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Numerical assessment of energy generation from photovoltaic cells using the CM-SAF PVGIS database

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Abstract: The main objective of this article is to assess the legitimacy of using different tracking systems applied to the photovoltaic panels, for the city of Wroclaw (Poland), using 2 numerical tools: the CM SAF (Climate Monitoring Satellite Application Facility) and PVGIS (Photovoltaic Geographical Information System). In order to identify the solar irradiation, the CM-SAF database (based on the measurements of MFG – Meteosat First Generation – and MSG – Meteosat Second Generation – satellites) was utilised, while the PVGIS (Photovoltaic Geographical Information System) – to calculate the energy yield from PV panels. Particular attention was given to the optimisation of the annual tilt angle and the determination of the energy benefits from the implementation of the various sun tracking systems. Conducted studies showed that up to 30% more electricity yearly can be yielded after the replacement of PV cells with optimally fixed both azimuth and tilt angles by the 2-axis tracking system (179 kWh/m^2 instead of 138 kWh/m^2). Moreover, by the adequate decreasing of tilt angles in the summer time or obtaining the most favourable local solar exposure conditions, the supply curve of PV units may be significantly flattened, which may be beneficial when energy storage systems have low capacities.

Key words: energy generation, photovoltaic cell, renewable energy source, solar radiation

1. Introduction

1.1. The actual context of photovoltaic technology explatation

The progressing implementation of rigorous pro-environmental energy policy in Poland leads to the diversification of energy sources as well as to a rapid replacement of emission-intensive power technologies by nearly zero-emission units. To adapt the national power system to strict European Union (EU) emission limits (concerning in particular CO_2 or Hg, related to 2010/75/UE Directive or new Best Available Technologies documents for Large Combustion Plants – BAT documents for LCP), several clean power technologies, due to a high dependence of the Polish economy on coal, need to be introduced in the reasonably near future as cost-efficient sources of electricity, heat and chill [1–7]. Several steps taken by the Polish government within the last 10 years to reduce the negative impact of the so far strictly coal-focused power sector are generally oriented at creating more pro-environmental fuel structure – for instance, in 2050 about 52% of annual electricity generation in Poland should be covered by nuclear and renewable energy sources (importantly, total consumption should increase from 159.8 TWh in 2015 to 222 TWh in 2040 as well) [2, 3]. As a result, it is crucial to evaluate economically justified technologies (concerning both power generation and storage units) and systematically introduce them to the Polish energy system. Understandably, particular attention is given to renewable energy sources (RESs) – wind, biomass, solar, geothermal energy, water – that in many cases seem to be more environmentally friendly (over the whole life-cycle) and economically justified than most of the conventional power technologies, both on a small (municipal) and large (professional) scale [3–10].

A prompt adaptation of clean power technologies contributes to, among others, the intensive development of several passive and active utilisation techniques dedicated to direct solar radiation. Currently available solar power technologies are focused mainly on three types of appliances: photovoltaic cells (PV), solar water heating (SWH) and concentrated solar power systems (CSP, i.e. power plants with heliostats coupled with boilers located on solar towers) [11]. Solar systems tend to have a wide variety of applications – they can constitute single-technology power units as well as be part of hybrid systems or can be adopted in micro, small, medium (PV, SWH) and large power systems (CSP) [12, 13]. Furthermore, to improve their competitiveness against conventional units, new solar technologies with higher efficiency as well as new solutions that can guarantee a higher energy yield from existing equipment, have been taken under evaluation.

When direct electricity generation from the RES on a small or medium scale is requested, it is reasonably – from the technical point of view (to balance the supply and demand and to conduct specific feasibility studies) – to assess, i.e. the impact of the implementation of PV units on power systems and grids [14]. That electrical devices employ a photovoltaic phenomenon to convert the energy of solar or artificial light into electricity [15]. Importantly, several currently available commercial PV technologies – relatively easy-to-implement (both off- and on-grid) and produced using large-scale production lines (i.e. in China and South Korea) – seem to be economically applicable within future power sectors in many countries [4–8, 17–19, 41].

Nowadays, the landscape of many countries is divided into urban and rural areas. Each of these two areas is more and more intensively used. The rural land is used for crops and the various industry workshops. The urban land has a high density of buildings. The common characteristic of both areas (rural and urban) is the fact that both are relatively precious. It causes that the implementation of photovoltaic technology needs to be optimised, in order to obtain the maximal electrical power from every square meter dedicated to this technology.

1.2. The possibilities to use boost energy yield from PV systems

Three main aspects should be identified in order to boost energy yield from a PV unit: location (solar irradiance), technology or types of PV cells and orientation (tilt angle, azimuth, regulation method) in relation to the sun position throughout the year. Consequently, a proper adaptation of the most favourable solutions will significantly affect the payback time of the PV unit, the value of the initial investment costs and stability of the power system (by identifying the variability of energy generation). To select the most suitable solution concerning the installation mode for each case, a preliminary assessment concerning energy generation potential for each case should be introduced.

Firstly, to create a national or international power sector that is based significantly on solar technologies (i.e. PV systems), the areas with a high radiant intensity (and, if possible, with low volatility through the year) should be adopted first. However, in the European Union, where energy policy focuses on unitary emission standards and factors, it may be difficult to economically operate solar units in these countries, where natural insolation is relatively low (i.e., the insolation conditions in the Iberian Peninsula are almost twice more favourable than in the Baltic Sea area) [7, 8, 20–23]. In many cases, it will be vital to optimise the utilisation rate of solar energy within PV systems mainly by the deliberate choice of both PV technology and solar cells orientation.

Secondly, the conversion efficiency of solar radiation into electricity in PV cells differs significantly depending on the PV technology. Therefore – when economically possible – to enhance the energy yield from photovoltaic units, highly-efficient solar panels should be used. Starting from the 1980s, the rates of the conversion of solar radiation into electricity in PV technologies have been at least doubled – currently, efficiencies of 10–46% can be achieved [9]. The highest (28–46%) values can be achieved when multijunction cells (two- and more junctions, gallium arsenides – with or without concentrator) are implemented. Crystalline Si cells (single- or multicrystalline, with silicon heterostructures) guarantee an efficiency of 21–28%. Slightly less electricity (14–24% of insolation) can be obtained from thin-film technologies (copper indium gallium selenide, cadmium telluride or stabilised amorphous silicon). Finally, the lowest quantity of energy (up to 10–14%) will be collected in PV systems when one of the low-cost emerging, steadily developing technologies (i.e. dye-sensitized, perovskite, organic, copper zinc tin sulphide or quantum dot solar cells) is implemented [24, 25]. Nowadays, the largest share of PV panels available on the market, mainly due to favourable efficiency to total investment costs ratio and widespread infrastructure, is covered by the crystalline silicon cells (Si-wafer based PV cells represent about 94% of total production worldwide) [2, 26]. This situation should change in the future, when cheaper solutions concerning manufacturing highly-efficient PV cells are adopted or non-conventional (i.e. perovskite) units are popularised [19, 24]. Importantly, the efficiency of PV units may be increased by the proper implementation of maximum power point tracking (MPPT) systems or reducing energy losses in cables and regulatory equipment (inverters, batteries) as well [27–29].

Nevertheless, even when the most efficient PV technology is selected, the core issue will be to identify and introduce the most appropriate mounting system related to the orientation of the

PV panel towards the sun. By enhancing the radiation delivered on the PV surface, the energy yield can be significantly increased. On the other hand, to calculate – as precisely as possible – the energy yields per each day or month, a validated solar database and numerical code need to be provided. According to many articles, the selection of the most favourable horizontal inclination of the PV panel is crucial to obtain a rewarding energy yield [11, 15, 21, 30]. In general, two main mounting systems of PV panels are possible to introduce – fixed (tilt and azimuth angle are constant throughout the year; coupled with roof, wall of a building or placed on a special frame) and tracking (manually or automatically, in one or two axes). Tracking systems boost energy yield from solar units but increase the capital costs, therefore they should be used when its implementation reduces total costs of investment per kWh net. To assess that, the comparison of energy generation potential between cheaper fixed systems and tracking systems should be conducted (by the real measurements or verified calculation methods). Importantly, fixed angles need to be selected properly too – in general, several empirical formulae to identify optimal (yearly) tilt angles have been already proposed, but, importantly, a lot of them are mutually exclusive or can be applied only in selected regions [30]. Alternatively, a system with manually regulated tilt angles that can be optimised monthly can be considered. To resume, it seems to be mandatory to determine as precisely as possible a universal, fast method to identify the most suitable solution, especially when the investment is sensitive to energy yield.

Direct coupling of power technologies highly susceptible to environmental issues and different grid energy storage devices might be unavoidable due to the changing weather conditions and variable power demand in RES-oriented power systems [12, 31].

1.3. Purpose of the study

As exposed above, the photovoltaic technology, related to the actual emission regulations, become more and more attractive. The implementation of this energy generation technology needs to meet many criteria to optimise the use of land, dedicated to this technology. One of the major aspects is to adopt the adapted panel exposition on the solar radiation, and this aspect will be analysed in this paper. The case of Wroclaw (Poland) will be studied, in order to assess the legitimacy of using the tracking system applied to the photovoltaic panels. To perform this analysis, five various attachments of photovoltaic panels were studied. The study was conducted numerically with the use of the CM SAF (Climate Monitoring Satellite Application Facility) database and PVGIS (Photovoltaic Geographical Information System) model.

2. Methodology

As mentioned above, to maximise the energy generation from PV units, the proper orientation of PV cells is mandatory to promote the most favourable array. However, when measurements in real time are impossible to perform, the adaptation of reliable, widely available solar databases and using one of calculation models for assessing both available solar energy and electricity generation from PV panels seem to be critical in the engineering venture. While the popularity of solar-to-electricity units is rising systematically, it seems to be justified to identify the energy generation potential (that varies according to i.e. the location) and promote easy to handle calculation methods that can be useful in sizing the PV arrays [6, 8, 15, 16, 21].

To highlight the differences in monthly and annual energy generation and supply curves of PV cells, selected calculations were conducted and analysed with regard to any solutions. Five different attachments were selected:

1) fixed with annually optimal tilt and azimuth angles,
2) with a two-axis tracker,
3) with a fixed azimuth (annually optimal) and monthly-adjusted tilt angle,
4) installed horizontally (i.e. placed on the ground) with an annually optimal azimuth and
5) installed vertically (i.e. on the wall) with an annually optimal azimuth.

Possible variations in energy yields should determine the reasonableness of the implementation of each mounting system.

2.1. Determination of the energy generation potential in PV cells

To predict the energy generation potential of PV cells, a mathematical model was identified and introduced. In order to simplify the calculations, both secondary radiation and shading of the panels were not taken into account. To calculate the energy yield from the abovementioned solar system, a reliable PVGIS database concerning local flux density of radiation as well as the movement of the sun, properties of the atmosphere and weather conditions (i.e. cloudiness) were directly harnessed.

Firstly, in order to calculate the estimated daily value of the extra-terrestrial (on a surface parallel to the ground) the incident radiation inside the atmosphere H_e, Eq. (1) was used [15]:

$$H_e = H_{e,b} + H_{e,d} = K_t \int_{\omega_{ss}}^{\omega_{sr}} G_{e,0} (\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta)\, d\omega\,, \tag{1}$$

where: $H_{e,b}$ is the direct (beam) daily radiation intensity, $H_{e,d}$ is the diffuse daily radiation intensity, K_t is the transparency coefficient (daily clearness index) of the atmosphere (0.3–0.6) [26], ω is the hour angle of the sun over the horizon (index "sr" concerns sunrise, "ss" – sunset), $G_{e,0}$ is the temporary flux density of radiation (solar irradiance) outside the atmosphere, ϕ is the latitude of a location, δ is the declination.

To evaluate the practical daily flux density (in the normal surface dedicated to the specified direction – parallel to the ground) of the irradiation outside the atmosphere $G_{e,0}$, Eq. (2) was proposed [33]:

$$G_{e,0} = G_{sc} \left[1 + 0.033 \cdot \cos\left(\frac{360^\circ}{365} n\right)\right] K_t^m\,, \tag{2}$$

where: G_{sc} is the global solar constant (1.366, 1 W/m^2), n is the Julian day of the year (for 1st January $n = 1$), m is the air mass that in turn can be assessed directly from Eq. (3) [12]:

$$m = \frac{\left(\frac{180}{\pi} + 6.07995\right)^{-1.6364}}{\sin\alpha_s + 0.50572}\,, \tag{3}$$

where α_s is the angle of the sun above the horizon. Furthermore, to evaluate the value of the declination δ, the Cooper formula can be used – Eq. (4) [34]:

$$\delta = -23.45 \cdot \cos\left(360^\circ \frac{n+10}{365}\right). \tag{4}$$

To identify the quantity of the radiation compounds (direct $H_{e,b}$ and sky-diffuse $H_{e,d}$), the empirical ratios presented in Eqs. (5) or (6) and Eq. (1) can be utilised [12, 30]:

$$(D/G)_e = \frac{H_{e,d}}{H_e} = \frac{H_{e,d}}{H_{e,b} + H_{e,d}} = \begin{cases} 1 - 0.561 \cdot K_t \leftrightarrow 0 < K_t < 0.17 \\ 1.17 - 1.561 \cdot K_t \leftrightarrow 0.17 \le K_t \le 0.7 \end{cases}, \tag{5}$$

$$(D/G)_e = 1.0045 + 0.04349 K_t - 3.5227 K_t^2 + 2.6313 K_t^3 . \tag{6}$$

When $H_{e,0}$, $H_{e,d}$ and $H_{e,b}$ are assessed, the calculations for the tilted and azimuth-oriented PV panels need to be conducted. To identify the daily irradiation values dedicated to specific surfaces tilted in any direction (azimuth angles), one of the estimation models may be introduced. In this article, the Andersen model (created on the basis of the modified by Klein, Liu and Jordan theory) was used [20].

To recalculate the practical primary irradiation on any PV panel H_t, both diffuse- and direct-radiation convention factors R_b and R_d are introduced in Eq. (7) [35]:

$$H_t = R_b \cdot H_{e,b} + R_d \cdot H_{e,d}. \tag{7}$$

Then, two mentioned factors need to be calculated using Eqs. (8) and (9) [15, 36]:

$$R_b = \frac{\int_{\omega_{t,ss}}^{\omega_{t,sr}} \cos\theta(\omega)\, d\omega}{\int_{\omega_{ss}}^{\omega_{sr}} \cos\gamma(\omega)\, d\omega}, \tag{8}$$

$$R_d = \frac{1 + \cos\beta}{2}, \tag{9}$$

where ω_t is the hour angle of the sun over the PV panel. Finally, the angle of incidence of the primary radiation θ – on the tilted at an angle β, with the azimuth angle γ surface – is defined as below (10):

$$\begin{aligned} \cos\theta = {} & \sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\gamma + \\ & + \cos\delta \cos\phi \cos\beta \cos\omega + \cos\delta \sin\phi \sin\beta \cos\gamma \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega . \end{aligned} \tag{10}$$

All the angles mentioned within the described mathematical model are presented in Fig. 1. It shows main angles that represent the temporary orientation of the PV panel in relation to the sun.

Using Eqs. (1)–(10), daily solar irradiance can be assessed. Then, the identification of energy generation potential may be evaluated. Importantly, 1 kW of PV peak power refers strictly to

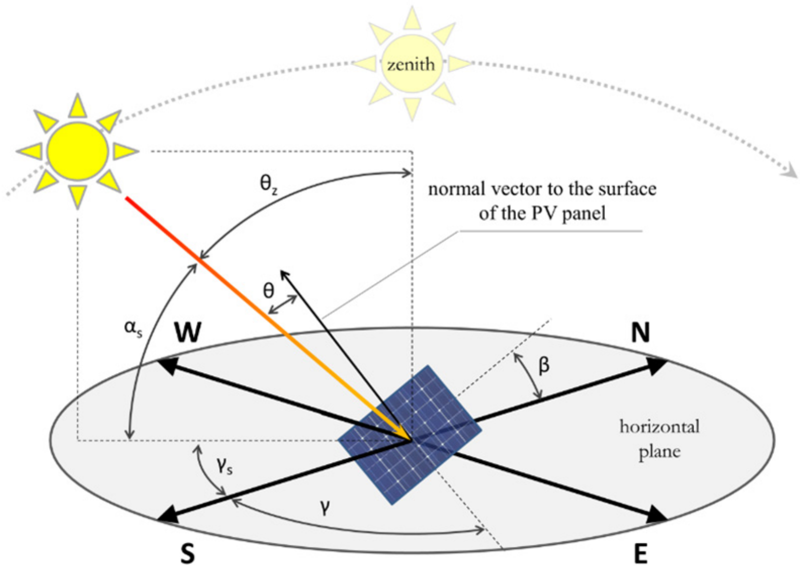

Fig. 1. The scheme of the angles used in the calculation model

the Standard Test Conditions (STC). For Central and Eastern Europe, the illumination in STC refers to 1 000 W/m^2 (with a spectrum identical to that at latitude 45°N in the summer), the temperature of the PV cells is 25°C, the value of the air mass is equal to 1.5, while the wind speed to 1 m/s [37]. As a result, when the working conditions of the PV panel are different (i.e. due to the higher temperature of PV cells in summer and lower in winter, lower or higher insolation), the power capacity need to be recalculated. Assuming both H_t and new working parameters of PV technology, to predict the value of the power output E_{PV}, simplified Formula (11) can be used [21, 38, 39]:

$$E_{PV} = H_t \cdot \frac{A_{PV}}{P_{PV(STC)}} \cdot Z_T \cdot Z_{AR} \cdot V_L \cdot V_a \cdot V_u = H_t \cdot a_P \cdot Z \cdot V, \tag{11}$$

where: H_t is the total radiation intensity per square meter received by the modules of the given orientation, A_{PV} is the effective area of PV cells, P_{PV} is the peak power of PV cells, Z_T is the temperature cell factor (that includes the influence of the deviation of the cell temperature from the STC on the power generation – see Table 1), Z_{AR} is the additional factor corresponding to the losses due to angular reflectance effects, V_L is the factor of cable losses, V_a is the factor of mismatching losses, V_u represents the conversion losses in the battery. Factor a_p that represents the area of PV

Table 1. The average temperature cell coefficient in months [39]

month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Z_T	1.00	1.00	0.98	0.96	0.93	0.90	0.88	0.88	0.90	0.94	0.97	0.99

cells per every 1 kW peak, differs depending on the PV technology (7–15 m^2/kWp) [25]. It can be easily identified – assuming that the standard flat crystalline silicon PV panel covers an area of 1.7–2.0 m^2 and that its peak power ranges between 200 kW and 300 kW, every 1 kWp requires 5.7–10.0 m^2.

As mentioned before, to achieve the most accurate results, both selection of a valid solar database and proper calculations for each day should be conducted. Moreover, to identify the differences in energy yields for each of the angles, calculations need to cover a wide range of pairs of β and γ.

Possible values of the temperature coefficient Z_T were presented in Table 1. When the temperature of the PV panel increases, the energy generation decreases. As a result, in summer, i.e. due to high ambient temperatures and ineffective cooling of PV cells, the significant reduction (by 7–12%) of nominal power of PV panels may be observed. Therefore, it seems to be vital to enhance the heat transfer i.e. by boosting the motion of the air close to the PV cells. To identify the value of the Z factor with higher accuracy, measurements in real time or more sophisticated models (i.e. G-S or SUR) should be implemented. The impact of the adaptation of i.e. MPPT systems should be included too [9, 27–29].

2.2. The location, irradiance database and adopted *PV* technology

The CM-SAF PVGIS database was applied for further deliberations and analysis. It contains the measurements of the MFG and MSG weather satellites from 1998–2005 and 2005–2011 and can be regarded as a reliable source of information on solar radiation in Europe [40]. Moreover, to analyse the impact of the humidity, cloudiness and clearness of the atmosphere, diffusion rate of the insolation, local ambient temperature, the length of the day and estimated wind on the solar energy conversion efficiency in PV cells, widely available calculation software was used [38].

All the calculations were performed for the localisation of Wrocław (51°06′36″N, 17°01′20″E). This city is located in Poland, in the Lower Silesia region, in Silesian Lowlands. Its average elevation is about 120 metres above the sea level. Wroclaw is situated in the northern temperate zone, in the transitional climate affected by both ocean and continental effects.

To assess the energy generation potential, the crystalline silicon PV technology was chosen. The assumed system power losses were set at a level of 14% (concerning cable, conversion in batteries and mismatching losses as well as energy distribution within power system) [41]. Therefore, V (Eq. (11)) in following calculations is equal to 0.86. The estimated average (in relation to a year) losses due to the temperature and low irradiance were equal to 7.9% and due to angular reflectance effects – 3.0%. As a result, the combined losses of the PV system were assumed as 23.2%. Moreover, it was estimated that a factor is equal to 7.2 m^2/kWp.

3. Results and discussion

Firstly, the annual beam radiation (in kWh/m^2) on the arbitrary plane – in relation to the fixed azimuth and tilt angle (horizontal inclination) – for the case of the fixed system was determined. As shown in Fig. 2, the highest primary radiation (power input for PV cells; over 1 200 kWh/m^2 per year) can be obtained when an azimuth is ±40° and a tilt angle is equal to 20–50°. Interestingly, from a practical point of view, it seems that there is no need to put a strong emphasis on placing PV panels or solar collectors at one precise angle (i.e. that may generate additional costs or the risk of shading). Although the highest radiation of approximately 1 290 kWh/m^2 per year can be obtained for an azimuth $-2°$ and fixed tilt angle 37°, the mentioned derogation from optimal angles should not lead to the notable reduction of solar radiation incident on a selected plane of PV cells. Importantly, only from annual energy yield point of view, the optimisation of both tilt and azimuth angles should be emphasised to enhance solar radiation in summer and late spring first – when the impact of the orientation of the PV unit on electricity generation is significantly more sensitive to tilt and azimuth angles than in autumn or winter.

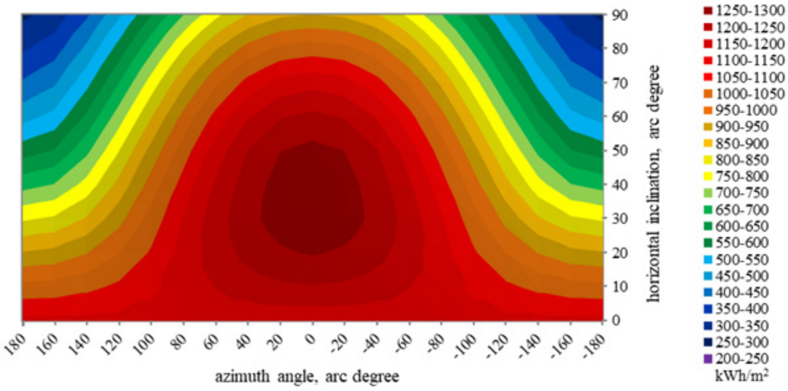

Fig. 2. Annual global (beam) radiation on the plane (in kWh/m^2) in relation to the azimuth and tilt angle – fixed within the whole year

To indicate this fact, the values of global radiation on the plane in relation to the azimuth and tilt angles in respect to the selected months were drafted (Figs. 3(a) and 3(b)). As presented, the decrease in the value of solar radiation on the inclined plane differs significantly for each month. For example, in June, there is no need for in–depth adaptation of the azimuth angle but it is strongly recommended to adjust the tilt angle between 0–20° to the horizontal plane. On the other hand, in August or September, the optimal azimuth angle ranges from ±40° to 0° and tilt angles from 20° to 50° for April and from 40° to 60° for September. Further, in winter and late autumn, the optimal azimuth range is quite similar to the rest of the year, while the tilt angles should be significantly higher to boost the energy yield. As a result, the adaptation of a proper selection of tilt and azimuth angles in winter, when the insulation is substantially lower than in summer, will lead to lower annual benefits in an additional energy yield from PV panels than in summer.

That leads to the conclusion, that by the proper regulation (even manually) of tilt angles, solar radiation can be boosted and the implementation of tracking systems may be justified, especially in summer. Additionally, when the production curve of PV units needs to be flattened, it seems to be justified to choose higher values of tilt angles in fixed systems (at the expense of decreased annual energy generation).

When both insolation incident on a selected surface (Eqs. (1)–(10)) and working parameters of PV cells are assessed, energy generation potential per every 1 m^2 of PV cells can be investigated using Eq. (11). The results for the case of annually fixed tilt and azimuth angles and selected crystalline silicon cells are shown in Fig. 4. According to the conducted calculations, the highest annual energy production in the Wroclaw region (ca. 138 kWh of electricity in year per every 1 m^2 of PV cells) in the case of the fixed azimuth-tilt angle, the system will be obtained for horizontal inclination that is equal to 37° and azimuth −2° . However, high annual primary insolation (over 130 kWh per every 1 kWp of PV cells) can be yielded in a relatively wide range of tilt and azimuth angles – when an azimuth is fixed between 40° and −40° and horizontal inclination varies from 10° to 50°. That fact strongly corresponds with Fig. 2. As demonstrated, the accurate orientation of the fixed PV panels towards the sun seems to be less sensitive than expected.

In the case of Wroclaw, it often occurs that about 120–140 kWh of electricity per every 1 m^2 can be obtained when both azimuth and tilt angles are fixed throughout the whole year. However, further enhancement of the annual energy yield can be introduced when one of the tracking systems in implemented. To indicate crucial power indicators and to compare selected orientations and tracking systems, 5 different cases were calculated in order to determine annual energy generation potential as well as the variability of energy production on a monthly basis.

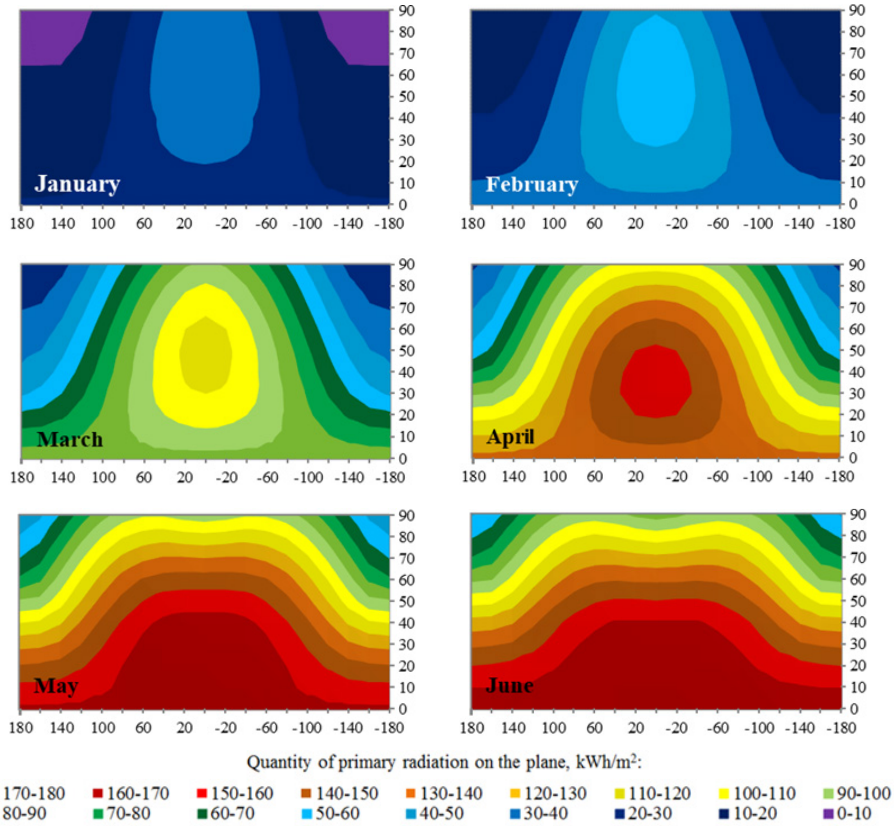

Fig. 3(a). Precicted global (beam) radiation on the plane in different months (January–June) in relation to the azimuth and tilt angle – fixed within the whole analysed month

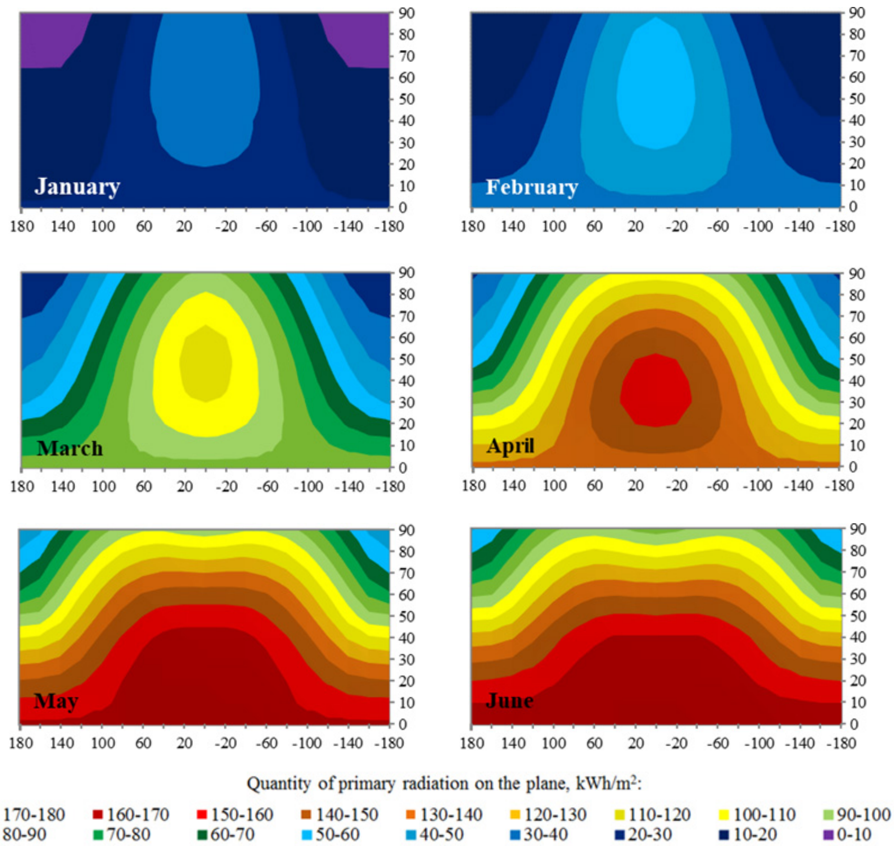

Fig. 3(b). Predicted global (beam) radiation on the plane in different months (July–December) in relation to the azimuth and tilt angle – fixed within the whole analysed month

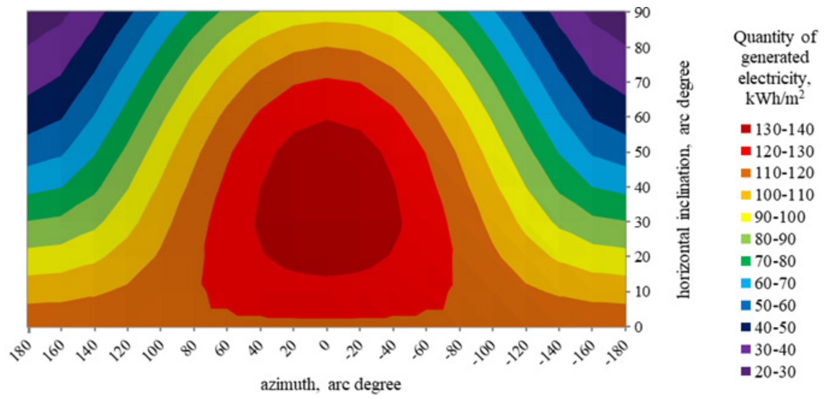

Fig. 4. Annual energy generation potential of crystalline silicon PV cells in Wroclaw – the case of fixed azimuth and tilt angles

Two tracking systems (fully two-axis and manually regulated – once a month – in order to adopt tilt angle to the optimum value for given month) and 3 systems with fixed angles (with an annually optimised tilt angle and azimuth of 0°, horizontally mounted – that simulates the flat roof – and vertically mounted with an azimuth of 0° – in respect to walls placed in the southern direction).

The results concerning energy yields in each month were presented in Fig. 5. Depending on the solution, energy generation rates in months vary considerably as well as the supply curves. For 3 systems – with optimal tilt and azimuth angles, a two-axis tracking system and with the regulation of horizontal inclination once a month – the energy yield will be significantly higher (even 3–5 times) in summer than in winter. Importantly, horizontally mounted PV panels in the summertime seem to have comparable values of energy yields in summer with the cases of optimal or monthly regulated tilt angles. A significantly reduced power generation potential in summer (in comparison to four other systems) may be observed when PV cells are installed vertically (i.e. on the wall of the building), however, the supply curve in this case seems to be more flattened too.

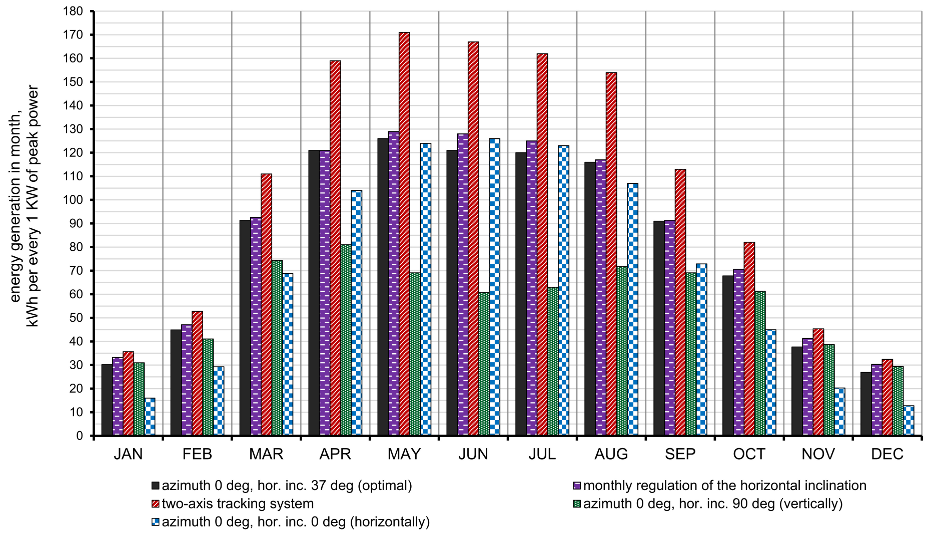

Fig. 5. Energy generation in months – 5 analysed cases located in the city of Wroclaw

To indicate the differences in monthly energy yields – with regard to the case of annually optimised and fixed tilt and azimuth angles – Fig. 6 was drafted. The replacement of the fixed, optimised in respect to annual solar condition system by a two-axis tracking unit can boost an electricity yield in month by 20–40% (in summer – up to 40%, in winter – by about 17–20%). However, the monthly regulation of tilt angles can improve it only by up to 10% (mainly in summer and winter). As a result, this type of regulation seems to have low potential in enhancing the energy generation potential of PV units and should be replaced by i.e. a daily regulated unit. Interestingly, two remaining directions – horizontal and vertical – will have a different impact on the electricity generation curve. When PV systems are installed i.e. on the flat roof, an energy yield in summer should be quite similar to the case of the optimised fixed unit, while in winter, spring and autumn the value of energy will be reduced by 25–50%. Quite different results will be observed when PV panels are placed on the southern wall of the building – up to 50% less energy will be yielded in summer, while in winter the energy generation rates will be 2–10% higher. That fact can be explained by the specificity of the sun motion along the celestial sphere over the PV panel in year, that, in selected localisation, promotes major inclination in winter and low values of tilt angles in the summertime. Moreover, when the surface follows the sun quasi-continuously (by tracking regulation of both azimuth and tilt angle), significant benefits in energy yield can be obtained (up to 40% in relation to annually optimised, but fixed azimuth and tilt angles).

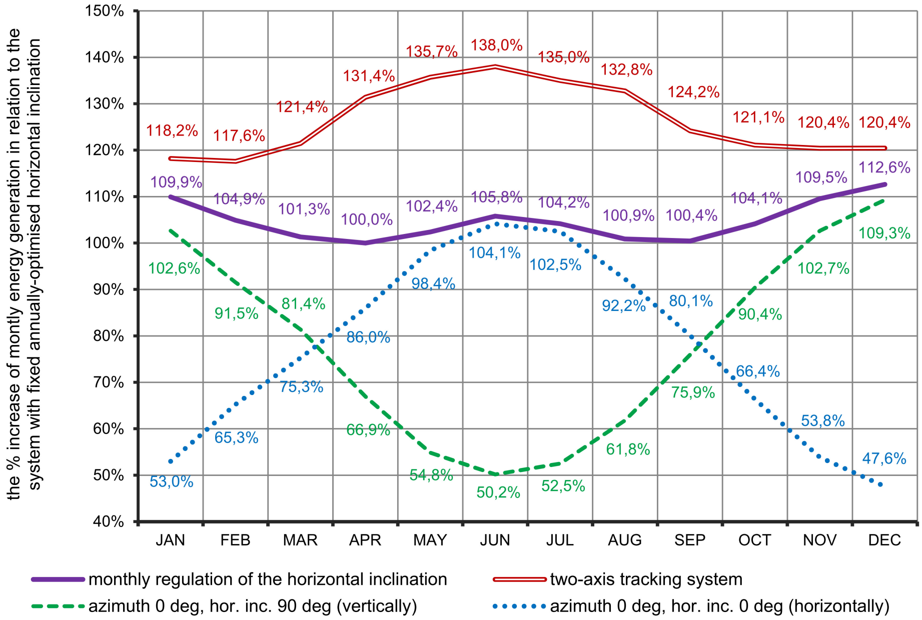

Fig. 6. The percentage differences in monthly energy yield from PV panels of 4 alternative mounting systems – in respect to the fixed, annually angle-optimised unit (horizontal incl. 37° and azimuth −2°)

To describe the differences in monthly energy production rates from PV panels, the coefficient of variation (CV) was adopted. It may be defined as the ratio of the standard deviation of the monthly energy production to the absolute value of the mean value over a whole year. It seems to be a reliable direct indicator to compare the changeability of the energy production in months or days of different PV systems, especially when storage systems or spinning reserve need to be introduced within the power system coupled with solar units. The cumulative results concerning both the CV and total, annual energy yield for 5 investigated cases were presented in Fig. 7.

The highest quantity of the power generated annually was obtained, understandably, in a two-axis tracking system. Annual potential, in this case, was equal up to 1 290 kWh per every 1 kWp, which corresponds with 179 kWh per every 1 m^2 of PV cells when a_p is 7.2 m^2/kWp. Two systems placed in a southerly direction – with the monthly regulation of the horizontal inclination and with 37° fixed horizontal inclination – achieved quite similar results (995–1 030 kWh/kWp and 138–143 kWh/m^2). Horizontally-installed PV cells should supply about 850 kWh/kWp (118 kWh/m^2) every year, while vertically – only 690 kWh/kWp (96 kWh/m^2). Interestingly,

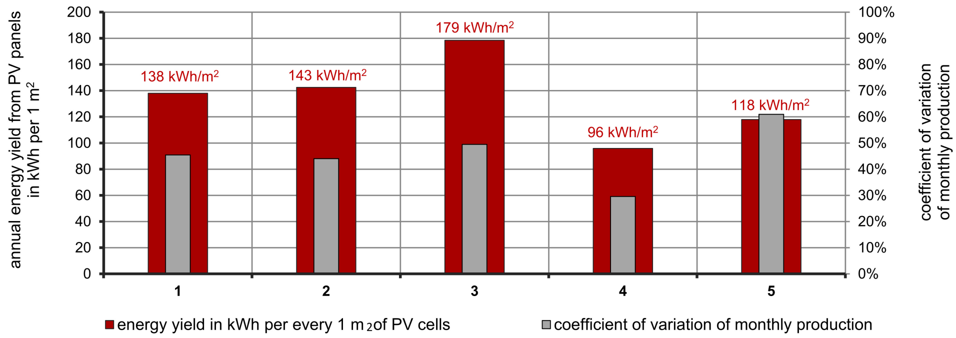

Fig. 7. The comparison of 5 selected mounting systems of PV panels – annual energy generation potential and the changeability of monthly production

when the horizontal inclination is equal to 0°, the annual power generation curve is flatter and seems to be more applicable when monthly power demand is relatively steady (CV was less than 50%, while in other cases it exceeded even 70–80%). Therefore, by the reduction of the annual energy yield, the lower variability of energy generation from fixed PV systems can be provided.

4. Conclusions

In this paper, a simplified engineering mathematical code, covered by the CM SAF database and PVGIS model, dedicated to the identification of the energy yield from PV panels was presented. It confirmed its high application potential, and, therefore, it is suggested to apply it directly in simplified power assessments concerning PV systems. As a result, it can be considered as a valuable source of knowledge about forecasted insolation in Europe, Africa and Asia, with respect to days or months.

Moreover, two of the abovementioned numerical tools were employed to assess the legitimacy of the application of 5 different tracking systems (with 3 fixed angles and 2 tracking ones), dedicated to photovoltaic panels. The assessment was conducted for the city of Wroclaw in Poland. This kind of study is needed to assess the feasibility of a PV system, without using expensive and time-consuming measurement initiatives. They both can be harnessed directly to identify the energy generation from PV for the most popular electrical solar systems.

The conducted calculations showed, that PV systems located in the city can provide annually up to 140 kWh of electricity per every 1 m^2 when both azimuth and tilt angles are optimised and fixed. However, when the azimuth angle diverges from the southern direction by ±40° and the tilt angle of the PV panel ranges between 10° and 50°, still up to 130 kWh/m^2 of electricity can be yielded annually. As a result, it seems to be less obligatory to install PV panels strictly in one direction, that may lead i.e. to the increase of total costs. Moreover, while the implementation of a two-axis tracking system can enhance an energy yield in a year by 29% (regarding optimised annually fixed angles), the manual adjustment of tilt angles once a month – only by 2%. Finally, when the variability of energy production from PV panels need to be reduced, the proper orientation of PV cells towards the sun can be analysed (among others using the described calculation model) and implemented – as a technical way both to minimise the differences in monthly electricity power generation of PV systems and to support the supply-demand balance in national power systems. As it was proved in this study, it is possible to select the adequate attachment of the PV system using the combined CM SAF and PVGIS calculation model.

All the problems mentioned in this paper have proven that the inclusion of RESs in future actions, especially within both small and medium PV capacities, is necessary. When relatively poor financial competitiveness of PV units – against large-scale coal-fired units – occurs, proper orientation of PV panels, as well as professional financial programmes (i.e. preferential tariffs, subsidising the purchase of the power systems, strict emission standards for LCP), seem to be necessary to be introduced to promote the development of solar units. In the case of the mentioned RES systems, the positive pay-back time will be strongly correlated with the location of investment and energy yield from the PV panel. Furthermore, to properly adjust working conditions of energy storage systems coupled with PV units, the identification of variability (from day to day) in energy generation seems to be crucial, however, surprisingly, it is not necessary to strictly obey the requirement of optimal orientation and tilt angles to meet a favourable annual energy yield. All these issues can be easily determined by the utilisation of the presented mathematical model and databases; therefore, it seems to be helpful for all PV assessments.

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