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Selected solutions in photovoltaic systems increasing their efficiency

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The basic objective in photovoltaics is obtaining electrical energy with the costs comparable to the costs of energy obtained from conventional fuels. The effectiveness of acquisition of electrical energy from solar cells can be improved, among other things, by using solar radiation concentrators. Photovoltaic systems with low concentration (LCPV) and high concentration (HCPV) were characterised [13]. The possibilities of their operation under various conditions were presented, whereas the impact of temperature and concentration angle were considered in particular. The most modern solutions were presented, including Spin cell, Ephocell, Interdigitated Back Contact (IBC), Luminescent Solar Concentrator (LSC), High Concentration PhotoVoltaic Thermal (HCPVT), Concentration PhotoVoltaic (CPV), Telecontrolli. Results of current Polish research were given. In the years from 1985 to 2010 the increase from 17,5 % to 40,7 % in the efficiency of solar cells with concentrators was achieved [18].

KEYWORDS: solar cell, concentrator, PV module, power gain

1. Concentrating systems in photovoltaics

Concentrators are optical systems for focusing and reinforcing the sunlight. They include, among other things, parabolic trough and Fresnel lens which are characterised by big ratio of the surface of input to output aperture. In this case, the focused solar radiation from a big area is “transferred” to solar cells which results in increased generation of electrical energy. However, such systems require to be equipped with a tracking system “behind the Sun” during its apparent motion [3,4,5,6]. Diagrams of such solutions were shown in Figures 1a and 1b.

Particularly interesting solutions include luminescent concentrators which have been gaining popularity in recent years [7,18]. Their main advantage is the possibility to “capture” sunrays falling at any angle. The structure of the solution consists of a thin (a few mm) glass or polymer dish, doped with lanthanide ions or transition metals. Solar cells with small surface are distributed around the dish. Radiation (also scattered) falling on the dish is absorbed, it activates the luminophore, which leads to its shining (visible light); as a result of complete internal reflection it is transferred to solar cells surrounding the plate [18].

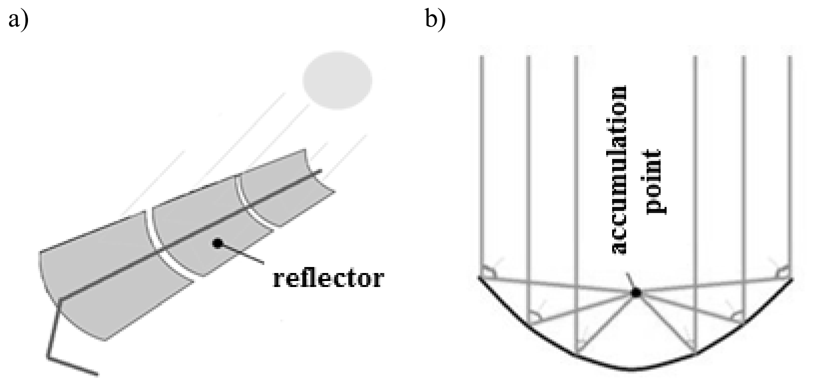

Fig. 1. Diagrams of solar radiation concentrators, cylindrical (pipe) (a) and dish (b)

The concentrator together with the luminophore are shown in Figure 2.

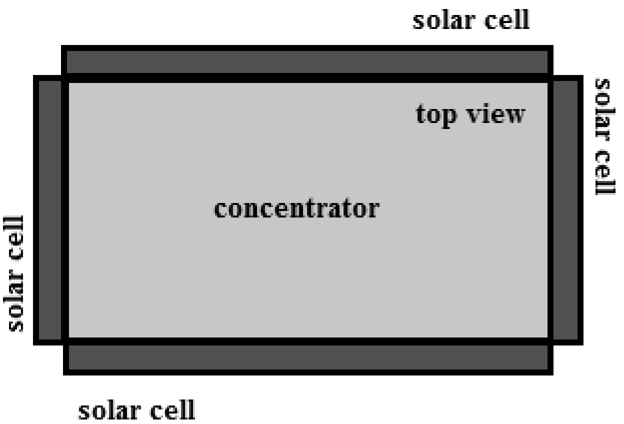

Fig. 2. Concentrator covered with luminophore together with the surrounding solar cells

Multi - stage concentrator systems constitute a different solution. Next material layers allow to "adjustment" to various lengths of radiation waves and to obtain maximum absorption for the siliceous diode. As a result, the effectiveness gets increased by including infrared and ultraviolet radiation to the conversion, which is disregarded in the operation of traditional concentrators. The layers make up the "concentrator stack". The last layer is a mirror [18].

The concentrator stack was shown in Figure 3.

Solar light spectrum, with regard to absorption via siliceous cell and with the consideration of extra doped layers which can also be used in luminophores with down - conversion (DC) and up - conversion (UC), allows to considerably increase the efficiency of the cell within the whole scope of the wavelength, Figure 4 [18].

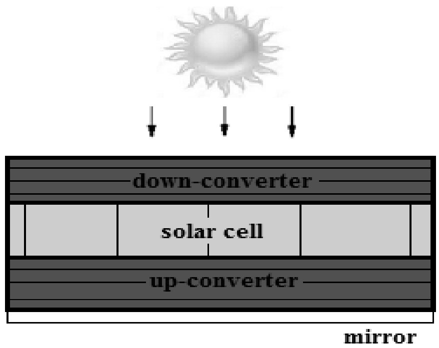

Fig. 3. Concentrator stack with siliceous cell and ion doped layers

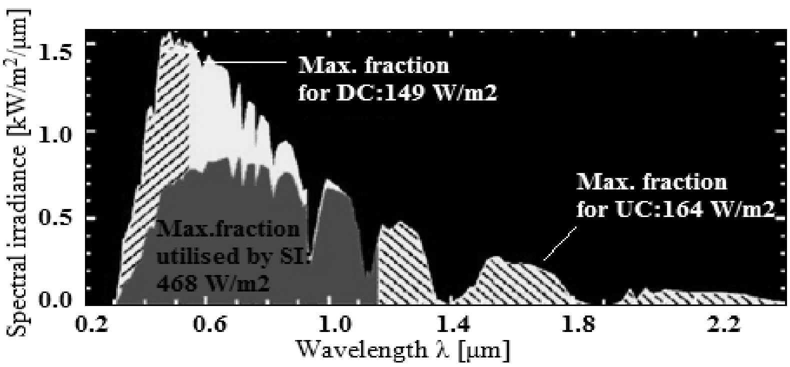

Fig. 4. Solar light spectrum, with regard to absorption via siliceous cell and with the consideration of extra doped layers which can also be used in luminophores with down-conversion (DC) and up-conversion (UC), own study on the basis of [18]

2. Cooperation of concentrators with solar cells

Two concentrator systems are most frequently used in solar cells: lens, using the phenomenon of refraction and mirror, basing on the phenomenon of reflection. The above - mentioned systems may concentrate the radiation in a linear or pointwise way. In case of the dish solution, the maximum theoretical concentration of the solar radiation (at the concentration angle φ = 0,5°) reaches the values from 12000 to 104000, depending on the value of the reflection coefficient. However, practically it does not exceed the value from 820 to 4800. The application of Fresnel lenses gives considerably lower concentration effects [10].

As a result of concentration, the density of radiation power on the surface of the module increases. Owing to that, the same results can be achieved with the use of smaller PV surface (even 500 to 1000 times), which results in drop of installation costs. In this solution the concentrator should have the follow - up system installed in order to „track the Sun” [5, 13].

In Figure 5 the view of pipe concentrator was presented, while in Figure 6 dish concentrator was respectively shown, operating at Instituto Tecnológico y de Energias Renovables (ITER) on Tenerife [5].

Fig. 5. View of cylindrical (pipe) concentrator of solar radiation operating at Instituto Tecnológico y de Energias Renovables (ITER) on Tenerife. Photo: Grażyna Frydrychowicz-Jastrzębska

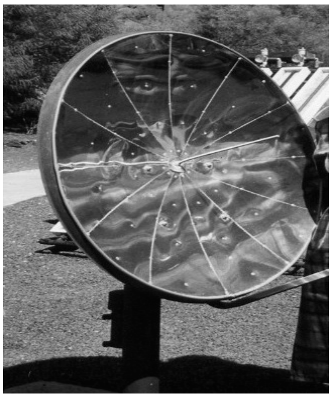

Fig. 6. View of dish concentrator of solar radiation at Instituto Tecnológico y de Energias Renovables (ITER) on Tenerife. Photo: Grażyna Frydrychowicz-Jastrzębska

The concentrating systems are most beneficial in places where direct component of radiation prevails. PV concentrators (apart from the flat solution) only focus direct radiation. They are constructed as units with the power from 20 to 35 kWp.

3. Impact of temperature in PV systems on their operation

However, concentration of radiation is the reason for unfavourable increase in temperature at the module surface. As it is known in most cases, the temperature has a negative impact on the parameters and characteristics of the cell. Owing to that, not all the materials can be used in cooperation with concentrators. The efficiency of the cells sensitive to changes of temperature drops along with its rise (the temperature rise by 1° results in drop in the efficiency by 0.35 – 0.45 %). Strong heating of the cell over the allowable value may even lead to its damage as a result of considerable concentration. Hence cooling is required. A combined conversion can also be a favourable solution [4, 5, 13].

In Figure 7 the impact of temperature on the characteristics of the selected solar cells was presented [5]. As the cells power and efficiency depend on the temperature Light Concentration Photovoltaic systems (LCPV) (from 2 to 10) are used for cooperation with conventional cells. In spite of increased capacity such system does not require cooling.

Only the cells made of gallium arsenide do not demonstrate big changes of parameters within the scope of increased temperature, even up to 400 °C. Fivefold increase in concentration to the value of C = 900 results in drop in efficiency of cells made of gallium arsenide by about 1.5 % [5, 11].

Hence in this case High Concentration Photovoltaic systems (HCPV) can be used. They comprise lenses or mirrors cooperating with two - axis follow - up systems, which allows to focus big volumes on light within a small radius. The system is equipped with monitoring.

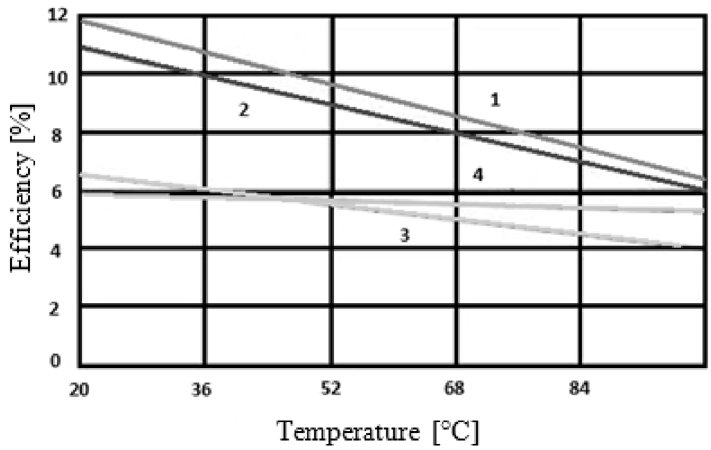

Fig. 7. Efficiency of the selected cells in the function of temperature with the density of radiation power of 1000 W/m^2. Explanations: siliceous cell SR-100 (1), siliceous cell SRT-50 (2), amorphic tandem MST-50 MV (3), ANTEC SOLAR (4)

The application of concentrators each time requires individual analysis, also experimental one. In Santa Pola power plant, Alicante region in Spain, from the complete number of 151 polycrystalic modules operating in two - axis follow - up system 27 are additionally equipped with High Concentration Photovoltaic systems (HCPV). Due to the selected location (about 38°10' north and 1°7' east) the use of High Concentration Photovoltaics should be favourable. However, the detailed analysis, after one year of the operation of the power plant demonstrated that the energy generated by conventional cells achieved profits bigger than planned (there was bigger sun exposure than it resulted from meteorological data), the modules with high concentration brought considerably smaller results than expected, which was demonstrated in Table 1 [10].

Table 1. Generation of energy in PV Santa Pola Alicante power plant (Spain), anticipated and actual values

	Theoretical energy generation GWh	Actual energy generation GWh	Δ%
Polycrystalic with HCPV	0.270	0.065	-76 %
Polycrystalic two-axis	1.430	1.485	+3.4 %
Whole installation	1.700	1.550	-9 %

4. Review of the most modern solution

The new solutions which perform well in cooperation with the concentrators include Interdigitated Back Contact (IBC) siliceous cells or point - contact cells. With the concentration coefficient of C = 30 their efficiency amounts to η = 18 % [13].

The concentrator can also be used for focusing and reinforcing the beam of radiation falling on the tandem cell, even for high concentration coefficients [11]. The projects of Moon from the year 1978 and Borden from the year 1981 are well known. In the first of the projects 2 GaAs and Si cells were used and with the concentration coefficient of C = 145 the tandem reached the efficiency of η = 28,5 %. The second tested tandem comprises 10 cells, whereas with the analogical concentration coefficient of C = 145 the efficiency η = 20,5 % was achieved [4].

Numerous tests concentrate around Luminescent Solar Concentrators (LSC). Among other things the solution in the form of plate or polymer foil containing luminesceous centres is used. Their role is fulfilled by the quantum dots, nanomaterials doped with rare earth ions as well as new generation perylene dyes. Dyes which are the most beneficial with regard to absorption are dcm - pyran, coumarin 151 and styryl 9 M [7]. These centres absorb solar radiation. The presented technology allows for strong absorption of solar radiation, above all within the wavelength up to 950 nm and emission maximum at about 1000 nm (close to unit) [7]. Owing to better adjustment of the cell to the falling radiation loss of infrared and UV radiation can be prevented [18].

Such a solution allows to considerably reduce the costs, also due to the fact that semi - conductor based on polymer was used. Luminesceous concentrators do not require cooperation with the follow - up system. Research problems within this scope are elaborated on by the scientists as part of "Fullspectrum" programme of the European Union [7], especially by scientists from Great Britain, Germany and Holland.

The most modern solution concerning solar cells cooperating with the concentrators was developed by scientists from Catalunya, who presented their project of increasing the efficiency of photovoltaic conversion as a result of using luminesceous concentrators of solar radiation energy. In the proposed Ephocell solution (intelligent system of collecting the light in order to enhance the efficiency of solar cells), the efficiency increases as a result of incorporation to the process, external conversion of radiation intensity modulation, which allows to better synchronise the wavelengths of the falling radiation as well as the absorption capacities of the receiver [16]. In October 2012, a seminar was held in Barcelona with the objective to exchange experiences on this subject.

In recent years there have been reports on numerous new solutions. The efficiencies of cells with concentrators already achieve the values of about 40 %, the best results include: National Renewable Energy Laboratory NREL 37 %, Boeing Spectralab – respectively 39 %. MEREG GMbH company (Material Energy Recoverz Engineering) declares the efficiency of 40 % for its new solution of cells with concentrators. It is the combination of semiconductors and "color selective reflective interference films". The beam of light, after its splitting into colours, is processed in semiconductors adapted to lengths of the falling radiation waves. It is important that scattered radiation can also be subject to this process, whereas unfortunately in this case the efficiency is much lower. The use of the so - called "concentrator stack" (multi - layer cell with an extra anti - reflection layer) brings the best results [4].

In Poland where solar radiation is characterised by a big share of scattered component it is advisable to use the above - mentioned solution [5].

A very promising solution is a project developed by the student, J.H. Karp from the University in San Diego, California, who developed a prototype of PV concentrator in Spin Cell technology based on the solar micro optics in the year 2010. The basis of the said equipment is the cone covered with solar cells in the shape of triangles, shown in Figure 8 [8, 9].

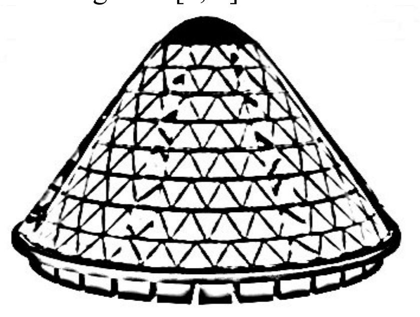

Fig. 8. Photovoltaic cone

V3Solar company (Nectar Design project) conducted test research for the cone solution. The Spin Cell captures the solar radiation and converts it into electric energy, where after it turns before the temperature of the panel rises. In this solution the concentrator creates the air - tight external layer. The cone is placed on a base equipped with electromagnets, powered with part of energy coming from conversion. Conversion with the use of cone cells is characterized by twentyfold bigger effectiveness than in case of traditional cells. What is also important is that as a result of turning of the cone the operating surface does not manage to heat, which would result in drop of efficiency [8, 9].

In Figure 9 the temperature values of modules operating with six-, twenty-, and thirtyfold concentration were presented, with the case without concentration. Standard and Spin Cell solutions were compared here. The last column in the specification shows the difference to the advantage of Spin Cell expressed in %.

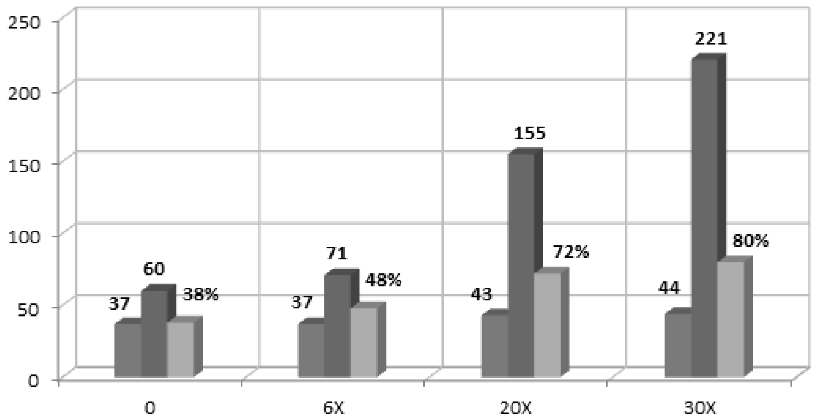

Fig. 9. Possibility of reducing the temperature of PV modules as a result of introducing the Spin Cell solution

Currently the highest efficiency of photovoltaic conversion of 44.4 % was achieved by Sharp company products, which used the three - joint set of cells with the concentrator. The value of the obtained efficiency was officially confirmed by Fraunhofer Institute for Solar Energy Systems (ISE) in Germany.

In its product Sharp used the stack of three layers absorbing radiation, including elements such as IN, Ga As. The company has conducted research on three - joint cells for over 10 years [21]. They are part of R & D in the project Innovative Solar Cells [14].

The scientists from Ben - Gurion University (BGU) from Negev in Israel in 2012 designed a completely new solution of the set of concentrator with the solar cell, which is characterised by the efficiency exceeding the efficiency considered maximum so far: 40 %. This opens further perspectives to photovoltaics. It is possible to use silicon in the solution, which is practically useless at high concentrations (big dependency of parameters on high temperature) [1].

Researchers from IBM, Airlight Energy are working on the effective photovoltaic system - High Concentration PhotoVoltaic Thermal (HCPVT) capable to concentration of 2000 Suns [15].

The system is based on an antenna with a parabolic shape and interior covered with many mobile mirrors. The mirrors are controlled and position themselves at the most optimum angle in relation to sun beams. It is anticipated that they will be capable of converting over 80 % of radiation energy. Cooling with sea water was applied, whereas the water evaporates while carrying away the heat, then it is liquefied and - already without the salt - after further treatment, is used as potable water [15].

Other solution of the researchers from IBM concerns the cooperation of thin - layer cells with Concentration PhotoVoltaic (CPV) concentrators. A record result of 230 W/cm^2 of the cell surface was obtained, that is five times more than in case of typical siliceous cell. This is possible thanks to an innovative cooling technology allowing to lower the temperature of cells from over 1600 °C to 85 °C. A layer of thin material made of gallium and indium was used to carry away the heat [17].

The energy efficiency will allow to use 80 % of radiation [15].

The new photovoltaic concentrator was developed as a result of cooperation between Telecontrolli and System Design R&D companies. It is based on material properties of aluminium oxide (with regard to thermal scattering) and was executed in screen process technology. The characteristic feature of materials used as optic concentrators is their relatively low electrical resistance. Also, small susceptibility to changes in temperatures is required due to the resultant drop in efficiency. The described solution can be equipped with individually adapted SOE secondary optical systems as well as appropriate cores, easy to install. Concentration with the coefficient 1024 x was used. As a result, the level of efficiency equals 31 % for a single module [22].

First copies of PV concentrators, after their approval by both cooperating companies, were manufactured by Evonik [22].

The scientists from AGH University of Science and Technology in Cracow, Faculty of Energy and Fuels, conducted preliminary tests concerning the possibility of supplying power to the photovoltaic cell with the concentrated light under Polish conditions. The object of studies was siliceous polycrystalic panel with the power of 0,8 W and the surface of 80 cm^2 [2].

The results obtained by the researchers are shown in Figure 10.

As it results from the included characteristics of power as well as conducted tests [2] the application of concentrators in the photovoltaic systems allows to improve their effectiveness. It shall be noted that already the same follow - up system increases the efficiency. The follow - up system equipped with the concentrator would ensure better results provided that the temperature on the surface of the module is reduced, which can be achieved by using the cooling system [3,4]. The follow - up system without the concentrating system achieves better value of power for bigger voltages, in a given case over 3 V (it operates in a wider scope of voltage scale). The follow - up system with the concentrator reaches its maximum for voltage below 2 V and operates in a narrower scope of voltages [2].

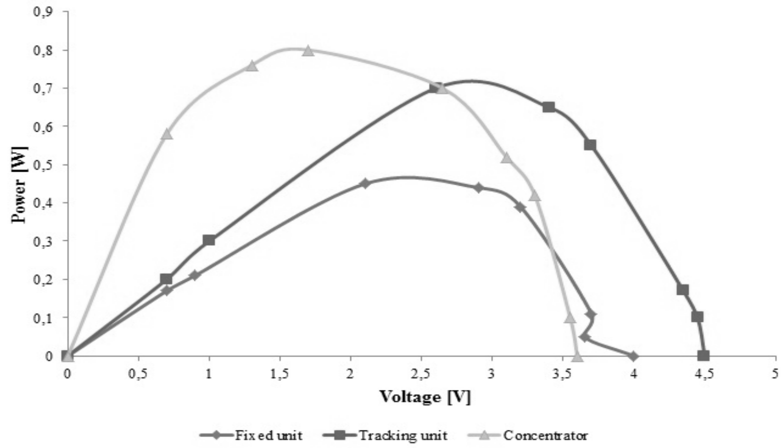

Fig. 10. Characteristics of power of the photovoltaic panel obtained by the researchers from AGH University of Science and Technology in Cracow. Explanations: curve for fixed unit β = 30° (1), curve for PV unit with "tracking behind the Sun" (2), curve for the system as (2) extra equipped with radiation concentration (3). Own study on the basis of [2]

Luminesceous concentrators also constitute the object of interest of the group of scientists from the Institute of Electronic Materials Technology in Warsaw as well as Helioenergia. Their works on the fluorescent concentrator of e-m radiant energy of radiation in the visible scope and near infrared are already advanced [7].

5. Exemplary high power photovoltaic objects with concentrators

Andasol

Andasol is the biggest solar power station in the world and the first one with parabolic concentrators. The concentrator operates in the follow - up system with the hydraulic drive.

The power station consists of three solar farms. Andasol is located near the city of Guadix (Spain), at the height of 1100 metres above sea level. This location (37°13'42,70" north and 3°4'6,73 west) is characterised with excellent sun exposure conditions, it reaches the value of 2136 kWh/m^2 per year. Atmosphere transparency index is also more favourable at this height. The power plants are equipped with concentrators (7488 pieces), hence there is a need to ensure big surface of the occupied area, 1,5 km^2. In all three cases mirrors in the shape of parabolic troughs were used.

The scale of the enterprise connected with the use of concentrators in high power facility is demonstrated by the following numeric summary:

- each of the concentrators was equipped with 29 mirrors covered with a silver layer and with 3 pipes for the cooling system; as a result, in each „solar field" space for 209 664 mirrors, 22 464 pipes and 624 solar sensors shall be provided,
- the system requires 870 000 m^3 of water for cooling per year.
  The heat obtained in such a way is subsequently stored in a melted salt (300 thousand tonnes) which is made up of the mixture of sodium nitrate (60 %) and potassium nitrate (40 %). The system of storing the heat in salt allows to increase the number of hours of the power plant's operation almost two times with regard to the operation of standard power plant. The stored energy enables an extra operation of turbine during clouded weather and in the night – time – 7,5 extra hours.
- as a result the efficiency of concentrators under favourable weather conditions reaches even the level 70 % and 50 % on average.

The concentrators installed in the follow - up system may operate with wind speed which amounts to 13,6 m/s, however, the system shall be switched off over 20 m/s [19, 20].

The power plant started generation of current in the year 2008 (Andasol I). The total installed power of all the three parts of the power plant (Andasol II in the year 2009 and Andasol III in the year 2011) reached the level of 150 MW_p, which makes it possible to produce electric energy of 540 GWh in a year that can satisfy the needs of a half - million city.

The cost of investment amounted to 350 million EUR[19, 20].

In Figure 11 the value of density of normal component energy of radiation within a month on the surface of 1 m^2 and corresponding to the value generated by the electrical energy system Andasol I system.

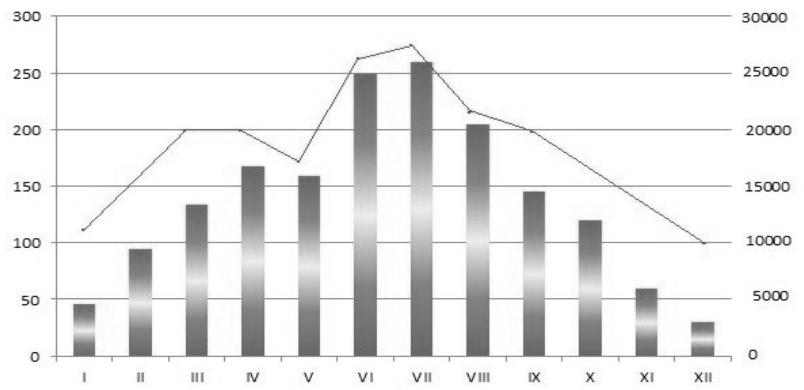

Fig. 11. Value of density of normal component energy of radiation within a month per m^2 and corresponding to the value generated by the electrical energy system within a month, based on [23]

Lujhu Township

At the end of the year 2009, near Lujhu Township, in Taiwan, a pilot photovoltaic power plant was opened, in which 141 high concentration photovoltaic panels (HCPV) were used, operating in a follow - up system (8040 modules with the unit efficiency of 25 %, that is 321600 single cells with the efficiency of 35 %). The selected location (25°03'14,7" north and 121°17'18,2" east) ensures optimum conditions of sun exposure throughout 300 days per year, that is 1600 hours. The efficiency of the whole system with total power of $1MW_p$, (120 x 7,5kW+21 x 5kW) is estimated at 21 % [12].

The installed power of the power plant allows to limit the emission of CO_2 per year by 670 tonnes. In perspective, after testing it is planned to extend the power plant up to 10 MW_p [12].

Maricopa Solar

Maricopa Solar, located in the city of Peoria in Arizona (33°33'31,0" north, 112°13'7,0" west), constitutes some type of a hybrid system with the installed power of 1,5 MW_p and is equipped with 60 SunCatcher parabolic dish concentrators with the diameter of 12 metres, operating in a follow - up system as well as with Stirling motor (25 kW). The whole system occupies the area of about 6 ha. In this solution the solar energy, after absorption, is stored in hydrogen, in an external heat exchanger. Gas, heated to 720 °C, supplies power to Stirling motor, and is subsequently cooled for reuse, the heat is released to the atmosphere [19].

Finally, the energy is converted into electrical energy, which satisfies the electrical needs of 375 households.

In Maricopa Solar conditions of work are tested before embarking on bigger investments of such type (even 75 - 850 MW_p) [19].

6. Conclusion

In recent years, technology of concentrators development (CPV) quickly developed. It is estimated that the power of the system will rise to 1,362 GW in the year 2020, the increase by even 750 % compared to the year 2013 is anticipated (160 MW).

The efficiency of cells with concentrators exceeded 44 % in the year 2013, while Amonix produces these modules with the efficiency of 34,2 %.

The development of CPV technology is fostered by drop in manufacturing costs; their drop in the year from 2012 to 2013 (for HCPV) amounted to 25,8 %. This tendency will be kept at the level of 15 % by the end of the year 2017.

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