Analysing productivity in Photovoltaic systems under different atmospheric conditions

Tiago D.L. Soares

Mestrado Integrado em Engenharia Física Tecnológica
Instituto Superior Técnico, Lisboa, Portugal

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Abstract

The analysis of photovoltaic systems considering different atmospheric conditions was the purpose of this study. Actual production data from different photovoltaic technologies was studied as well as meteorological data received from the experience of SunLab, own by *EDP*, in four different geographic locations in continental Portugal. The data was collected between August 2012 to February 2013. Concerning the procedure, in a first phase the data was validated, and experimental errors were identified. The real power was compared with the modelled power from the application of the electric 3-parameter model and the difference between those was analysed. Analyses were conducted varying the power at intervals of irradiance and temperature, taking into account different photovoltaic technologies and geographic locations. The comparison of photovoltaic technologies was accomplished through calculus and representation of the evolution of the coefficient of performance for each geographic location. Afterwards, statistical analyses were performed by multiple linear regression for power and coefficient of performance with respect to different photovoltaic technologies. In the case of the coefficient of performance it was necessary to resort to techniques of variable transformation so that the assumptions demanded by the multiple linear regression would be fulfilled. The linear regression analyses allowed the identification of which atmospheric variables considered significant when explaining the variability of the variables listed. One concludes that the irradiance explains the totality of power variability independently from the technology in study. Thermal amplitude, atmospheric pressure, and irradiance were all considered significant predictors and responsible for the more elevated marginal effect in the study of performance ratio.
Keywords: photovoltaic, solar energy, solar radiation, power, performance ratio.

1. Introduction

There is an increased need for analysing the effect of atmospheric variables on photovoltaic (PV) production and performance. The outputs from the different PV cells in different atmospheric conditions, such as humidity and wind velocity, differ from each other evidencing knowledge deficiency in PV systems [6]. The possibility of studying the performance of different types of modules within real conditions allows an assessment of future installation of appropriate and adequate technology to the existing conditions, ensuring a better energetic efficiency [1]. The following article is based on the analysis of atmospheric variables in real conditions, taking into account data collected from meteorological stations in distinct places in continental Portugal. Portugal belongs to the group of European countries with highest availability of solar irradiation. The variation of irradiation is $[1450; 1850] KWhm^{-2}$ and its distribution geographical throughout the country is shown in Figure 1. The analysed data was received from SunLab which is an *EDP*(Portuguese electricity company) project. SunLab has its activity based on confronting the different PV technologies. Its method is one of exploration, studying the several technologies in real outdoor conditions. That is because there is the acknowledgement that performance of PV modules varies according to atmospheric and environmental conditions.

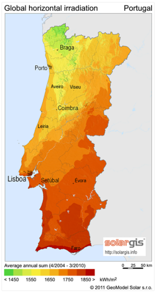

Figure 1: Irradiation distribution in Portugal [17].

2. Theoretical Background

A description of the different existing photovoltaic (PV) cell technologies will be presented as it is needed for better understanding the present matter of study. The latter is followed by a review on the influences of atmospheric variables on the PV production.

2.1. Photovoltaic cell technologies

There are two main types of PV cells, crystalline silicon based cells and thin films. Silicon cells have the biggest distribution on the global market, representing a share of 85%. The remaining 15% represent the share of thin films [5]. In outdoor conditions, currently produced Si-pc (Si) PV cells, present efficiency values between 18% to 24% [13]. Also, this technology presents a higher spectral response than that of thin films, showing values between $380nm$ and $1050\,nm$ [15].
In outdoor conditions CdTe thin film technology has efficiency levels among 10% and $12,4\%$ [13]. Regarding spectral response, this technology shows values between $500\,nm$ and $840nm$.

2.2. Influence of atmospheric conditions

Irradiance is considered to be the most influential variable in PV output. The influence of the IV curve is based on the following equations [2] [8]:

$$I_{sc} = I_{sc,ref}\frac{G_i}{G_{i,ref}}(1+\alpha\,(T_c - T_{c,ref})), \quad (1)$$

$$V_{oc} = V_{oc,ref}(1+\beta\,(T_c - T_{c,ref})) + \ln\,(\frac{G_i}{G_{i,ref}})V_T, \quad (2)$$

$$P_{mp} = P_{mp,ref}\frac{G_i}{G_{i,ref}}(1+\gamma\,(T_c - T_{c,ref})). \quad (3)$$

The short-circuit current I_{sc} and the maximum power P_{mp} both increase linearly with the incident irradiation. On the other hand, the open circuit tension V_{oc} increases logarithmically with the incident irradiation. These equations make use of the parameters of reference, given by the manufacturer datasheet, measured on Standard Test Conditions (STC).
Temperature is considered to be the second most influential variable in produced PV energy. With the environmental temperature it is possible to estimate the cell temperature in in Normal Operation Cell Temperature (NOCT) conditions. Established that value, it is then possible to use it in the previous equations (Equation 1, Equation 2 and Equation 3) [2].
Overcast weather reduces the direct irradiance that reaches earth surface, while diffuse irradiance suffers a positive variation. Therefore, the availability of radiation for PV conversion approaches the blue light spectrum mainly because of the *Rayleigh* scattering [6].
Having present the convection heat transfer factor, it is expected that wind could retrieve heat from PV cell module surface [12]. It is also to be taken into account that higher wind velocities induce an increase in the accumulation of dust on the surface of the PV modules which consequences will be further described later.
When exposed to humidity, the PV cells performance is decreased since it damages the PV cell itself. Not only air humidity has effects on the physical structure of the PV cell, but also has a direct effect on the levels of irradiance that reach the PV module. This irradiance may then be diminished by being reflected, refracted or diffracted [12].
As mentioned earlier, dust has also its share of impact on PV production. Dust deposition provokes significant changes on short-circuit current [7] [9].

Table 1: Variables collected by Sunlab.

Time settings	Variable
Minute-to-minute	Temperature T $[°C]$
	Global Irradiance G_t $[Wm^{-2}]$
	Direct Irradiance Gb $[Wm^{-2}]$
	Diffuse Irradiance Gd $[Wm^{-2}]$
	Wind velocity V $[ms^{-1}]$
Daily	Mean Temperature $Tmed$ $[°C]$
	Direct Irradiance Gb $[Wm^{-2}]$
	Diffuse Irradiance Gd $[Wm^{-2}]$
	Mean Wind Velocity V $[ms^{-1}]$
	Thermal Amplitude dT $[°C]$
	Mean Relative Humidity $Hmed$ [%]
	Relative Humidity Amplitude dH [%]
	Mean Atmospheric Pressure $PAmed$ $[hPa]$
	Atmospheric Pressure Amplitude $dPAmed$ $[hPa]$

3. Methods

The output variables studied in this article are the PV power and the PV performance ratio PR both from different PV cell technologies: Si and CdTe. The first variable is given in the collected data and the second is calculated based on the collected variables and module datasheet reference values. The PR calculated is expectable to be higher than the common literature reference values [16] since these have into account losses in the conversion of current and the designed experiment by SunLab does not. The analyses were all performed with data from modules in the horizontal position.

Both the atmospheric and the PV production data were collected according to two distinct temporal settings. The variables with minute-to-minute reference and those with daily reference are organized on the Table 1. The data was collected between August 2012 to February 2013.

Primarily were analysed minute-to-minute referenced variables. In this case, it was investigated the influence of irradiance and temperature in PV production. The collected data was also applied to the three parameter model already largely studied [2] [4]. The main objective is to compare the real DC power and the modulated power by the referred model. At this stage, MATLAB was used to run the three electrical parameter model [11].

In order to identify the influence of the atmospheric variables, beyond irradiance and temperature, on the PV production, statistical methods were used. Therefore, multiple linear regression studies were performed with the daily collected data. At this stage, SPSS was used to run the regression studies [18].

4. Results and Discussion

4.1. Minute-to-minute collected data

Aiming at the control of the effect of the temperature in the PV power, the temperature was divided in intervals of $2°C$ each. Subsequent graphic representation of power as a function of irradiance was performed (Figure 2). With irradiance also divided in $5W/m^2$, it is shown in Figure 3 the influence of the temperature on PV power. The intervals were chosen to point out the individual effects of each of the variables.

In all the studied locations and PV technologies, the pattern of PV power was the same as shown in Figures 2 and 3. It is evident the effect of irradiance in both cases. In Figure 2 the PV data points form approximately coincident line patterns. In Figure 3 one can see that PV data points form clearly spaced and defined lines correspondent to each irradiance interval. Temperature, on the contrary, shows a slight tendency for decreasing PV power and only for values above the $20°C$.

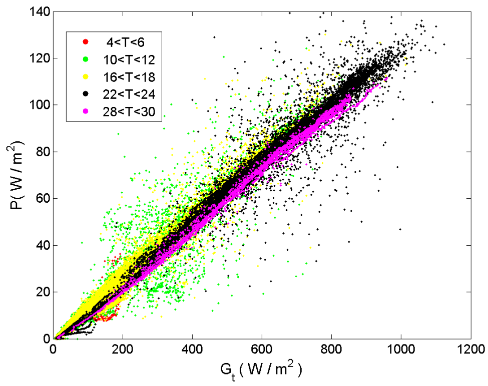

Figure 2: PV power Vs Global irradiance.

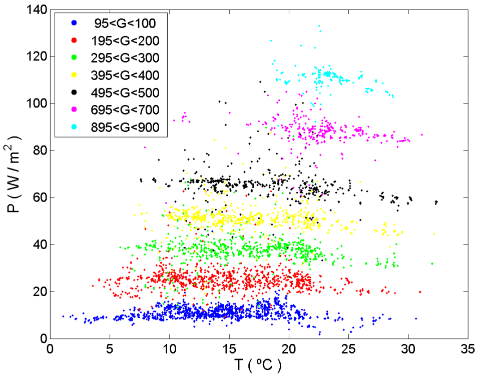

Figure 3: PV power Vs Temperature.

In order to compare both technologies, graphic representations of PR were performed (examples Figure 4 and 5. Given the bigger variability of irradiance, intervals were defined so that the graphic visualization would be perceptible.

It was observed that for all range of irradiance and temperature, CdTe was better in only one location (Figure 5). Trying to understand this odd result, diffuse irradiation distribution was studied in all four locations. The obtained pattern of this distribution was very similar in all cases, without any significant variance capable of explaining the distinct behaviour of PR. As a result, with the minute-to-minute data collected by SunLab, it was not possible to identify the reason for this distinct PR pattern just in one location.

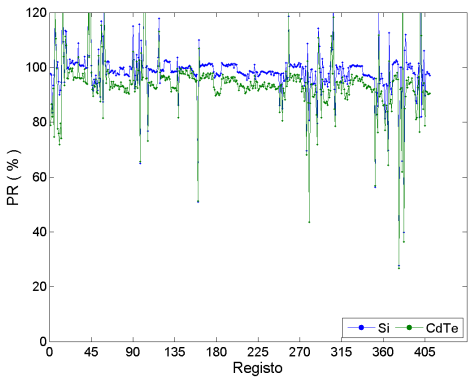

Figure 4: Propitious to Si technology.

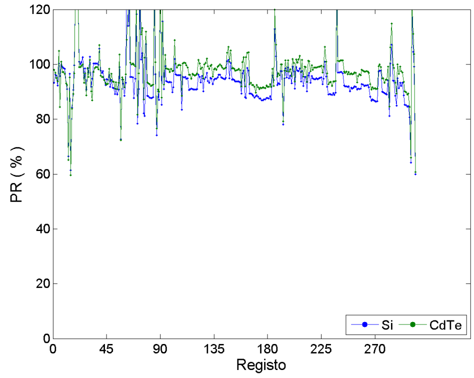

Figure 5: Propitious to CdTe technology.

The model of three parameters is validated solely for the Si technology, for in this analysis it is only considered the production data from the SunLab Si technology [2] [4].The irradiance and temperature data was introduced in the model with hourly frequency, having been used the data from SunLab and from all the geographical localizations simultaneously (Figure 6).

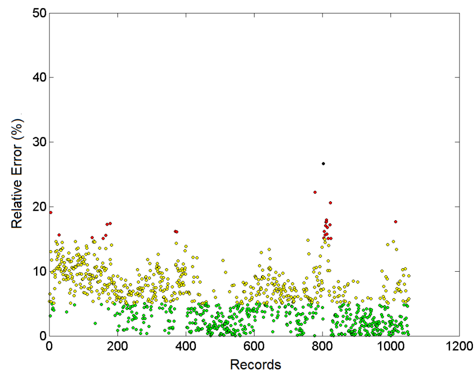

Figure 6: Difference between modelled and real PV power for irradiance in $[350; 500]\,W/m^2$.

The average value of the difference between real and modelled power of total distribution lies arount 14%. However, the amplitude of that difference presented a decreasing tendency for superior irradiances. In the interval characterized for higher irradiance indices $[650; 850] W/m^2$, the difference between the two powers did not exceed 10%, and presented an average value of 7%. The amplitude and variability are both superior for irradiances inferior to $100\,W/m^2$. It is also included for this irradiance interval the records correspondent to the status transition periods OFF/ON/OFF of the PV module (66% of the records in this interval were collected before 8 a.m. and after 5 p.m.). In the case of modelled power such factor is not contemplated, justifying the bigger discrepancy in the results.

4.2. Daily collected data

The purpose of the present case studies is modeling the variability of Pmed and PR of PV modules and the total variability of atmospheric variables, through multiple linear regression (MLR) methods. The explanatory predictors correspond to the SunLab daily measured atmospheric variables (Table 1). The method was applied to both Si and CdTe technologies.

After a *Pearson* correlation analysis were defined the eligible predictors to include in the regression model. For the Pmed dependent variable, the set of predictors were the same for both technologies. The predictors were then the following: *Gbmed*, *Gdmed*, $Tmed$, dT, $Hmed$, and dH. The sample size was higher than 600 records for both technologies. Also for both technologies, the output of the model fulfilled all the assumptions associated with the regression model.

The results obtained for both technologies are exposed in the Tables 2 and 3.

The values of the F-test of the regression for the two technologies highlighted the chosen set of predictors as globally significative in explaining the variability of the dependent variable.

For the Si technology the $Tmed$ predictor was excluded for significance levels of 5%. Qualitatively, the R-square value indicates that more than 99% of the verified variance in the dependent variable Pmed, was explained by the variance of the predictors included in the model. As expected, the variables *Gbmed* and *Gdmed* presented as being variables with bigger regression coefficients in both standardized and non-standardized regression coefficients. In order to identify the influence of individual variables, it was performed a hierarchical regression with the same set of predictors [10]. The results showed that the irradiance (Gbmed and Gdmed) effect explains almost the 99% of the variability in Pmed. The remaining predictors only improve the results in 0.1%. That happened for both CdTe and Si technologies.

The preliminary analyses indicate that the RLM assessments for PR did not satisfy the required regression normality assumptions. In this case it is needed to resort to variable transformation for those assumptions to be attained [10] [3]. Therefore, the Cox-Box model was used for screening the transformation to be used in the dependent PR variable [14]. After variable transformation, the assumptions were satisfied being now possible to infer about the results of the LRM for $PR(\lambda)$ (λ being the transformation parameter). The Pearson correlation test indicated for CdTe technology the following predictors *Gbmed*, *Gdmed*, dT, dH, $PAmed$. For Si technology, the included predictors were *Gbmed*, *Gdmed*, dH, and $Hmed$. The Tables 4 and 5 contain the MLR results for both technologies.

The values of the F-test of the regression for the two technologies highlighted the chosen set of predictors as globally significative in explaining the variability of the dependent variable.

Qualitatively, the MLR for the CdTe technology indicates that 55,8% of variance verified in the $PR(\lambda)$ dependent variable is explained by the variance of the predictors included in the model. On the other hand, the coefficient of determination for the Si technology was 12,2%.

The predictors dT and dH are excluded from set of significant predictors of $PR(\lambda)$, CdTe technology, for significance levels of 5%. In the same manner for Si technology is excluded the predictor $Hmed$.

For the CdTe technology, $PAmed$ is the responsible predictor for the biggest marginal effect. For the Si technology, the biggest marginal effect is contained by the dT variable.

Table 2: RLM results for Pmed CdTe technology.

	R^2	R_a^2	B	$DP(B)$	β	t
Modelo	0,992***	0,992***				
Constante			-7,196	0,719		-10,012
Gbmed			0,101	0,001	1,036***	161,380
Gdmed			0,108	0,001	0,383***	88,634
$Tmed$			0,073	0,013	0,024***	5,723
dT			0,041	0,021	0,012*	2,007
$Hmed$			0,045	0,007	0,033***	6,092
dH			0,029	0,007	0,028***	4,114

Statistical Significance: $^*p < 0,05$, $^{**}p < 0,01$, $^{***}p < 0,001$

Table 3: RLM results for *Pmed* Si technology.

	R^2	R^2_a	B	$DP(B)$	β	t
Modelo	0,994***	0,994***				
Constante			-1,766	0,713		-2,479
Gbmed			0,122	0,001	1,055***	193,580
Gdmed			0,129	0,001	0,365***	102,435
Tmed			-0,005	0,012	-0,001	-0,425
dT			-0,153	0,020	-0,039***	-7,579
Hmed			0,020	0,007	0,023***	2,674
dH			0,031	0,007	0,026***	4,409

Statistical Significance: $^{*}p < 0,05$, $^{**}p < 0,01$, $^{***}p < 0.001$

Table 4: RLM results for $PR(\lambda)$ CdTe technology.

	R^2	R^2_a	B	$DP(B)$	β	t
Modelo	0,558***	0,555***				
Constante			21244217	1095755		19,388
Gbmed			3114	235	0,570***	13,258
Gdmed			7339	500	0,448***	14,676
dT			-15919	8920	-0,080	-1,785
dH			-5280	2885	-0,089	-1,830
PAmed			-19453	1060	-0,550***	-18,368

Statistical Significance: $^{*}p < 0,05$, $^{**}p < 0,01$, $^{***}p < 0,001$

Table 5: RLM results for $PR(\lambda)$ Si technology.

	R^2	R^2_a	B	$DP(B)$	β	t
Modelo	0,122***	0,116***				
Constante			29922	2256		13,265
Gbmed			-4	2	-0,125*	-1,983
Gdmed			23	4	0,213***	5,250
dT			-197	59	-0,165**	-3,357
Hmed			-27	24	-0,059	-1,098

Statistical Significance: $^{*}p < 0,05$, $^{**}p < 0,01$, $^{***}p < 0,001$

5. Conclusions and Future Work

The obtained results throughout the work allowed the confrontation of the two analysed technologies taking into account the output PV power and the performance ratio. From the set of atmospheric variables, it was confirmed the preponderance of the effect of irradiance in PV production. When controling the effects of temperature and irradiance it was verified that PV power variation is proportional to the incident irradiation. On the other hand, on the same analysis the effect of the temperature was not concluded as relevant.

The modelling of the output power of the Si technology presented an average difference around 14% when compared with the real power. The removal of the records corresponding to the transitions OFF/ON/OFF of the PV modules reduced that difference to levels inferior than 10%. It was then established that the modeling of PV power, only considering the irradiance and temperature variables, conduct to reasonable results, especially when irradiance values are superior than 500 W/m^2.

Regarding the statistical analyses of *Pmed*, the values of the F-test indicated the statistical significance of the MLR for both technologies. Also for the technologies in question were verified the coefficient of determination higher than 99%. Again, the effect of irradiance (*Gbmed* and *Gdmed*) was overlapped the other atmospheric variables, presenting the biggest regression coefficient. In conclusion the results of hierarchical regression showed that global irradiance compound by *Gbmed* and *Gdmed* explains itself the variability of the Pmed in both technologies studied.

In the case of PR, the observed coefficients of determination were characterized by substantially inferior values when compared to the analysis with Pmed: 55,8% for CdTe technology and 12,2% for Si.

There were a few limitations found during this investigation. The non-existing PV cell real temperature records made it impossible to study of its influence on PV production. An analysis based on a bigger temporal record would improve the statistical analysis and establishment of atmospheric patterns could be made.

As for future work, it is suggested the use of non-linear models for PR variability studies, using as a starting point the results of RLM that were presented.

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