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Optimization Parameters of PV Plants for the Needs of the Sewage Treatment Plant

Jarosław Knaga[1], Krzysztof Nęcka[2], Tomasz Szul[3]
Krakow University Of Agriculture, Faculty Of Powering And Automation Of Agricultural Processes, Poland

ABSTRACT:- *This study provides an analysis of insolation, as well as determines the fluctuation of its parameters depending on the solar radiation flux density. These properties have established the basis for the definition of the scope of minimum density of solar energy flux at which a photovoltaic plant is able to cover the current power demand of a municipal waste water treatment plant. Therefore, three variants of a photovoltaic farm as a supporting power source of the waste water treatment plant have been developed.*

Keywords:- *solar energy, radiation flux density, insolation, photovoltaic cell*

I. INTRODUCTION

Renewable power generation is a considerable branch of industry in a number of countries and it keeps developing at a very rapid pace. Its growth leads to new scientific problems of an increasingly complex nature necessitating the application of sophisticated mathematical modelling methods. Renewable energy is currently one of the youngest scientific disciplines which nevertheless covers a very broad scope of research with solar energy as one of its basic areas, the theoretical foundations of which were formed in the second half of the 20th century [2, 3, 11, 15]. Solar power research deals with the estimation of solar energy potential and its fluctuation for the needs of solar power systems [9, 10, 12, 13, 14], growing of crops, including energy crops, and promotion of agrotourism [1, 5, 6, 7, 8, 18]. In terms of research of solar power systems one may distinguish field [9] and laboratory surveys. Field surveys in Poland most frequently focus on the application possibilities of the existing solutions of thermal solar power systems for low-temperature heating purposes, such as hot tap water installations in particular. On the other hand, a certain market niche may be noticed in the field of applying photovoltaic farms for powering of concrete projects or providing power supplies to the power grid itself. Certain practical experience in Poland may be drawn from the only photovoltaic farm in Poland located in Wierzchosławice near Tarnów. On this site however, microelectronic systems have operated for less than two years, so it is difficult to find any reports on its operating effects. This gives rise to another question: why so few of such installations have been established nationwide in spite of the fact that EU directives force Poland to promote renewable energy. One of possible answers is a lack of a stable state policy in this respect or programmes supporting investments in photovoltaics. In these considerations one should also ask whether power generation in such systems is profitable within the current conditions.

The aim of the study is to analyse the solar energy resources at the photovoltaic farm location which is intended to generate electric power for a waste water treatment plant situated in the South of Poland. In the course of research also the size of the farm has been determined.

II. RESEARCH METHOD AND SCOPE

The study objective was accomplished on basis of own research performed at a switching station powering the municipal facility located in the Rzeszow province and monthly power consumption volume data within a yearly cycle. Own research consisted of permanent measurement and recording of active power load values averaged per 15 minutes and determination of power consumption in the specific periods of time. Own research was carried out by means of a specialist AS-3 plus grid parameter analyser manufactured by the Twelve Electric company from Warsaw. The performed research allowed to create a database including historical power consumption data in each hour of day and night.

In order to determine the resources of solar energy and their fluctuation, hourly statistical data collected for a typical reference year and regarding the total flux of solar energy have been used, as recorded at the nearest weather station of the planned photovoltaic farm site. A typical reference year for ISO energy calculations was developed by the International Organization for Standardization and accepted by CEN as standard EN ISO 15927-4. The yearly sequence of weather data for power generation calculations has been compiled on basis of 12 months selected from a period of a minimum of 10 years of meteorological records of a given site. The selection of a reference month is based on a mean annual rate of three months for which the sum of Finkelstein-

Schafer's statistics of total intensity of solar radiation, dry thermometer temperature and relative humidity is the smallest. Out of these three months, the strongest month is the one in which the divergence of the average wind speed from the long-term mean monthly value is the smallest. The analysis also covers the determination of fluctuation of solar energy per absorption surface at different angles and southern azimuth.

The area of the photovoltaic farm was defined on basis of the following relation (1) [4]:

$$P_P = \beta_{PV} \cdot U_{PP} \cdot I \cdot A_{PV} \quad (1)$$

where:

β_{PV} – proportionality rate for PV module ($A \cdot W^{-1}$),
P_P – power of PV farm at operating point (W),
U_{PP} – voltage at operating point (V),
I – intensity of solar radiation per PV area ($W \cdot m^{-2}$),
A_{PV} – PV module area (m^2),

whereas the proportionality rate for selected silicon structures of cells was determined on basis of relation (2) provided in the study [4]:

$$\beta_{PV} = \frac{I_{SC}}{I \cdot A_{PV}} \quad (2)$$

where:

β_{PV} – proportionality rate for PV module ($A \cdot W^{-1}$),
I – intensity of solar radiation per PV area ($W \cdot m^{-2}$),
I_{SC} – through fault current of a photovoltaic module (A),
A_{PV} – PV panel area (m^2),

After substituting nominal data one can determine the proportionality rate of the panels for research purposes.

The equation of power generated by a module can be supplemented with the fluctuation of efficiency caused by dynamic cell temperature [16, 17] relationship:

$$\eta_{PV}(T) = \eta_{PV}(300) \cdot (1 + \beta_T(T_{PV} - 300)) \quad (3)$$

where:

$\eta_{PV}(300)$ – photovoltaic cell efficiency rate at 300 (K),
β_T – temperature efficiency coefficient ($1 \cdot K^{-1}$),
T_{PV} – photovoltaic module temperature (K).

The area of a photovoltaic farm was determined on basis of relationship (1) of limit insolation value at which PV farm will cover the power demand of the waste water treatment plant with the consideration of cell efficiency fluctuation as a result of changing operating temperature (3). Also the relationship (1) supplemented with equation (3) was used to define the value of power generated by the farm after differentiating it.

III. RESEARCH RESULTS

The total power of electric receivers installed within the municipal facility, as determined on basis of information provided in its Technical Process Plan, amounts to 120 kW. Asynchronous motors used to power treatment process devices are the most frequent type of receiver with a rated power of 1 to 18,5 kW. The total power demanded by receivers for the waste water treatment process amounts to 40 kW. In order to reflect the real operating conditions it was assumed that daily electric power consumption would amount to 0,5 MWh.

In the coming years, the facility is planned to be expanded, thus causing a growth of installed power and power demand of receivers up to 183 kW and 60 kW, respectively. This process will also cause an increase of daily power consumption up to approx. 0,9 MWh.

Figure 1 presents the recorded variation of power consumption in the specific months. According to the performed calculations, the actual yearly power consumption by all receivers operating at the facility amounted to 150 [MWh]. The monthly power consumption value (E_m) has fluctuated from 10,32 [MWh] in September to 17,83 [MWh] in July, while on average it amounted to 12,47 [MWh]. The monthly power consumption variation rate amounted to 15%. This rate was greatly affected by the abnormal power consumption in July. Its main reason were very intensive and frequent rains in this period. When this phenomenon was excluded from the analysis, the variation rate fell below 8%, and also the average power consumption decreased below 12 [MWh].

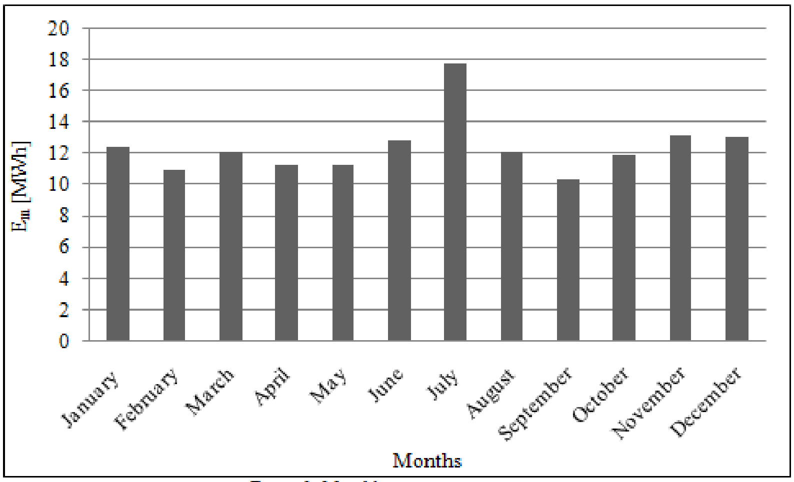

Figure 1. Monthly power consumption

Figure 2 presents the average fluctuation of power load in the specific hours of the day and days of the week, together with the recorded momentary maximum values of active power load of the electric system.

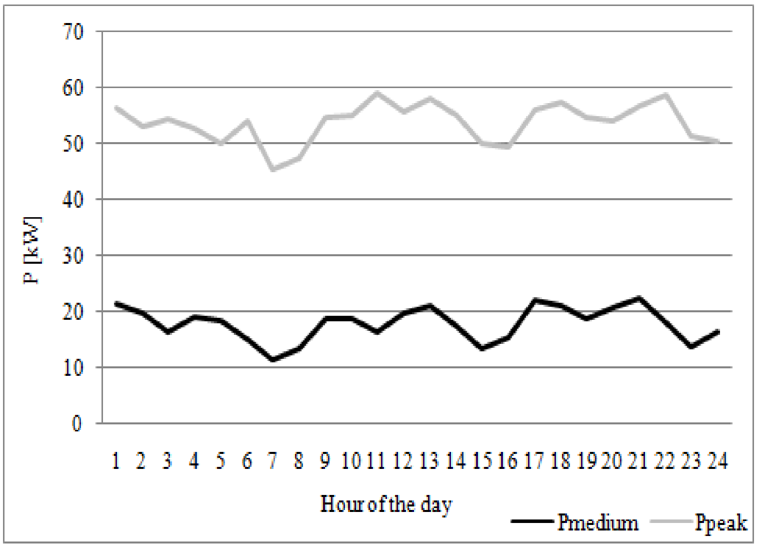

Figure 2. Profile daily average and peak load

The load fluctuation in the consecutive hours of the specific days of the week was similar. Average active power load in the analysed facilities amounted to 17,89 [kW], ranging in the specific days from 10,9 [kW] to 24,5 [kW]. The variation rate of the analysed daily diagram amounted to 18%. According to the performed analysis, no significant differences occur between the load values of the specific days of the week. On basis of the performed research it was decided to create a mean hour profile of power consumption for all days of the year at the examined facility, as presented in picture 6.

The maximum momentary active power load fluctuation recorded during the research reached almost triple value while ranging between 36,00 [kW] and 69,57 [kW]. Their variation rate was lower and it amounted to 11%. Also in the time series of maximum load no noticeable impact of the day of the week on value or course was observed.

IV. ANALYSIS OF RESEARCH RESULTS

The research data pertain to hourly parameters of total solar radiation intensity on a surface in a reference year calculated on basis of EN ISO 15927:4. On basis of these data, the total angle-dependent (0^O, 30^O, 45^O, 60^O) insolation of southward receiving surface was determined in the specific months, as presented on the diagram (fig. 3).

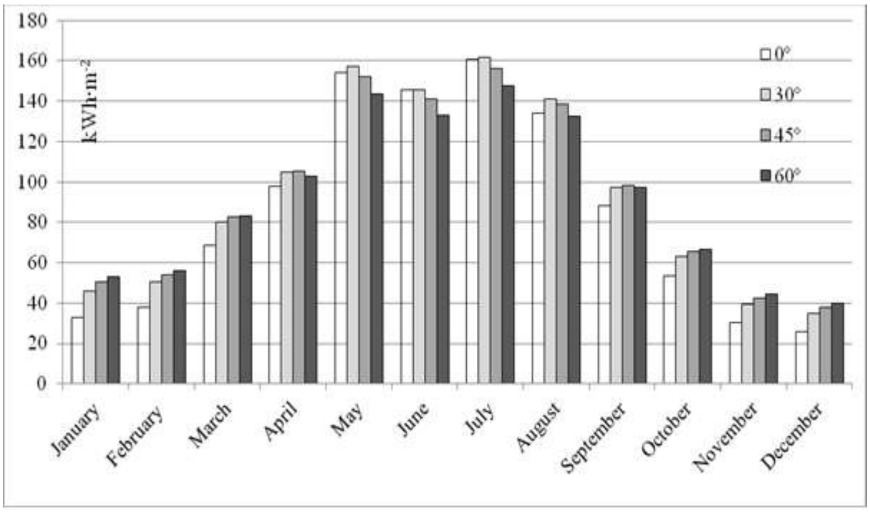

Figure 3. Monthly distribution of insolation depending on the angle of receiving surface

Insolation fluctuates strongly in the specific months between 25 kWh·m^{-2} in December and 161 kWh·m^{-2} in July (fig. 3). The insolation value is influenced by the angle of the receiving surface. Optimal tilt for the autumn-winter season (from October to March) should be 60^{O} and 30^{O} for other. However, within the whole year, the amplitude of insolation value is not so noticeable (table 1).

Table 1. Annual insolation value

Angle	Insolation kWh·(m^{2}a)$^{-1}$
0^{O}	1026
30^{O}	1118
45^{O}	1122
60^{O}	1096

The maximum insolation difference within a year between 45^{O} and 60^{O} is 28 kWh·(m^2 a)$^{-1}$, that is 2,5%, whereas the insolation difference between surfaces inclined at 30^{O} and 45^{O} is only 4 kWh, bearing no practical impact on power yield.
Also the distribution of insolation depending on the density of solar radiation (insolation) [16, 17] is an important parameter, as presented in fig. 4 for the analysed area.

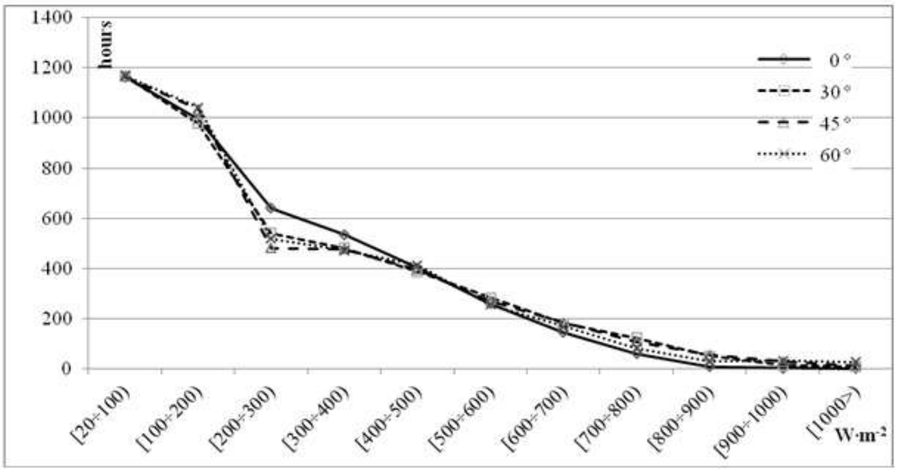

Figure 4. Distribution of insolation at selected angles of receiving surface as a function of insolation

The above diagram presents the insolation value as a function of insolation, with the latter presented below the diagram. As it is evident on basis of the chart (fig. 4), over 50% of daily time in a mean year ground is reached by a radiation flux density of 200 W·m^{-2}. At such a small flux of solar energy, the efficiency of photovoltaic cell conversion efficiency must be considered in the calculations [17]. According to the presented diagram (fig. 2) one can notice that the optimal angle of the receiving surface in terms of small densities of solar radiation flux, that is 500 $W \cdot m^{-2}$, should amount to 0^O. Due to the fact that for this value of solar radiation, a horizontal alignment is optimal, one may conclude that diffused radiation makes up as much as 85% of the daily volume. Only above 500 $W \cdot m^{-2}$ should the angle of the receiving surface should be from 30^O to 40^O, so as to ensure the maximum capturing of solar radiation.

In order to determine the parameters of a photovoltaic farm, a detailed insolation analysis of the preselected actinometric station representing the site was performed. Figure 3 presents the distribution of insolation in the specific months depending on the density of solar energy flux and with the consideration of the optimal angle of the receiving surface. According to the diagram (fig. 5), the greatest yield of solar energy occurs in May, June, July and August at an angle of 30^O (insolation distribution curves in the diagram align with each other). Furthermore, the distribution of insolation in April resembles the one in September, just as October and March, at an angle of 45^O. In November, December and February, the distribution of insolation is virtually identical, whereas the number of hours where the density of solar energy flux is less than 200 $W \cdot m^{-2}$ does not exceed 80 per month.

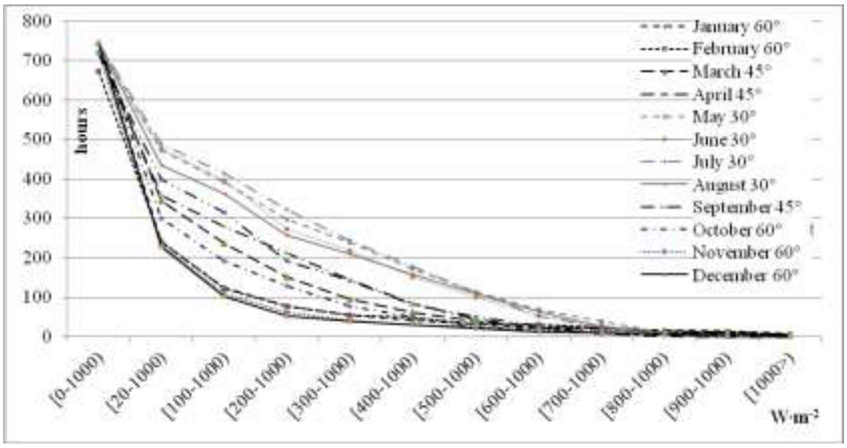

Figure 5. Monthly insolation values for optimal angle of the receiving surface

Provided that the following optimal angles are kept in October, November, December, January and February at 60^O, in March, April and September at 45^O, and in May, June, July and August at 30^O, the sums insolation hours have been determined depending on the density of the solar radiation flux (fig. 6).

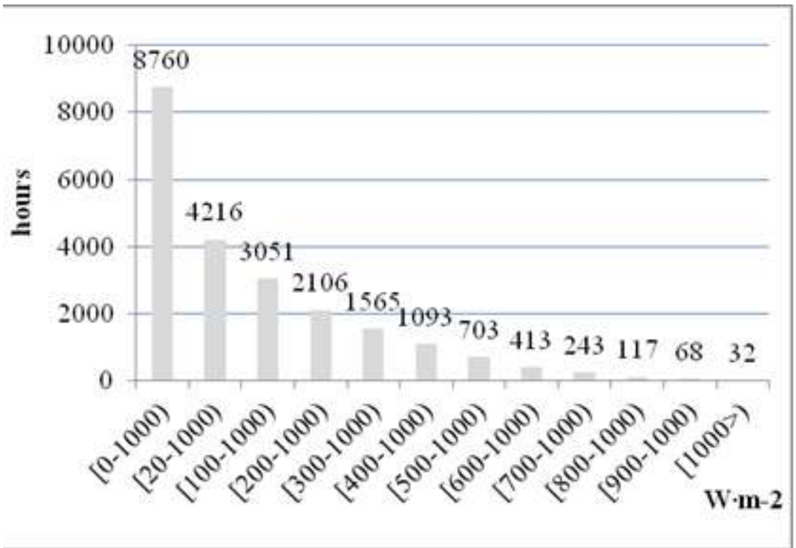

Figure 6. Yearly insolation as a function of radiation density

The performed analysis of insolation distribution provided a basis for the definition of the value of solar energy reaching the receiving surface, which is more practical in power generation analyses. The results of such an analysis are provided on the diagram (fig. 7).

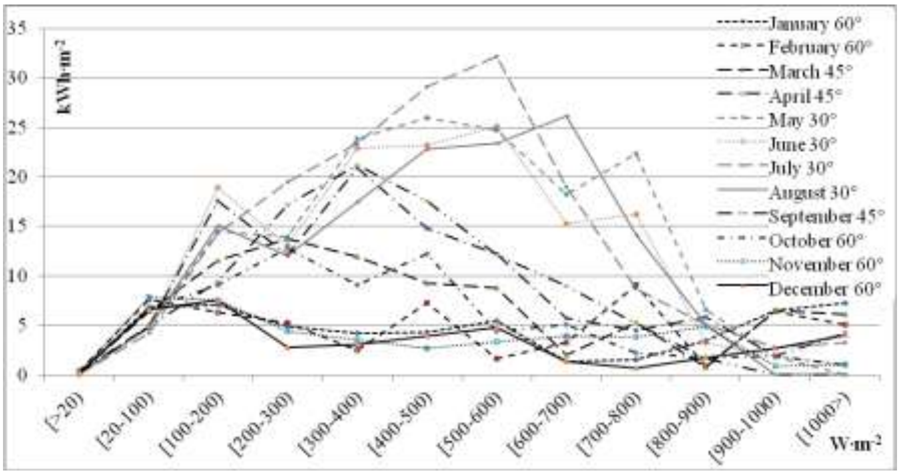

Figure 7. Insolation value depending on solar radiation flux density

According to the diagram (fig. 7), the maximum yield in the specific months amount to 200-700 W·m^{-2}, while the maximum falls on July between 500-600 W·m^{-2}. In the diagram, a certain relationship may be observed in the occurrence of the maximum yield in summer months moving towards higher densities in July and August. In September and April, the maximum yield corresponds with a flux density of 300-400 W·m^{-2}. On the other hand for late autumn and early winter no clear maximum has been observed in terms of insolation distribution. Its values move around 5 kWh·m^{-2}, virtually regardless of the solar radiation flux density. In the further analysis an evaluation of the optimum angle of the receiving surface was performed (angle step-adjusted in the course of the year), determining the energy percentage depending on its flux density, with 100% as the optimum tilt angle. The annual insolation value analysis with its percentage values depending on the flux density is presented on the diagram (fig.8). In the presented diagram it is evident that the (continuous) line marked as an optimum mostly forms an envelope of other curves, thus confirming that the amount of energy in the course of the year will be the highest, if the step-adjustment of the receiving surface angle is performed.

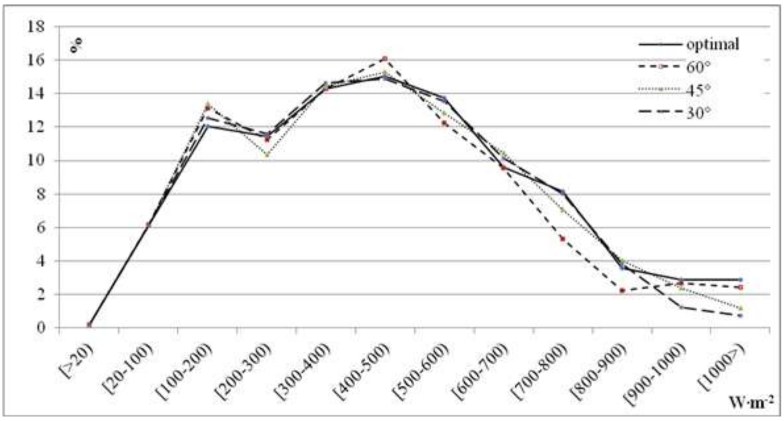

Figure 8. Percentage value depending on solar radiation flux density

Within a year, the greatest intensity of radiation reaching the surface, depending on the solar radiation flux density within 400-500 W/m^2, amounts to 15%. It is worth nothing that almost half of total energy reaching the ground has a flux density value of 300-600 W·m^{-2}.

Thanks to the performed broad analysis of solar radiation energy at the location of the small photovoltaic farm intended as a supporting power source of the waste water treatment plant, it was possible to define the scope of solar radiation density flux values in which the power generated by the PV farm should cover the demand of the waste water treatment plant. This scope was determined as 200 W·m^{-2}-350 W·m^{-2}, whereas for the purpose of further analysis it was split into three variants: W1 200 W·m^{-2}, W2 250 W·m^{-2} and W3 350 W·m^{2}. The following criteria were used for the calculation of active surface of photovoltaic modules:

1. Maximum photovoltaic farm power should not exceed the maximum power subscribed with the power supplier, increased by the mean value of power demanded by electric devices installed at the waste water treatment plant.
2. Power generated by the PV farm should cover at least 90% of demand in the summer half of the year (April-September).

3. Points 1 and 2 should be fulfilled assuming that two reactors of the plant are operating; therefore, a growth of power consumption and power demand by electric devices of the waste water treatment plant by 62,26% was assumed.
4. The smallest photovoltaic farm to be considered in the analyses should meet the criterion 1 and 2 at current power and energy demand, that is operation of a single waste water treatment plant reactor.

On basis of the adopted criteria 1-4 and considering the limit values of solar radiation flux density from 200 W·m^{-2} to 350 W·m^{-2}, three variants were developed: **W1** 200 W·m^{-2}, **W2** 250 W·m^{-2}, **W3** 350 W·m^{-2}. Based on relationship (1) and the adopted criteria 1-4, the surface of photovoltaic modules was determined, as specified in table 2.

Table 2. Listing of photovoltaic plant parameters for three variants

Variant	W1	W2	W3
Mean power demand [kW]	30	30	30
Threshold flux density [W·m^{-2}]	200	250	350
Required receiving module surface [m^2]	1100	860	620
Peak farm power [kWp]	153,06	120	85,72
Maximum farm power [W]	137,76	108	77,14

Furthermore, power generation volumes in the specific months of the year was determined and compared with the current and forecast power demand after the commissioning of the second reactor, as specified on the diagram (fig. 9).

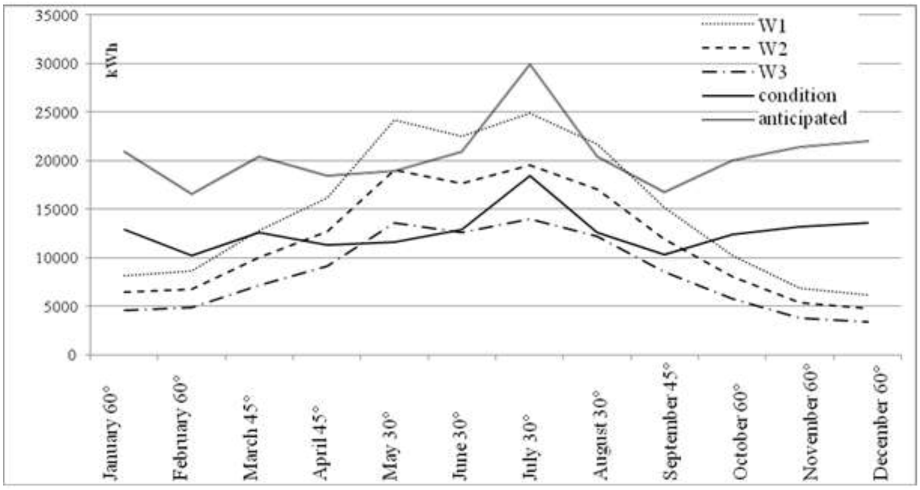

Figure 9. Power generation within specific variants

After determining the power generation potential, a further analysis of coverage of power demand of the waste water treatment plant could be performed. On this stage the conducted research will consider a photovoltaic farm connected to the grid with an option of feeding power to the grid in case of overproduction and an autonomous system which will generate power exclusively for the needs of the waste water treatment plant without the possibility of supplying power to the grid.

V. SUMMARY

In order to determine the parameters of a photovoltaic farm, a detailed insolation analysis of the preselected actinometric station, regarded as a reference station for the site, was performed.

1. Insolation fluctuates strongly in the specific months between 25 kWh·m^2 in December and 160 kWh·m^2 in July. The insolation value is influenced by the angle of the receiving surface. Optimal tilt for the autumn-winter season (from October to March) should be 60^O and 30^O for other.
2. Within a year, the greatest intensity of radiation reaching the surface, depending on the solar radiation flux density within 400-500 W/m^2 amounts to 15%. It is also worth noting that almost half of total energy reaching the ground has a flux density value of 300-600 W·m^2.
3. The performed solar radiation analysis at the photovoltaic farm location, in connection with the adopted functional and operating assumptions no. 1-4 allowed to develop three variants of such a PV farm which would cover the current power demand at such low solar radiation flux density as 200-350 W·m^{-2}.
4. For variants W1 200 W·m^{-2}, W2 250 W·m^{-2} and W3 350 W·m^{-2} the necessary area of photovoltaic monocrystalline modules was determined, together with other parameters of the PV farm, while a complete specification is provided in table 2.

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