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CONSIDERATIONS ON THE OPPORTUNITY OF USING VARIOUS OPTIMUM TILT ANGLES FOR FIXED PHOTOVOLTAIC PANELS IN IASI, ROMANIA

BY

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Abstract. The photovoltaic conversion of the solar energy is expected to become one of the most important sources of energy as concerns regarding the climate change require significant measures in terms of how we produce electricity. In this context this paper aims to present some aspects regarding the possibility of increasing the energy output of the fixed photovoltaic panels by using different optimum tilt angles. The specific optimum tilt angles were determined for different time intervals, such as monthly, seasonal, biannual and annual, considering the geographic coordinates for the city of Iasi, Romania. A laboratory model of a photovoltaic panel was used in order to experimentally evaluate the energy output increase when setting the panel in the previously determined optimum angles.

Keywords: photovoltaic conversion; tilt angle; energy output.

1. Introduction

The development witnessed by the solar energy in the last decade is the result of the need of clean energy sources which must be able to ensure the

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increasing demand of electricity with minimum impact on the environment. This spectacular evolution was determined by the technological development, which led to more efficient solar conversion installations, available at more attractive costs. Also, the renewable sector benefited from decisive political decisions, like the EU Commission's plan that, by the year 2020, 20% of the total consumed energy should come from renewable sources (European Commission, 2009). Later, in 2014, the EU Commission has set a new target, of a minimum 27% share for renewable energy by 2030 (European Commission, 2014).

Nowadays the photovoltaic conversion is the most important technique for solar energy conversion, as significant large photovoltaic power plants, of hundreds of megawatts installed power are already built (IEA, 2019) and by 2050 is expected that the renewable sources will supply almost 86% of the world's electricity consumption (IRENA, 2019), while the photovoltaic conversion will ensure 25% of the entire electricity, thus contributing to the transition to a decarbonized global energy system.

While the efficiency of the current PV panels is slightly above 20% it is obvious that significant land areas are needed to be covered in order to obtain large PV plants. From this point of any method which will lead to the overall increase of PV systems' energy output will be beneficial.

Today most of the photovoltaic capacities are installed on large utility scale projects which are usually developed using fixed PV panels. Although less costly, this solution is not providing the maximum solar radiation over the entire year, and thus the solar potential of a certain location is not properly exploited. Single axis or dual axis sun tracking systems represents now the best technological solution in this sense, but it comes with significant larger costs.

A less costly solution could be the use of an adjustable fixed angle system, which will allow modifying the tilt angle of the PV panels considering the optimum value for a certain smaller period. Thus, changing the PV panels' tilt angle on a monthly, seasonal, or even biannual regular basis, an increase in terms of the solar radiation incident on the PV panels' surfaces will be noticed, followed by an increase in terms of the energy output. The efficiency of this technique is investigated by numerous researchers all over the world (Ihaddadene *et al*., 2017; Nazmul, 2017; Othman *et al*., 2018; Tirmikçi *et al*., 2018; Danu *et al*., 2015) and many others.

Consequently, this paper aims to estimate the monthly, seasonal, and biannual optimum tilt angles for the city of Iasi, Romania and then to conduct an experimental evaluation of the fixed PV panels' power output increase when the tilt angle is periodically adjusted throughout the year. Experiments will be conducted on a PV panel laboratory model within the faculty's ENERED research platform.

2. Analytical Models for Determination of the Optimum Tilt Angle

Since the idea of using optimum tilt angles was first proposed, in the late 80's (El-Kassaby, 1988), a significant number of analytical models were developed, the simplest one using only the latitude and declination angles, while the more complex models are able to estimate the optimum tilt angles depending on the solar radiation on the PV panel's surface.

Considering the specific latitude, ϕ, of a certain location on Earth and using the declination angle, δ, the daily value of the optimum tilt angle can be determined using the following expression (Stanciu, 2014):

$$\beta_{\text{opt}} = \phi - \delta \,. \tag{1}$$

For larger periods of time, like seasons or a year, the tilt angles can be calculated as following (Patko *et al*., 2013):

$$\beta_{\text{summer}} = \phi - \delta, \tag{2}$$

$$\beta_{\text{winter}} = \phi + \delta, \tag{3}$$

$$\beta_{\text{spring}} = \beta_{\text{autumn}} = \beta_{\text{year}} = \phi, \tag{4}$$

If monthly optimum tilt angles are needed, one can use the following empirical expressions, (El-Kassaby, 1988):

$$\begin{aligned}\beta_{\text{opt}} = 60.00012 + 1.49986M - 3.49996M^2 + (\phi - 30)\times \\ \times(0.7901 + 0.01749M + 0.0165M^2),\end{aligned} \tag{5}$$

$$\begin{aligned}\beta_{\text{opt}} = 216.0786 - 72.03219M + 6.00312M^2 + (\phi - 40)\times \\ \times(1.07515 + 0.11244M - 0.03749M^2),\end{aligned} \tag{6}$$

$$\begin{aligned}\beta_{\text{opt}} = 29.11831 - 20.52981M + 2.50186M^2 + (\phi - 50)\times \\ \times(-11.17256 + 2.70569M - 0.15035M^2),\end{aligned} \tag{7}$$

$$\begin{aligned}\beta_{\text{opt}} = -441.2385 + 84.54322M - 3.50196M^2 + (\phi - 40)\times \\ \times(4.2137 - 054834M + 0.0223M^2),\end{aligned} \tag{8}$$

where: M is the specific month and (5) is used from January to March, (6) from April to June, (7) for July to September and (8) for the last three months of the year (October – December).

Along with these relatively simple models there are also the models which can determine the optimum tilt angles considering the solar radiation intensity. In this case the optimum tilt angle is identified after evaluating the solar radiation levels on a specific surface while varying the tilt angle between 0° and 90°. Obviously, the corresponding tilt angle for which the solar radiation is maximum will be considered the optimum angle.

In this sense, first there is the possibility of determining the optimum tilt angle considering the extraterrestrial solar radiation, which for a tilted surface can be determined according to (Soulayman, 1991) as:

$$H_t = H_0 R_b. \quad (9)$$

In (9) H_0 is the extraterrestrial solar radiation on a horizontal surface and it can be calculated (Duffie, 2013) using:

$$H_0 = \frac{24G_{sc}}{\pi}\left(1+0.033\cos\frac{360n}{365}\right)\left(\cos(\phi)\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin(\phi)\sin\delta\right), \quad (10)$$

where: n is the considered day of the year (where n = 1 for 1st of January), G_{sc} – the solar constant (1,367 W/m^2) and ω_s – the sunrise and sunset angle.

The R_b from (9) represents the tilt factor which can be determined as (Soulayman, 1991):

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega'_s + (\pi/180)\omega'_s\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\phi\sin\delta}. \quad (11)$$

in which ω'_s represents the sunrise and sunset hour angle for a tilted surface, which can be determined with the following relation (Soulayman, 1991):

$$\omega'_s = \min\{\omega_s, \arccos(-\tan(\phi-\beta)\tan\delta)\}. \quad (12)$$

Another possibility of determining the optimum tilt angle requires the evaluation of the solar radiation intensity on a certain surface disposed on the ground. Thus, for a tilted surface the total incident radiation can be calculated with expression:

$$H_t = H_b R_b + H_d \cdot R_d + \rho H R_r. \quad (13)$$

where: H_b and H_d are the beam and diffuse components of the daily radiation on the tilted surface, H is the daily total radiation on a horizontal surface, R_b, R_d and R_r are conversion factors and ρ is the ground reflectivity coefficient, which generally is considered as 0.2.

The conversion factor R_b can be determined according to (11), while R_d and R_r are given below, for isotropic conditions:

$$R_d = \frac{1+\cos\beta}{2},\ R_r = \frac{1-\cos\beta}{2}. \quad (14)$$

3. Estimation of the Optimum Tilt Angles for the PV Panels Installed in Iasi, Romania

Using the mathematical models presented in the previous section of the paper, an extensive analysis was conducted in order to estimate the optimum tilt angles required for fixed PV panels in Iasi, Romania, considering that the city's geographic coordinates are 47°09'12" (47.153) North and 27°35'40" (27.592) East.

The previously presented models were named as following: Model 1 (M1) – model based on the declination angle (Stanciu, 2014), Model 2 (M2) – model based on monthly empirical relations (El-Kassaby, 1988), Model 3 (M3) – model based on extraterrestrial radiation (Soulayman, 1991) and Model 4 (M4) – model based on solar radiation at ground level (Duffie, 2013).

A monthly optimum tilt angle was determined considering the average days for each month of the year, for which the declination angle is closest to the monthly averaged declination, as presented table I. As Model 4 requires the values of the daily total irradiation on a horizontal surface, these values are also presented in Table 1, being calculated as the mean of the monthly average values recorded between 2007 and 2016 (PVGIS, 2019).

Table 1
Monthly Average Day and Average Daily Irradiation on a Horizontal Plane

Month	Average day	*n*	*H* [kWh/m²/day]
January	17	17	0.94
February	16	47	1.62
March	16	75	3.13
April	15	105	4.59
May	15	135	5.74
June	11	162	6.27
July	17	198	6.49
August	16	228	5.64
September	15	258	3.92
October	15	288	2.27
November	14	318	1.26
December	10	344	0.81
* *n* is the number of each monthly average day along the year, when considering *n*=1 for 1st of January.			

The optimum tilt angle for a PV panel installed in Iasi, Romania, was calculated with the models M1,...,M4, for the data presented in Table 1. The obtained results are presented in Table 2 and the monthly variation of the optimum tilt angle, according to all four models used, is presented in Fig. 1.

The seasonal values of the optimum tilt angle were determined while considering the following definition of each season:

- Spring: March, April and May;
- Summer: June, July and August;
- Autumn: September, October and November,
- Winter: December, January and February.

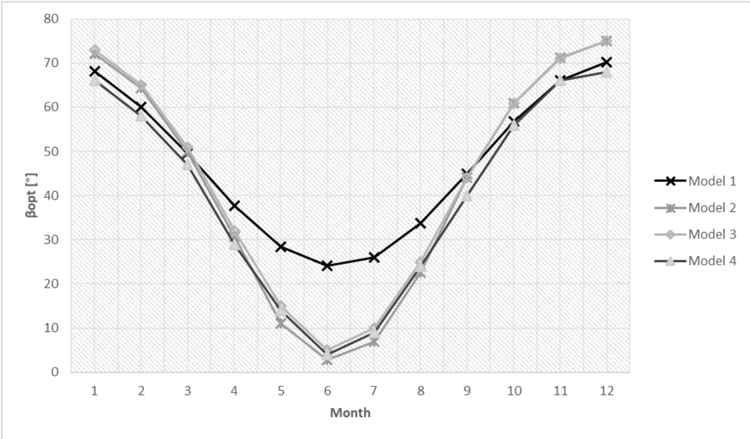

Fig. 1 – Optimum tilt angle variation along the year.

When the biannual values were calculated the Summer interval was considered between March and August, while the Winter period was considered from September to February. Thus, the tilt angle of a PV panel should be adjusted only two times per year, at the beginning of March and September.

Table 2

The Optimum Tilt Angles for Fixed PV Panels when Installed in Iasi, Romania

Model	M1	M2	M3	M4
Interval	Monthly values [°]			
January	68.07	72.13	73	66
February	60.10	64.28	65	58
March	49.57	50.00	51	47
April	37.74	30.61	32	29
May	28.36	11.00	15	14
June	24.06	2.86	5	4
July	25.97	6.86	10	9
August	33.70	22.57	25	24
September	44.93	44.15	44	40
October	56.75	60.86	61	56
November	66.06	71.29	71	66
December	70.20	75.04	75	68
Interval	Seasonal values [°]			
Spring	39	31	33	30
Summer	28	11	13	12
Autumn	56	59	59	54
Winter	66	70	73	64
Interval	Biannual values [°]			
Summer	34	21	23	21
Winter	61	65	66	59
Interval	Yearly values [°]			
Annual	47	43	40	44

The optimum tilt angles determined with the second (M2) and the third (M3) model are in a very good correlation, while the first model (M1) tends to overestimate the optimum tilt angle between April and August and underestimate it in the first and the last three months of the year. The fourth model (M4) provides optimum angles which are in a very good correlation with M2 and M3 values only for the months between May and August, while underestimating it in the remaining months.

4. Experimental Evaluation of the Energy Output of a PV Panel when Using Different Optimum Tilt Angles

While different optimum tilt angles were determined in the previous section of the paper, it is important to evaluate if changing the tilt angle of a PV panel along the year will actually lead to a significant increase in terms of the power output of the panel. In this sense an experimental evaluation was further conducted by adjusting the PV panel's tilt angle according to the optimum monthly, seasonal, biannual and yearly values.

The experimental analysis was conducted on a small-scale photovoltaic model from the INDISREG Laboratory (Availability of Energy Systems Supplied from Renewable Sources) from the ENERED research platform of the "Gheorghe Asachi" Technical University of Iasi. The presented PV model is composed of a 10 W PV panel along with a 500 W halogen lamp which emulates the sun.

The 10 W PV panel has a 26 V open voltage and a 650 mA short-circuit current, while the halogen lamp intensity can be adjusted in four steps. The main features of the model are related to the possibility of adjusting the elevation and azimuth angles along with the PV panel angle with a 10° or 15° fixed step, between + 90°,...,– 90°.

Table 3
Real and model approximated values of the optimum tilt angle

Monthly	β_r [°]	β_m [°]	Seasonal	β_r [°]	β_m [°]
January	68.07	70	Spring	39	40
February	60.10	60	Summer	28	30
March	49.57	50	Autumn	56	60
April	37.74	40	Winter	66	70
May	28.36	30	Biannual	β_r [°]	β_m [°]
June	24.06	20	Summer	34	30
July	25.97	30	Winter	61	60
August	33.70	30	Yearly	β_r [°]	β_m [°]
September	44.93	40	Annual	47	50
October	56.75	60			
November	66.06	70			
December	70.20	70			

For evaluating the opportunity of adjusting the tilt angle of a PV panel several times per year only the tilt angles determined according to first model

(M1) were considered. Due to the adjusting limitations imposed by the PV panel model the calculated values of tilt angle, β_r, were approximated to the closest values which can be set on the model, β_m, as presented in Table 3.

Similar approximations were necessary for the solar elevation and azimuth angle as well, the real and the specific model values being presented in Table 4.

Table 4
Real and Specific Model Values of the Monthly Solar Elevation and Azimuth Angle

Month	Elevation angle [º]		Azimuth angle [º]	
	Real	*Model*	*Real*	*Model*
January	21.79	20	175.06	0
February	29.65	30	173.23	0
March	40.26	40	173.79	0
April	49.46	50	152.91	0
May	58.61	60	149.00	0
June	62.25	60	144.15	0
July	59.89	60	143.11	0
August	52.96	50	149.37	0
September	42.96	40	157.85	0
October	31.96	30	164.04	0
November	23.93	20	178.58	0
December	19.80	20	179.22	0

After setting up the halogen lamp of the model according to the angles presented in Table 4, the tilt angle of the PV panel was modified considering the values presented in Table 3, while monitoring the PV panel's current intensity, voltage and power as well. The measured values of the electrical parameters are presented in Tables 5,...,7, where M, S, B, Y stand for the type of the tilt angle:

Table 5
PV Panel's Current Intensity when Using Different Tilt Angles

Month	I [mA]			
	M	S	B	Y
January	180	180	160	150
February	190	170	190	180
March	190	160	160	190
April	180	180	160	170
May	190	180	190	140
June	190	190	190	120
July	190	190	190	140
August	180	180	180	170
September	180	170	170	180
October	190	190	190	160
November	180	180	180	150
December	180	180	180	150
Average	185.00	179.17	178.33	158.33

monthly – M, seasonal – S, biannual – B and yearly – Y. For each set up the panel's time of exposure was of three minutes, with other two, or three minutes break between measurements. The halogen lamp was used at the rated power and the PV panel's load was only the internal resistance of the digital multimeter used.

Table 6
PV Panel's Operating Voltage when Using Different Tilt Angles

Month	U [V]			
	M	S	B	Y
January	2.25	2.25	2.25	2.10
February	2.15	2.15	2.15	2.12
March	2.24	2.22	2.04	2.24
April	2.00	2.00	1.99	2.04
May	1.97	1.98	1.97	2.01
June	1.96	1.97	1.97	2.01
July	1.97	1.97	1.97	2.01
August	1.99	1.99	1.95	2.03
September	2.02	1.99	1.99	2.00
October	2.15	2.15	2.15	2.12
November	2.25	2.25	2.06	2.10
December	2.25	2.25	2.06	2.10
Average	2.10	2.10	2.05	2.07

Table 7
PV Panel's Output Power when Using Different Tilt Angles

Month	P [mW]			
	M	S	B	Y
January	405	405	360	315
February	408.5	365.5	408.5	381.6
March	425.6	355.2	326.4	425.6
April	360	360	318.4	346.8
May	374.3	356.4	374.3	281.4
June	372.4	374.3	374.3	241.2
July	374.3	374.3	374.3	281.4
August	358.2	358.2	351	345.1
September	363.6	338.3	338.3	360
October	408.5	408.5	408.5	339.2
November	405	405	370.8	315
December	405	405	370.8	315
Average	388.37	375.48	364.63	328.94

The graphic representation of the current intensity variation along the entire year is presented on Fig. 2.

From Table 5 and Fig. 2 one can notice that the current intensity maximum values are recorded when monthly, seasonal or biannual optimum tilt angles were used.

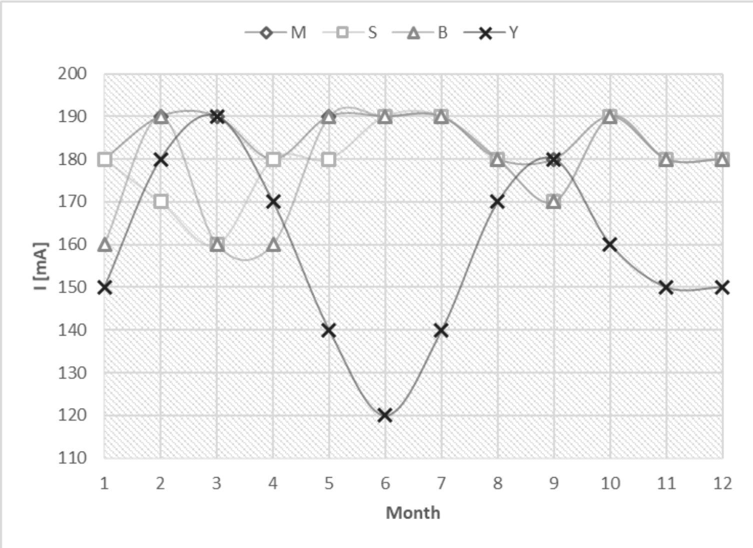

Fig. 2 – PV current intensity variation along the year.

The PV panel’s operating voltage variation across the year is represented in Fig. 3. From this representation it can be noticed that between April and September when using monthly, seasonal and biannual tilt angles smaller values of the operating voltage were recorded. This is explainable as in these months the current intensity was higher than that associated with the annual tilt angle, as can be seen also in Table 5, fact which led to a higher operating temperature of the PV panel and thus to a decrease of the operating voltage.

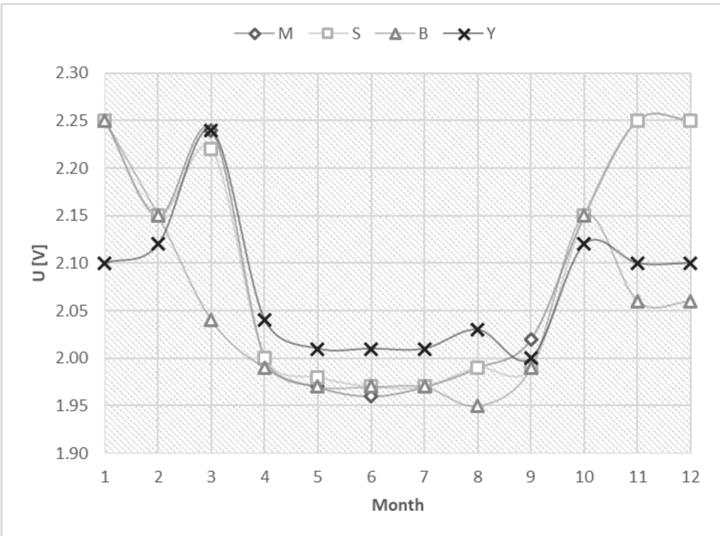

Fig. 3 – PV operating voltage variation along the year.

Regarding the PV panel's power output, from Table 7 it can be noticed that the monthly, seasonal and biannual optimum tilt angles will provide higher values most of the time across the year.

An overview of the gains, in terms of current intensity and output power, when using monthly, seasonal and biannual optimal tilt angles instead of a single yearly angle is presented in Table 8.

Table 8

Current Intensity and Output Power Increase when Using Different Optimum Tilt Angles for the PV Panel

Parameter	Current			
	M	S	B	Y
I_m , [mA]	185	179.17	178.33	158.33
ΔI, [mA]	26.67	20.83	20.00	–
ΔI, [%]	16.84	13.16	12.63	–
Parameter	Power			
	M	S	B	Y
P_m , [mW]	388.37	375.48	364.63	328.94
ΔP, [mW]	59.43	46.53	35.69	–
ΔP, [%]	18.07	14.15	10.85	–

When analyzing the values presented in Table 8 it becomes obvious that adjusting the tilt angle of the PV panel to optimum monthly values represent the best solution as an average of 18.07% increase of the output power is recorded over the case when a single yearly angle is utilized. If adjusting the tilt angle every month may seem difficult one should notice that even a biannual optimum angle set up could provide a 10.85% increase of the average output power, while seasonally adjustments will lead to an average 14.15% increase.

Considering the data from Table 8 the relative power gains were calculated for each month and represented in Fig. 4. Thus, it is obvious that using different optimum tilt angles a significant increase in output power is

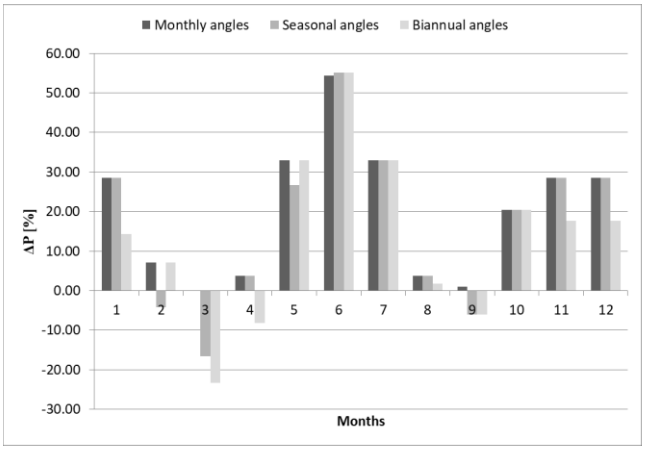

Fig. 4 – Output power percental gains depending on the optimum tilt angle type.

obtained in January, May, June, July, October, November and December, while in the other months the yearly optimum angle ensures similar performances, or even better for March and September. The biggest increase was obtained in June, when the PV panel's output power was 50% higher than when using the yearly optimum tilt angle.

5. Conclusions

The power output of PV panels was investigated while adjusting panels tilt angle several times across the year. Experiments were conducted on a laboratory scale PV panel model within the INDISREG Laboratory of the "Gheorghe Asachi" Technical University of Iasi, Romania.

Considering the monthly, seasonally, biannual and yearly optimum tilt angle for the geographic coordinates of the city of Iasi, Romania, and setting up the model's lamp according to the sun's elevation and azimuth angle the PV panel's current, voltage and output power were measured for each month of the year.

A significant increase, of 18.07%, in terms of annual average output power was recorded, when setting the PV panel on the monthly optimum tilt angle instead of using a yearly tilt angle. Seasonal or biannual adjustment of the tilt angle also provides noticeable gains in terms of output power, of 14.15% and 10.85% respectively. When analyzing the output power for every month it is obvious that adjusting the tilt angle on each month or seasonally will lead to an over 20% increase in 7 months across the year, the most significant being of over 50% in June.

While these results are definitely encouraging, they must be taken with precautions as they were obtained on a low scale PV model, in a laboratory environment, were the distance between the halogen lamp and PV panel is very small and the ambient temperature was constant.

Further experimental evaluations are requested when considering real size PV panels used in real conditions in order to fully assess the advantages of modifying the tilt angle more than once per year. In this way the influence of air temperature and wind speed can also be considered and thus more rigorous conclusions can be established.

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CONSIDERAŢII ASUPRA OPORTUNITĂŢII UTILIZĂRII UNOR UNGHIURI DE ÎNCLINARE OPTIME PENTRU PANOURILE FOTOVOLTAICE FIXE, ÎN IAŞI, ROMÂNIA

(Rezumat)

În prezent conversia fotovoltaică a energiei solare este condiţionată de randamentul de conversie relativ mic, uşor peste 20%, al panourilor fotovoltaice, motiv pentru care se caută permanent soluţii de creştere a producţiei de energie electrică a sistemelor fotovoltaice. În acest context, lucrarea de faţă abordează una din posibilele soluţii ce pot fi implementate pentru creşterea producţiei de energie electrică a sistemelor fotovoltaice şi anume ajustarea periodică a unghiului de înclinare al panourilor fotovoltaice fixe, în funcţie de valorile optime determinate pentru fiecare lună a anului, pentru fiecare anotimp, respectiv bianuale. Astfel, considerând diverse modele matematice din literatura de specialitate au fost determinate valori optime lunare, sezoniere, respectiv bianuale, ale unghiului de înclinare. Utilizând aceste valori optime ale unghiului de înclinare au fost efectuate apoi o serie de determinări experimentale pe un stand fotovoltaic din cadrul platformei de cercetare ENERED a Universităţii Tehnice „Gheorghe Asachi" din Iaşi. Rezultatele înregistrate arată o creştere semnificativă a puterii generate de panou în condiţiile ajustării lunare a unghiului de înclinare a acestuia, creşteri notabile, de peste 10%, fiind semnalate chiar şi în cazul ajustării numai de două ori pe an a unghiului de înclinare, comparativ cu valorile obţinute prin utilizarea unui unghi de înclinare optim anual.