energy is in the ultra-violet region, 44% is in the visible region, and 48% is in the infra-red region. Although the Sun produces a radiation at almost constant level and spectrum (excluding solar eruptions and other disorders), the level of usable radiation on the Earth surface widely differs. The main reason for this is, of course, the weather and air pollution.

Solar rays come through the atmosphere and some of them are dispersed, reflected and absorbed on surfaces of clouds, dust corpuscles, water drops, fog elements, on interfaces of air layers on different temperature etc.

The dispersion of the solar radiation is mainly caused by molecules of air and water vapor, by water droplets, and by small dust corpuscles. This process returns about 6% of the incident radiation back to space as unusable energy, and about 20% of the radiation reaches the Earth surface as diffuse solar radiation. Air molecules disperse the sunlight with an intensity proportional to λ^{-4}, where λ is the wavelength of the radiation. This process is called Rayleigh scattering and it is very important for particles with a radius less than $\lambda/10$. This wavelength effect can be seen in the blue color of the clear sky and in the red color of the sunset. The sky appears blue because the shorter wavelength of the blue light is dispersed more strongly than the longer wavelength of the red light. The setting sun appears red because much of the blue light has been scattered out of the direct beams. Scattering of the beams from large particles with radius greater than $25*\lambda$ is independent of the wavelength. As a result, sunlight rays dispersed from the water droplets in mist and clouds, and from the dust particles in haze, have a white color.

The absorption of solar radiation is mainly caused by molecules of ozone and by water vapors. The absorption by ozone takes place in the upper atmosphere levels at altitudes above 40 km. It occurs mainly in the ultra-violet region of the spectrum, where it is so intensive that only very little dangerous radiation of the wavelength less than 0.3μm reaches the Earth surface. This example also shows the importance of the ozone layer. About 3% of solar radiation is absorbed in this way. At low levels of the atmosphere about 14% of the solar radiation is absorbed by water vapors, mainly in the near infra-red region of the spectrum. Clouds absorb only very little solar radiation, which explains, why they do not evaporate in sunlight. There is also a small amount of absorption caused by oxygen molecules. The absorption of the solar radiation by molecules of CO_2 is also slight, but their absorption and emission of long-wave atmospheric radiation is very important in the greenhouse effect.

The reflection of the solar radiation depends on the nature of the reflecting surfaces. The fraction of the solar irradiation that is reflected from the Earth surface is called albedo of the surface. But it depends also on the angle betwee the surface and the rays. For example when the Sun is low above the horizon, the albedo of a water surface is much greater than it is when the Sun is in zenith. The albedo of clouds depends on their thickness.

With today's state of technology we are not able to use the indirect radiation in an effective way.

The sum of direct and indirect (diffuse) radiation produces the available energy on the Earth surface and it is known as global irradiance.

$$I = I_{dir} + I_{dif}\ \left[W / m^2\right]$$

The intensity on the boundary of atmosphere is about 1360W/m^2 and this value is nicknamed solar constant. In comparison with this value we can usually gain 1000 W/m^2 on Earth surface approximately during sunny day while during rainy day we can expect only about 200 W/m^2. These values do depend not much on geographical latitude.

A more significant relation on the latitude is in the time of solar exposure. It is evident, that in the northern countries such as Norway or Iceland the solar exposure times are much shorter than around the equator. Furthermore these times vary depending on the season of the year. This is caused by the inclination of the Earth axis and the ellipticity of the Earth's orbit around the Sun.

The theoretical distribution of solar irradiance on horizontal layer and its variations during the year valid for the central Europe can be seen on the Fig. 1.

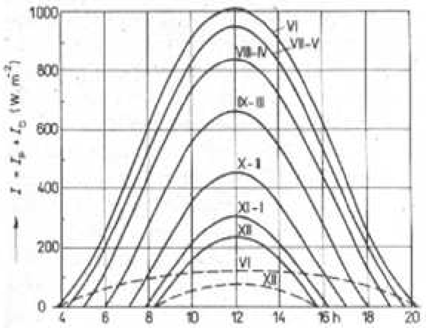


Fig. 1.: Theoretical solar irradiance

The next very important relations in service conditions of photovoltaic systems can be found in the spectrum structure of the incident light, temperature and load dependencies etc. Excluding the load characteristics the most significant phenomenon is the thermal dependency. In contrast with thermosolar systems photovoltaic systems have a negative thermal characteristic. That means the higher the operating temperature, the lower the efficiency is. This is very unpleasant, because the lower temperatures are available in winter months where also the lowest solar irradiances are reached. The approximate relation is the efficiency decrees about 0,5% for every increased degree of temperature. Nominal efficiency is about 16% for monocrystalline silicon in referential temperature 20°C.

But how do all these phenomenan affect the real service of a photovoltaic system? This is very complex question. Members of Department of electrical power engineering and ecology of University of West Bohemia participates on this research for few years and have obtained some interesting results.

Issue of solar systems in Pilsen

Department of electrical power engineering and ecology members cooperated since 2002 in research of basic service conditions for solar systems with ZCE (local electricity distribution company). The main task was to explore and describe the basic conditions in Pilsen. Fundamental 3 years lasting measurements were executed and data was recorded in 1 min period. The measurement chain consisted of:

- solar irradiance sensor SG-420
- datalogger Comet MS-3.

The sensor SG-420 was installed in the center of the demonstration thermosolar system belonging to ZCE in the Pilsen downtown. The collectors were situated to south and mounted at an angle of 45°.

The most important results are natural time distributions of solar irradiance in Pilsen, calculations of estimated energy gains and air pollution factor for the same location. Because for duration of the measurements for more than 3 years the results are accurate enough to be a good starting point for design of solar systems in Pilsen.

Adequate samples of monthly distributions are shown on Fig. 2 – 5. These graphs illustrate the typical values and distributions of solar irradiance in each year season.

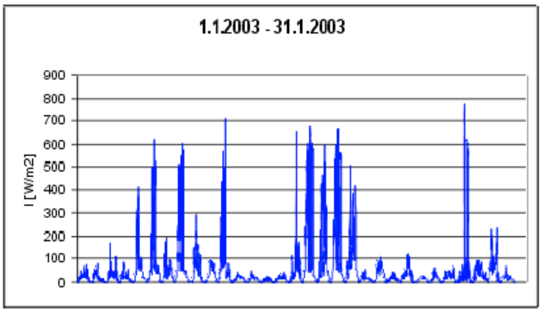


Fig. 2.: Characteristic monthly time distribution of solar irradiance in winter season

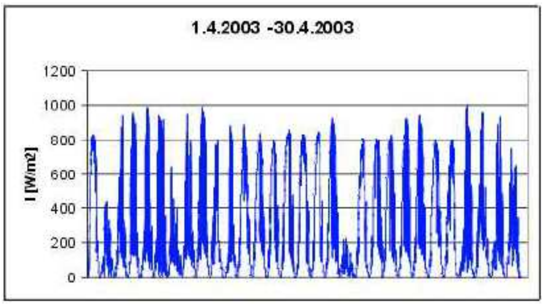


Fig. 3.: Characteristic monthly time distribution of solar irradiance in spring season

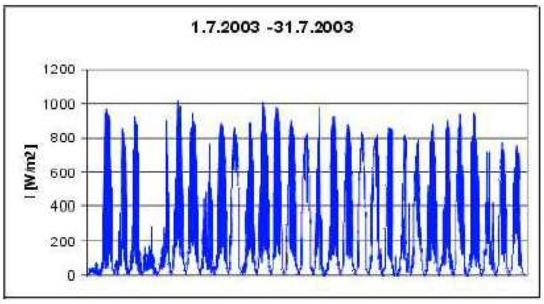


Fig. 4.: Characteristic monthly time distribution of solar irradiance in summer season

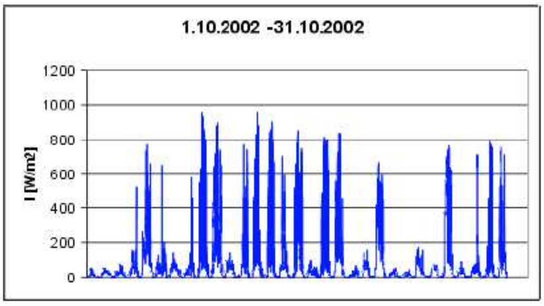


Fig. 5.: Characteristic monthly time distribution of solar irradiance in fall season

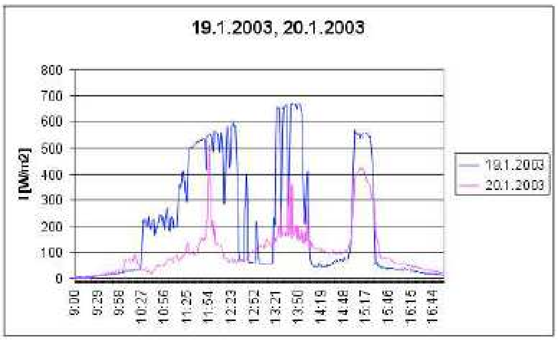


Fig. 6.: Characteristic daily time distribution of solar irradiance in winter season (19.1.2003 – sunny day, 20.1.2003 – cloudy day)

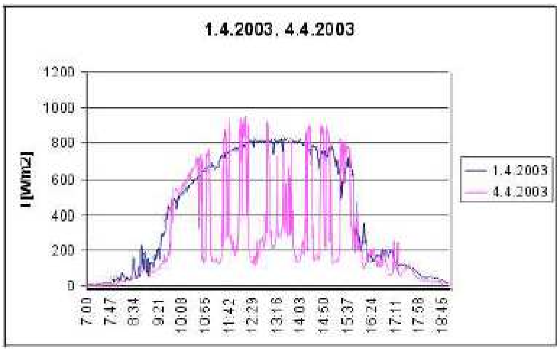


Fig. 7.: Characteristic daily time distribution of solar irradiance in spring season (1.4.2003 – sunny day, 4.4.2003 – cloudy day)

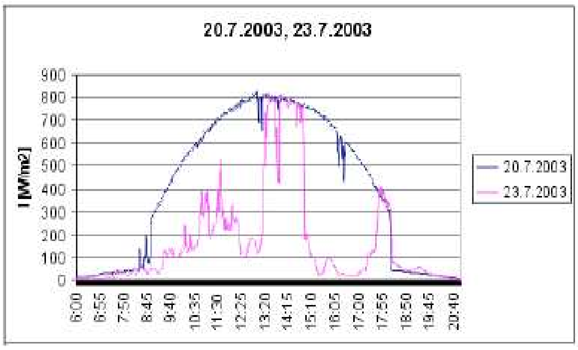


Fig. 8.: Characteristic daily time distribution of solar irradiance in summer season (20.7.2003 – sunny day, 23.7.2003 – cloudy day)

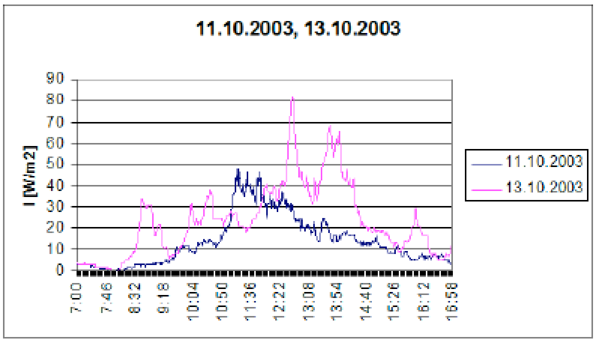


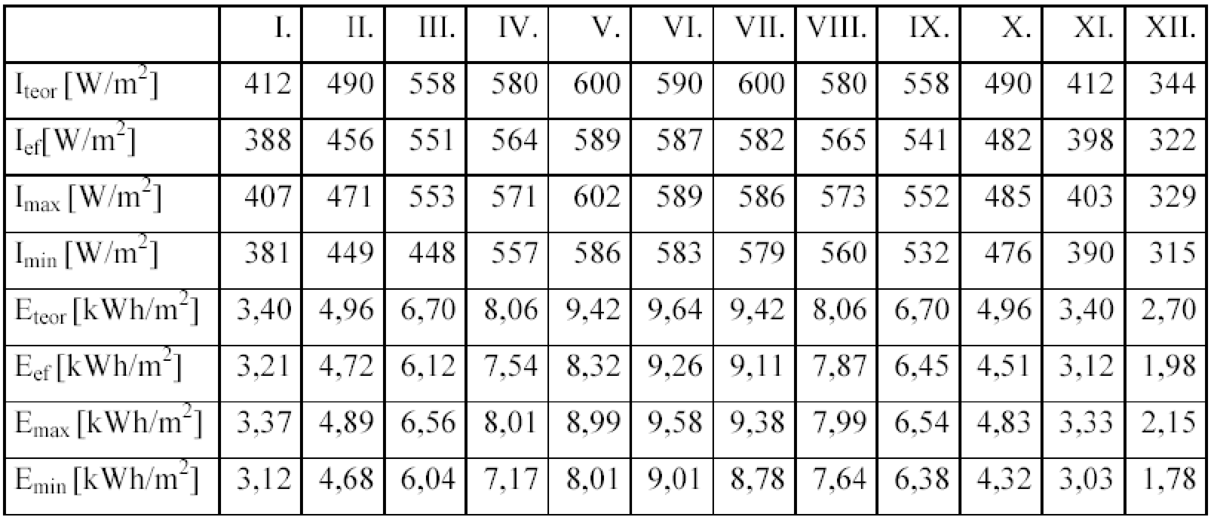
Fig. 9.: Characteristic daily time distribution of solar irradiance in fall season (13.10.2003 – sunny day, 11.10.2003 – cloudy day)

As you can see, the peak values are almost similar in all seasons, but great differences can be seen in the density of the total energy (surface under the curve). This is caused by various exposure times and, of course, by different weather conditions during the year (best visible on winter and fall samples). Typical daily distributions are shown on Fig. 6 – 9 for better objectivity. Typical sunny and rainy days are compared together for each season so that we can compare in detail exposure times, peak values, average values and total energy for every case.

The accurate average values of solar irradiance I and estimated energy gains E are calculated from these time distributions. The fundamental equation for estimated energy:

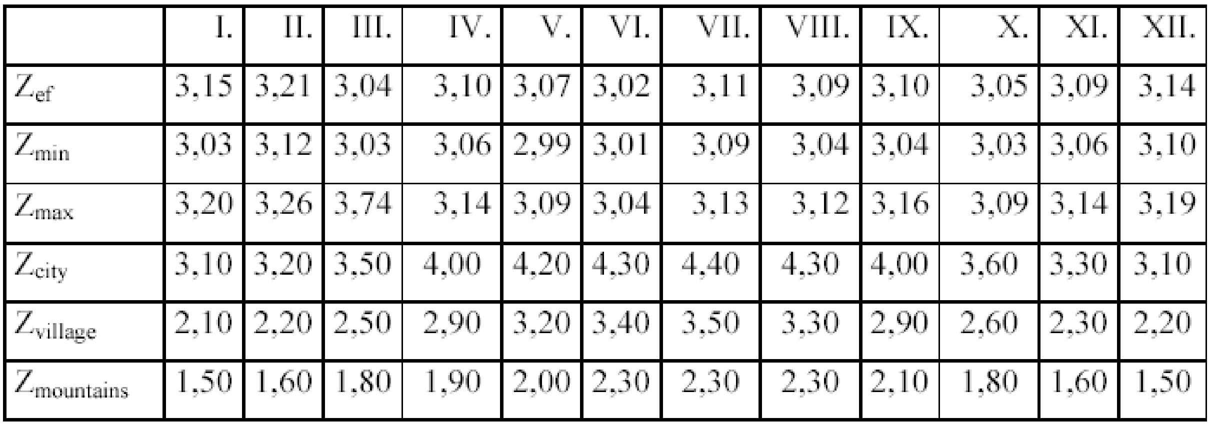
$$E = \int_0^T I(t)dt$$

The computed monthly average values of solar irradiance and energy are compared with theoretical values valid for central Europe in Tab. 1. Minimal and maximal daily averages are also displayed in the table for the complex view of the value range in every month.



	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
I_{teor} [W/m^2]	412	490	558	580	600	590	600	580	558	490	412	344
I_{ef}[W/m^2]	388	456	551	564	589	587	582	565	541	482	398	322
I_{max} [W/m^2]	407	471	553	571	602	589	586	573	552	485	403	329
I_{min} [W/m^2]	381	449	448	557	586	583	579	560	532	476	390	315
E_{teor} [kWh/m^2]	3,40	4,96	6,70	8,06	9,42	9,64	9,42	8,06	6,70	4,96	3,40	2,70
E_{ef} [kWh/m^2]	3,21	4,72	6,12	7,54	8,32	9,26	9,11	7,87	6,45	4,51	3,12	1,98
E_{max} [kWh/m^2]	3,37	4,89	6,56	8,01	8,99	9,58	9,38	7,99	6,54	4,83	3,33	2,15
E_{min} [kWh/m^2]	3,12	4,68	6,04	7,17	8,01	9,01	8,78	7,64	6,38	4,32	3,03	1,78

Tab. 1.: Average solar irradiance and estimated energy gains



	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
Z_{ef}	3,15	3,21	3,04	3,10	3,07	3,02	3,11	3,09	3,10	3,05	3,09	3,14
Z_{min}	3,03	3,12	3,03	3,06	2,99	3,01	3,09	3,04	3,04	3,03	3,06	3,10
Z_{max}	3,20	3,26	3,74	3,14	3,09	3,04	3,13	3,12	3,16	3,09	3,14	3,19
Z_{city}	3,10	3,20	3,50	4,00	4,20	4,30	4,40	4,30	4,00	3,60	3,30	3,10
$Z_{village}$	2,10	2,20	2,50	2,90	3,20	3,40	3,50	3,30	2,90	2,60	2,30	2,20
$Z_{mountains}$	1,50	1,60	1,80	1,90	2,00	2,30	2,30	2,30	2,10	1,80	1,60	1,50

Tab. 2.: Air pollution factor

Computed data presented in Tab. 1 were used for precise calculation of air pollution factor Z. This factor Z shows how many atmospheres laid on themselves cause the same reduction of crosscutting solar irradiance as the real atmosphere in discussed case. The factor is defined with Linke’s equation:

$$Z = \frac{\ln I_0 - \ln I_N}{\ln I_0 - \ln I_Z}$$

Where $I_0 = 1360 W/m^2$ (solar constant), I_N means solar irradiance on horizontal plane while real air pollution and I_Z is theoretical value of solar irradiance on horizontal plane reachable while clean air.

Tab. 2 shows computed monthly average values and minimal and maximal daily averages in every month (similar way as used in Tab. 1). Typical values for industrial city (such as Pilsen), agricultural village and clean mountains are shown for better understanding of air quality in Pilsen.

20kWp systems operated in Pilsen

During the construction of the new building of the Faculty of electrical engineering a 20 kWp photovoltaic array was installed on the flat roof of the building. This system is connected to the public grid and until recently it was the largest one operated in Czech Republic and in Cetral Europe.

The system is 165 m^2 large, is situated southbound, inclined in 45° angle and consists of 192 photovoltaic panels SG-72-110, 8 one phase inverters Sun Profi SP-2500 and measurement chain. The fixed orientation and inclination is a compromise between purchase costs and full year operability with maximal efficiency. The panels SG-72-110 are made by czech manufacturer Solartec. They are designed from dark blue colored monocristalline silicon cells because this is the most efficient technology, and for architectonic and esthetic reasons. These panels are connected together into 8 sub-circuits and each sub-circuit has its own 2,5 kW inverter. Produced energy is supplied into the buildings network via switchboard and essential protections. The measurement chain is capable of metering and storing main operating values such as:

- main meteorological conditions
- global solar irradiance
- temperature of the array
- DC, AC voltage and current
- output power (P, Q, S)
- power factor
- phase unbalance
- total harm. deformation (U, I).

The interesting part of the system is a computer controlled tracker that can be adjusted in any inclination gaining appropriate values of power and solar irradiance on its surface.

Beside these experiments the influence of air pollution on photovoltaic systems was also monitored. 3 twins of PV panels were installed in 3 different inclinations (30°, 45°, 60°). One panel in each couple was periodically cleaned while the second one was left on weather conditions.

Interesting results of self-cleaning ability were gained, but the detailed explanation of them is beyond limits of this paper. Briefly the self-cleaning ability is sufficient in this span of inclinations and it is not worthwhile to proceed with any additional cleanings. Only the snow cover in winter stays very long time on small inclined panels, but these inclinations are not suitable for this season anyway because of the low inclination of the Sun.

The view of the 20kWp PV system installed on the roof is shown in Fig. 10.

Fig. 10.: 20kWp photovoltaic system

Influence of 20 kWp systems on network

The main task during a trial period was the confrontation of service conditions and the “Connection rules”. The system was found serviceable and, only the voltage in phase L1 exceeded the limits what can be solved by voltage reduction on the main transformer.

Since that, additional measurements have been executed in cooperation with ZCE. All electrical values mentioned in previous chapter have been measured using analyser Unipower 900F. Samples stored in 1 min period have been used as inputs for Fourier analysis which shows spectral components of current and voltage in all phases. Because of the data quantity not all the samples have been processed yet.

Fig. 11 – 12 show an.example of spectral voltage and current components in phases L1, L2, L3. This exemplary measurement was performed during “standard” operating conditions. I.e. sunny summer day and all the sufficient conditions were as favourable and as constant as possible (I=800W/m^2, t_{out}=20°C, forceless wind, weak cloudiness). The Fourier analysis was made up to 50th harmonic whose depth is required by standard EN 50160. The values of 1st harmonic (approximately 230V in voltage spectrum and 11A in current spectrum) are not displayed on the graphs because of better visualization of relatively small values of the higher harmonics. The graphs present the daily averages of monitored values.

The values don’t exceed the limitations set in standard EN 50160 so that this system does not impact the network in the cause of definitions in the standard. Higher value of the 5th harmonic in current spectrum (than 3rd harmonic) is probably caused by setting of filters in the inverters.

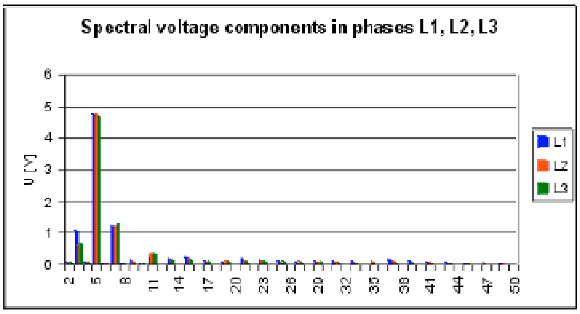


Fig. 11.: Spectral voltage components

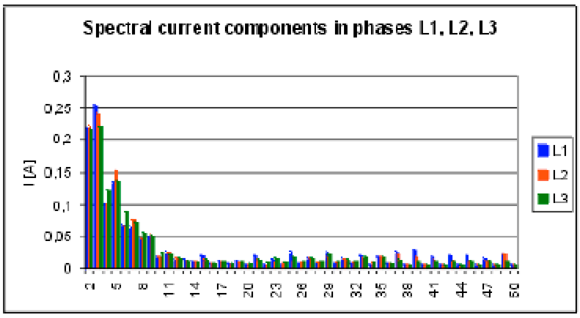


Fig. 12.: Spectral current components

Efficiency of 20 kWp system

One very important issue is the real efficiency of a photovoltaic system. As was mentioned in the beginning, the efficiency of the most frequently used monocrystalline silicon cells is approximately 16%. This value is however valid only in ideal conditions. Expressive losses can be caused by limitations of a serial-parallel integration into panels during partial shadowing. The next additional losses also occur in inverters. Therefore what is the efficiency in real service?

Theoretically we can expect that this system operated in average conditions of central Europe should produce 20 – 25 MWh per year. Based on our measurements of primary conditions we can expect higher values from this theoretic range.

For the present the 20 kWp system has been monitored for 1,5 year. Increments of produced electricity in one calendar year are displayed on Fig. 13 - 14. We can see a non-uniformity of the production and a remarkable decrease in the summer. Fig. 15 compares the real energy gains with theoretically estimated gains.

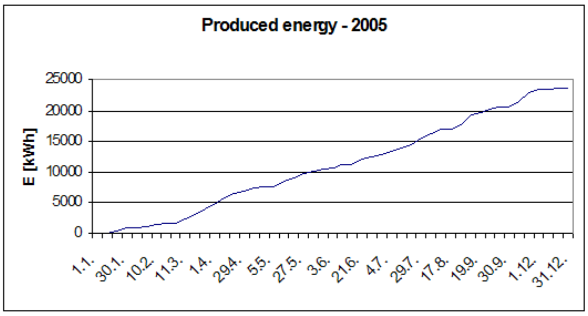


Fig. 13.: 20 kWp system – produced energy (2005)

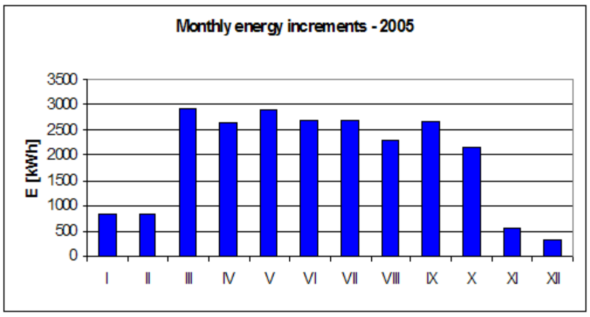


Fig. 14.: 20 kWp system – Monthly energy increments (2005)

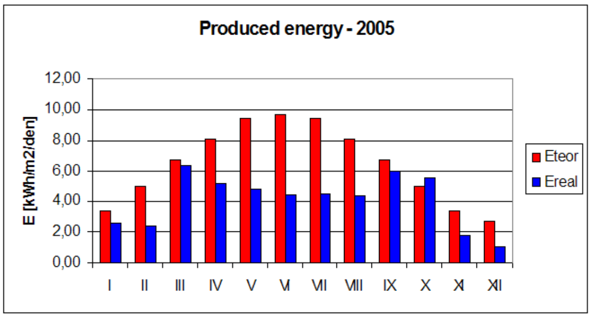


Fig. 15.: 20 kWp system – Theoretical comparison of produced energy - daily increments (2005)

The results in the “best” season – in summer may seem rather strange. The energy increments and also the efficiency is lower than in late spring. There are several reasons for this phenomenon.

Firstly the position of the Sun in the sky is in summer higher than in spring and this needs smaller inclination of the photovoltaic system. Our system has the fixed inclination 45°, which is full year compromise and is not the ideal inclination for the summer. Easy improvement of the system can be a manually adjustable inclination for the summer (30°), winter (60°) and change-over season (45°).

Next longer summer times of solar exposure cannot be equally utilized in the system with fixed orientation. The system improvements in this way are very difficult and expensive.

Finally the higher temperatures in summer decrease the efficiency of the system from the nature of semiconductors. Some improvements can be achieved by additional passive coolers. But the integration of these coolers into the construction is not easy. Active ventilators need energy and would complicate the electrical system as well.

So, the easiest way to increase the efficiency and energy gains is the modification of the construction for adjustable inclination and, perhaps, some additional passive coolers.

Conclusions

When we compare the theoretical hypothesis with measured data we can see, that although Pilsen is an industrial city, it is quite pleasant for servicing solar systems. In addition the air pollution is lower than was expected, above all in summer season. This also contributes to good service conditions and this was proven with measurements of self-cleaning ability.

The service mode of installed 20 kWp photovoltaic system does not impact conditions in supply network at least while it is operated in optimal service conditions (high and constant values of relevant quantities). A rather different result can be obtained in unsteady conditions such as changing weather causing bouncing solar irradiance in the lower values. These occurrences are next step in our research.

Very interesting results also were obtained in field of the efficiency of the 20 kWp PV system. However the accuracy of the values must be steadily observed because of the relatively short time of the experiment, which is still ongoing. Nevertheless the principle of this issue is relatively accurate.

Acknowledgment

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