INFLUENCE OF INSOLATION & MODULE TEMPERATURE ON THE PERFORMANCE OF FIRST & SECOND GENERATION TYPE PV CELL MODULES

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***Abstract*—Solar cells can be classified into first, second and third generation cells. This classification is made on the basis of the type of material, the type of cell structure and the technology used for fabrication. The first generation cells are made of crystalline silicon and associated forms. Second generation cells are thin film solar cells, that include amorphous silicon, CdTe and CIGS cells The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics, and most of them are still in the research or development phase.**

In this paper we examine the relative performance of Photovoltaic (PV) cells of the first and second generation category. The performance is estimated for the changes in maximum power output when the insolation and temperature varies.

Linear regression models are developed to aid the analysis and obtain the desired conclusions.

***Keywords— Performance of PV cells, First and second generation cells, Regression analysis modeling, Insolation and temperature variations*.**

I. INTRODUCTION

The Solar Photovoltaic (PV) cell is a promising and potentially important technology for providing sustainable energy for the human civilization. Ever since the Becquerel discovered the first photovoltaic effect in 1839, the research in solar energy has been a key goal in the scientific world. PV technology offers a number of significant benefits. Solar power is a renewable resource that is available globally.

Solar PV technologies are highly modular and can be used virtually anywhere, unlike many other electricity generation technologies demanding space. Further, unlike conventional power plants using coal, nuclear, oil and gas, solar PV has no fuel costs and relatively low operation and maintenance costs. Thus, PV will continue to be a favored technology of electric power indefinitely and as long as solar energy is available. Photovoltaics is thus a sustainable and environmentally friendly technology for producing electrical energy. [1]

A First generation PV Cell Technologies

Bell Laboratories developed the first silicon solar cell in 1954 with an efficiency of 6%. The earliest commercial silicon traditional solar cells are made from silicon, are currently the most efficient solar cells available for residential use and account for around above 80 % of all the solar panels sold. First generation silicon solar cells are made from a single silicon crystal (mono-crystalline), or cut from a block of silicon that is made up of many crystals.

Crystalline silicon cells are classified into three main types depending on how the Si wafers are obtained. The main types are:

(a) Monocrystalline (Mono c-Si);
(b) Polycrystalline (Poly c-Si); and
(c)Amorphous Silicon Cells.

Monocrystalline PV cells are the best as compared to the other types of Solar PV cells. They have a higher efficiency up to 26%. Polycrystalline silicon and amorphous silicon are less pure than the single crystalline silicon, and are therefore more common because of their low cost. The highest recorded efficiency for polycrystalline silicon cell is 21%. [2]

B Second Generation PV Cell Technologies

Second-generation solar cells are also known as *thin-film solar cells* because as compared with crystalline silicon based cells they involve layers only a few micrometers thick.Second generation are thus basically thin-film type of solar cells. These are less expensive to produce than traditional silicon solar cells since they require a lesser amount of material for fabrication.

They are only slightly less efficient than other types but do require more surface area to generate the same amount of power [3]. After more than 20 years of R&D, thin-film solar cells are now being deployed in significant quantities for various commercial applications. Thin-film solar cells could potentially provide lower cost electricity than c-Si wafer-based First generation solar cells.

Second generation solar cells account for around 20 % of the total panels sold in past years.

There are basically three primary types of *thin film solar cells* that have been commercially developed:

(a) Amorphous silicon (a-Si and a-Si/µc-Si)
(b) Cadmium Telluride (Cd-Te)
(c) Copper-Indium-Selenide (CIS) and
(d) Copper-Indium-Gallium-Selenide (CIGS).

One major advantage of using very thin layers of silicon is that the panels can be made flexible.

CIGS cells have the highest efficiencies of thin film cells at 21.6%; CdTe cells have an efficiency of 21.4%, and amorphous silicon type has an efficiency of 11.8%.[1]

Although these thin film solar cells have a lower costs and good efficiencies, they suffer from the following drawbacks:

(1) Most of the material used are either becoming increasingly rare or more expensive (indium)
(2) Some materials (cadmium) are highly toxic

In fact, Cadmium telluride is highly toxic if ingested, if its dust is inhaled, or if it is handled improperly (i.e. without appropriate gloves and other safety measures)[4].However, with appropriate processing and recycling procedures for used cells, the environmental risks are greatly minimized [5]

C Third Generation PV Cell Technologies

Due to high costs of first generation solar cells and toxicity and limited availability of materials for second generation solar cells, a new generation of solar cells has emerged. Currently considerable research is being carried out in what is being referred to in the in the photovoltaic industry as *Third-generation solar cells. Third generation solar cells* are inherently different from the previous two generations in the sense that they do not rely on the p-n junction design. This new generation of solar cells is made from a variety of new materials besides silicon, including nano-materials, silicon wires, solar inks, organic dyes, and conductive plastics. The goal is to improve on the already available commercial solar cells in terms of better efficiencies, lower costs and lesser toxicity of environment, and development of greater diversity in applications.

Prominent among the third generation PV cell technologies are those relating to:

(a) Dye-sensitized solar cells (DSSC)
(b) Organic/Polymer cells

Among various solar cells, DSSCs possess specific advantages over other photovoltaic devices, because of their high efficiency, low cost, simple fabrication procedures, environmental friendliness, transparency, and good plasticity. Though DSSCs perform well under laboratory conditions relative to other solar cells, parameters such as efficiency, lifetime, and cost determine their viability for commercial applications. An overall solar conversion efficiency of more than 12% has been achieved by employing liquid electrolytes in DSSCs. However, the use of liquid electrolytes causes many problems in DSSCs such as:

(a) Short-term stability due to organic solvent evaporation and leakage
(b) Difficulty in sealing the device
(c) Electrode corrosion and
(d) Limited solubility of inorganic salts such as KI, NaI, and LiI

Organic or polymer solar cells were developed to make a more flexible solar cell. Organic or polymer cells are named as such because the active layers of the cell are completely made of organic materials. These cells can either have a bilayer structure or a bulk-heterojunction structure, but the mechanism of both designs is essentially the same. Their popularity in recent years has been due to many significant improvements that have led to higher efficiencies which are now in the range 8% to 10% for commercial systems. Organic cell production uses high-speed and low- temperature roll-to-roll manufacturing processes and standard printing technologies. As a result, organic solar cells production is far cheaper than other PV cell types in terms of manufacturing technologies costs. Hence, organic cells may be able to compete with other PV technologies.

In addition to the mentioned third-generation technologies, there are a number of novel solar cell technologies under development that rely on using quantum dots/wires, quantum wells, or super lattice technologies. These technologies are likely to be used in concentrating PV technologies where they could achieve very high efficiencies by overcoming the thermodynamic limitations of conventional (crystalline) cells. However, much of this work is still in the research stages.

D The Research Issue

It is clearly seen from the previous discussion that the PV cells that are widely in use are those belonging to the *First and Second generations*. Those of the *Third generation* are still at the research stage. It was proposed to examine the *relative* performance of PV cells belonging to the first two classes of generations. The present paper is an attempt to carry out the proposed investigation and draw relevant conclusions.

II. METHODOLOGY

A. Linear Regression as an Analytical Tool

One of the convenient ways to model PV performance is by the use of Linear Regression models. This is a statistical approach that obtains the best coefficients required to model the system with a minimum cumulative least square error. The accuracy obtainable for the prediction will depend on the value of the parameter R^2. This value lies between 0 and 1, and the nearer is this value to 1, the better is the predicted accuracy of the regression model designed for the PV module. In the literature, some researchers have tried to apply linear regression to model PV systems. Some of these studies are reported in [6-10].

Linear Regression is mathematically a tool for modeling the relationship between a scalar dependent variable *y* and one or more explanatory variables (or independent variables) denoted *X* in a linear frame. If one explanatory variable is involved the regression is termed as *simple linear regression*. For more than one explanatory variable, the process is called *multiple linear regression*. A multiple regression model is given by the general expression:

$$y_i = \beta_0 + \beta_1 x_{i1} + \cdots + \beta_p x_{ip} + \varepsilon_i = \mathbf{x}_i^{\top} \beta + \varepsilon_i, \qquad i = 1, \ldots, n,$$

where: y_i denotes the dependent variable and x_{in}th independent variables. ε_i denotes the error term involved [11] . Often these equations are grouped and collectively represented in vector form by the expression:

$$\mathbf{y} = X\boldsymbol{\beta} + \boldsymbol{\varepsilon},$$

Where:

$$\mathbf{y} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix}$$

$$X = \begin{pmatrix} \mathbf{x}_1^\top \\ \mathbf{x}_2^\top \\ \vdots \\ \mathbf{x}_n^\top \end{pmatrix} = \begin{pmatrix} 1 & x_{11} & \cdots & x_{1p} \\ 1 & x_{21} & \cdots & x_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & \cdots & x_{np} \end{pmatrix}$$

$$\boldsymbol\beta = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_p \end{pmatrix}, \quad \boldsymbol\varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}.$$

Ordinary least squares (OLS) is the most commonly used estimator being conceptually simple and computationally straightforward. The OLS method minimizes the sum of squared residuals, and leads to a closed-form expression for the estimated value of the unknown parameter β.

$$\hat{\boldsymbol\beta} = (\mathbf{X}^\top\mathbf{X})^{-1}\mathbf{X}^\top\mathbf{y} = \left(\sum \mathbf{x}_i\mathbf{x}_i^\top\right)^{-1}\left(\sum \mathbf{x}_i y_i\right).$$

The estimator is unbiased and consistent if the errors have finite variance and are uncorrelated with the regressors, i.e.

$$\mathrm{E}[\,\mathbf{x}_i\varepsilon_i\,] = 0.$$

The degree of "fit" of the model is evaluated in terms of the R^2 statistic value that lies between 0-1. A value closer to unity indicates a good fit to the input data. When the variable in the regression equation are related in a non-linear fashion, the linearity condition of the regression can be maintained if logarithmic transformations of the variables are involved. This gives rise to use of the Log-Log models in which both the dependent variable as well as the independent variables are in the logarithmic form [12]. Such a model is expressed as:

Ln (y)= β_0+ β_1*Ln(x_1) + β_2*Ln(x_2) + β_3*Ln(x_3)+…….

B Data for Developing the Model

The study aims at developing Linear Regression models for two sets of PV cells , namely,

(a) First Generation PV cells

(b) Second Generation PV cells

In the First Generation category, we have considered the following PV cells

(a)SM55 (monocrystalline cell)

(b)MSX-60(polycrystalline)

(c)KC200GT (multicrystaline /polycrystalline photovoltaic modules)

In the Second Generation category, we have considered the following PV cells :

(a) FS-277 (Cadmium Telluride)

(b) SPV80-TF (CIS Family Thin-Film)

(c) QS60DU (a-Si:H i.e. Hydrogenated Amorphous Silicon.)

Data for developing the regression models was taken from reference [13]

The linear regression model developed for each category of PV cells is given by the general form :

$$Pmax = \beta 0 + \beta 1 * (Voc) + \beta 2 * (Isc) + \beta 3 * (insolation\ level) + \beta 4 * (Temperature)$$

Where Voc and Isc represent the open circuit voltage and short circuit current respectively. The data is used to obtain the coefficientsβ_0 to β_4 for each category model.

III. Details of the Models

A Details of Model Coefficients

The details of the model coefficients and other features of importance for the two generation categories of PV cells is indicated in Tables 1 & 2.

Table 1 Results of the Regression Model (Linear Form) for First Generation PV Cells

S.No.	Feature	Value		
1	R^2	0.9952		
2	F- Statistic	415.14		
3	Standard Error	4.951		
4	**Coefficients of Regression Terms**	**Coefficient Value**	**Standard Error**	**t-Statistic**
	β_0	-18.89	19.075	-0.9903
	β_1	1.3034	0.7814	1.667
	β_2	24.205	2.3115	10.4710
	β_3	-0.026	0.0099	-2.579
	β_4	-0.407	0.1419	-2.869

Table 2 Results of the Regression Model (Linear Form) for Second Generation PV Cells

S.No.	Feature	Value		
1	R^2	0.9358		
2	F- Statistic	29.153		
3	Standard Error	5.8737		
4	**Coefficients of Regression Terms**	**Coefficient Value**	**Standard Error**	**t-Statistic**
	β_0	-21.56	15.593	-1.3826
	β_1	0.432	0.2193	1.9699
	β_2	22.572	9.4178	2.3966
	β_3	0.0337	0.0180	1.873
	β_4	-0.273	0.1584	-1.7206

B Testing of Models

Taking a random sample of 10 sets of readings from the developed database for each model, the mean percentage error in estimation of the two regression models (First Generation PV cells model and Second Generation PV Cell model) was analyzed. Table 3 shows the results obtained.

Table 3: Comparison of Model Results

S.No	Pmax (watts) (actual)	Estimation for First Generation PV Cell Model (watts)	% absolute error	Pmax (watts) (actual	Estimation for Second Generation PV Cell Model (watts)	% absolute error
1	43.7	45.03	0.752	31.2	33.50	1.539
2	49	45.8	1.632	47.1	46.44	0.290
3	10.7	9.07	3.769	62.3	59.40	1.099
4	34.3	37.4	2.226	73.1	64.49	2.738
5	60	64.67	1.922	15.2	10.22	6.838
6	46.8	42.99	2.021	31.8	28.51	2.157
7	76.3	80.69	1.4221	48.5	46.11	1.029
8	159	151.72	1.133	64.6	63.48	0.361
9	178	174.89	0.4323	60.3	63.89	1.244
10	156	163	1.1093	11.7	14.95	5.803
		Mean % Error	**1.6419**		**Mean % Error**	**2.3099**

Figures 1 and 2 show the variation of the % absolute errors for the two models.

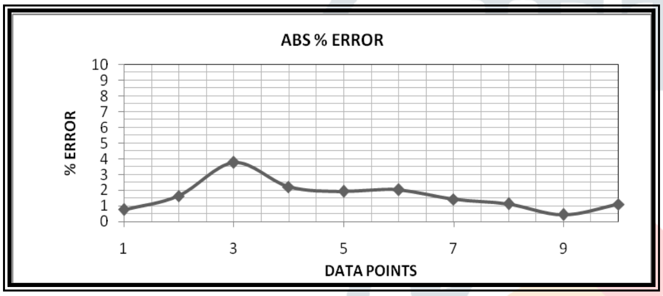

Fig 1: % Error Variation in model for First Generation PV Cell

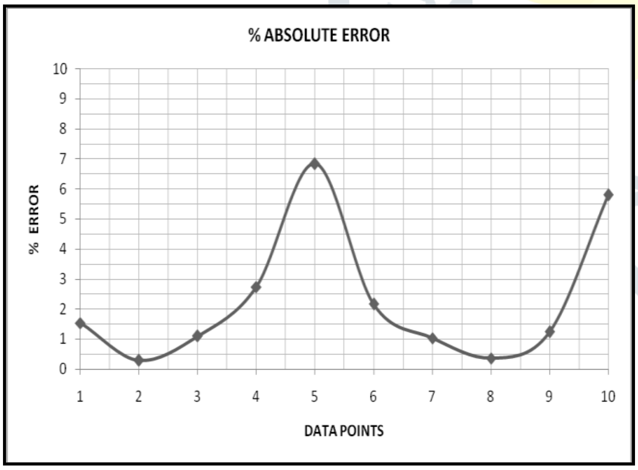

Fig2:% Error Variation in model for Second Generation PV Cell

IV. PERFORMANCE SIMULATIONS

A Simulated Results

The models show mean percentage absolute errors of 1.6419 % for the First generation PV cells and 2.3099 % for the second generation PV cells. These low values can be sufficient to validate the accuracy of the models. The models are now used to examine the effects of two variables of their performance. These variables are :

(a) Temperature of the module

(b) Insolation

Since two variables are to be investigated, we have taken standard conditions as the basis. i.e insolation of 1000 w/ m^2 and temperature of 25ºC. . For the simulations involving the max power variations with temperature, the insolation level was fixed at 1000 w/ m^2. While on the other hand, the for simulations involving the effects of insolation on power variations, the temperature was kept fixed at 25ºC. Values of Voc and Isc were taken as the mean values of the respective data for the two generation categories of PV cells

Figures 3 and 4 show the simulated performances for the two generation categories of PV cells.

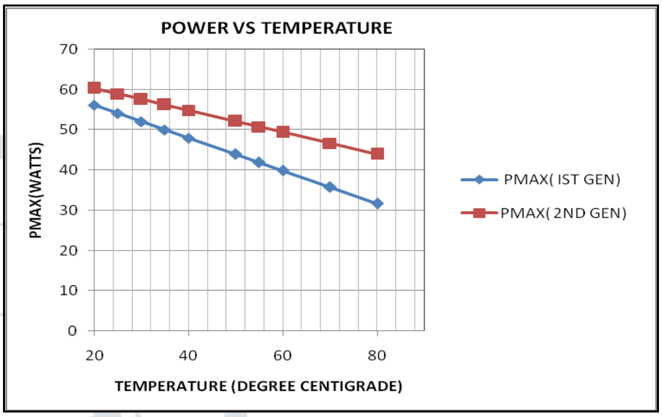

Fig 3: Power vs Temperature Simulations

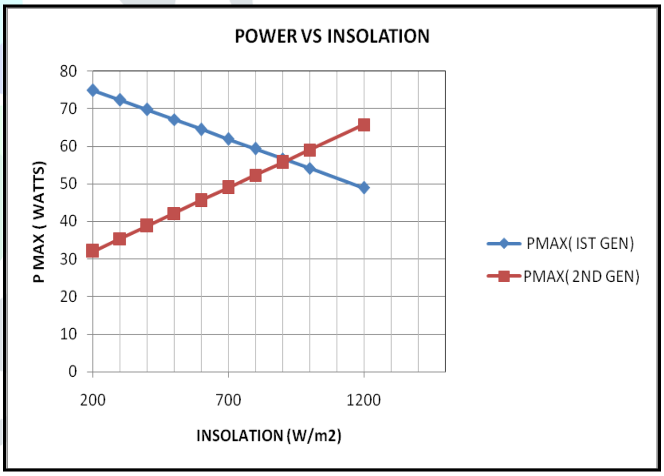

Fig 4: Power vs Insolation Simulations

B Discussions on Results

The results of the simulations need to be analyzed critically. It is well known that the temperature increase will lessen the power output of the PV cell while higher insolation levels will increase the power outputs. Figure 3 shows this to be true for the case of temperature increases. Further, the simulated results seem to imply that the second generation PV cells have a lower gradient of fall as compared with the First generation cells. This means that as the temperature rises, the fall in power outputs of the second generation PV cells is lesser than that of the first generation PV cells for the same level of insolation.

However in the case of the influence of insolation on PV cell performance at a fixed temperature level, it appears that while the second generation PV cells are influenced positively, the first generation cells show the reverse trend. The regression models show the coefficients of the insolation level to be positive for the second generation PV cells but negative for the first generation PV cells. The actual cause is not clear and further investigations are necessary to arrive at some definite conclusions. Probable causes are the complex interactions between the voltage of the PV cells and the generated currents which will both vary as load is adjusted for obtaining Pmax. Moreover, data of cells of different output ratings have been used , which might also have some effect in deciding the directions of the overall trends.

None the less, it is clear that this study shows the following main conclusions.

1. Both insolation levels and temperature variations will affect the power outputs of the PV cells.
2. The magnitudes of these impacts are different for the two generation categories of PV cells.
3. The performance of the second generation PV cells appears to be better than the performance of the first generation PV cells as far as power changes are concerned with regard to the model simulations

V. CONCLUSIONS

A study was carried out using regression models for understanding the influence of the insolation and temperature changes on the performance of two categories of PV cells i.e. First generation and Second generation. The study shows that both these variables affect the power outputs of the concerned types of cells differently. The simulations appear to suggest that the second generation type cells perform better than the first generation cells.

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