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Comparison of Mathematical Models for Photovoltaic Maximum Power Calculation

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Abstract: This report presents the comparison of three different methods for modelling a PV Panel. The presented models include the single diode model, maximum-power model and fill-factor model. These models accept the irradiance and temperature pair as inputs and output the maximum power. In this paper models outputs will be compared with values from the PV panel datasheet used for testing. This paper further observes the short-circuit current and open-circuit voltage to study its effect on the maximum output power. All the models are programmed using Python. Considering the results, a credible modelling technique is selected.

Key words: IPP - Independent Power Producer, MPPT - Maximum Power Point Tracker, NOTC - Nominal Operating Cell Temperature, PV - Photo Voltaic, STC - Standard Test Conditions

1. INTRODUCTION

This study showcases the comparison between three different models for PV panel. These models include the *single diode*, and the other two models are referred on this paper as *fill-factor* and *maximum-power*. These models uses the temperature and irradiance as input parameters and compute the maximum power. The single-diode model also provide the I-V and P-V characteristic for any input parameter pair provided. The models will be compare with respect to maximum power, other parameters such as open-circuit voltage and short-circuit current current will also be considered.The results obtained from each model will be compared with the characteristic of the PV provided on the manufacturer datasheet and later select the most efficient model. The chosen model will be used to predict the amount of power the IPP can provide to Eskom if the coordinates of their location is known (for knowledge of temperature and irradiance of the particular location).

2. BACKGROUND

2.1 Constraints and Assumptions

- The independent power producers PV uses MPPT to achieved maximum power possible.

2.2 Success Criteria

For this study to be deemed successful, different PV modelling techniques have to be compared and an the most accurate and credible model should be obtained which provides maximum power output more equivalent to the value provided by the manufacturer datasheet of a PV panel used for testing.

2.3 Literature Review

2.3.1 ***PV cell model*** Reference [1–3] shows different models of presenting a PV panel as a diode. Most of them contain large exponential that requires difficult procedure.This complexity is also witnessed by high number of parameters in the model which is usually an attempt to achieve high accuracy on results. Reference [4] comparison results shows the single-diode and two-diode model providing similar results.[4] further emphasize that for the single-diode model with series resistance (R_s), the maximum power point of the model is near to the value of manufacturer specified value, while in the two-diode model maximum power point has great deviation. Reference [1] presents an excellent representation using a single-diode model which is simple, accurate and considers the series resistance (R_s). Therefore, considering simplicity and accuracy the single-diode model will be applied in this paper.

Reference [5] provides two equations to independently calculate the maximum power of the PV panel. The first equation uses the maximum power at STC to predict the maximum power at NOTC, the second equation make use of the fill factor and other parameters to calculate the PV power. Unlike the single-diode model in [1], these methods do not provide an analytical solution to the current and voltage of the PV, thus they are limited to calculation of maximum power. Since the IPP are using MPPT, this implies the PV panels they use will always be operated at the maximum power point. Therefore, this two method are applicable in this study since the main focus is on the maximum power that can obtained from a particular solar panel given the specific temperature and irradiance respectively.

3. PV MODELS & POWER CALCULATION

This section provides the details of the different approaches that will be applied to calculate the maximum possible power from a panel at any given temperature and irradiance pair.

3.1 Single-Diode

In this model a PV is modelled as a single-diode [1]. This modelling approach gives a good insight to operation of the panel with varying irradiation and temperature. It gives a genuine relationship between voltage and current outputs of the PV panel that can be applied to obtain effectively calculate maximum power and any parameter of the PV at NOCT. This model is expressed by equation 1 below.

$$V = V_{oc} + V_T \ln(1 - \frac{I}{I_{sc}}) - R_s I \tag{1}$$

$$V_{oc}(G, T_c) = V_{oc0}[1 + \beta(T_c - T_0)] + V_{T0} \ln(\frac{G}{G_0}) \tag{2}$$

$$I_{sc}(G, T_c) = I_{sc0}\frac{G}{G_0}[1 + \alpha(T_c - T_0)] \tag{3}$$

$$R_s = \frac{V_{mp}}{I_{mp}} - \frac{2V_{mp} - V_{oc}}{I_{mp} + (I_{sc} - I_{mp})\ln(1 - \frac{I_{mp}}{I_{sc}})} \tag{4}$$

$$V_T = \frac{(2V_{mp} - V_{oc})(I_{sc} - I_{mp})}{I_{mp} + (I_{sc} - I_{mp})\ln(1 - \frac{I_{mp}}{I_{sc}})} \tag{5}$$

$$V_T(T_c) = V_{T0}\frac{T_c}{T_0} \tag{6}$$

where the constant are redeemed from any solar panel data sheet used as follows:

- R_S is the series constant resistance [3].
- T_0 is the temperature equal to 25°, G_0 is the irradiance equal to 100W/m^2 is the irradiation and V_{T0} is thermal voltage all at STC.
- β and α are V_{oc} and I_{sc} temperature coefficients respectively.
- V_{oc0} and V_{mp0} are corresponding open circuit and maximum power voltage at STC respectively.
- I_{sc0} and I_{mp0} are corresponding open circuit and maximum power currents at STC.

3.2 Fill-Factor Model

This approach calculates the maximum power using fill factor, short-circuit current and open-circuit voltage respectively as shown by equation 7 below. The open-circuit voltage and short-circuit current at NOCT are calculated using equation 2 and 3 respectively.

$$P_{max} = V_{oc} \times I_{sc} \times FF \tag{7}$$

The fill-factor (FF) is calculated using equation 8 below. All the parameters to calculate the fill-factor are directly obtained from the PV module manufacturer datasheet at STC.

$$FF = \frac{P_{max0}}{I_{sc0} \times V_{oc0}} = \frac{I_{mp0} \times V_{mp0}}{I_{sc0} \times V_{oc0}} \tag{8}$$

3.3 Maximum Power Model

This model depends on the maximum power(P_{max0}) at STC. It then uses the temperature (T_c) and irradiance (G) to calculate the maximum for that given temperature-irradiance pair. This model is shown by equation 9 The symbol γ, is the normalize irradiance temperature coefficient.

$$P_{max} = P_{max0} \times \frac{G}{G_0}[1 + \gamma(T_c - T_0)] \tag{9}$$

4. SIMULATION RESULTS AND ANALYSIS

All the models aforementioned were programmed using Python. The evaluation for the I-V and P-V characteristic of the PV was using single-diode model was performed using the 37W PV module used in [1].

4.1 Single-Diode Model I-V and P-V characteristics

Figure 1-4 below shows the expected relationship between the I-V and P-V of the PV panel. All these curves do not reach completely reach the left of the vertical axis. This was due to fact that the single-diode model is analytical, and required the current to be varied, therefore a very small change in current was required for the curve to be completely filled but that was an issue since the longest memory of the Python list was not enough to store all the current and voltage coordinates pair. The analysis of the curves is detailed below.

4.1.1 ***I-V Characteristics*** Figure 1 and 2 depict the I-V curves of the 37W PV aforementioned using single-diode model for varying irradiance and temperature respectively. Figure 1 shows that with an increase in irradiation the short-circuit current also increases proportionally with a minor increase on the open-circuit voltage.

From Figure 2 it can be observed that the open-circuit voltage decreases as the temperature increases and there is no visible change on the short-circuit current.

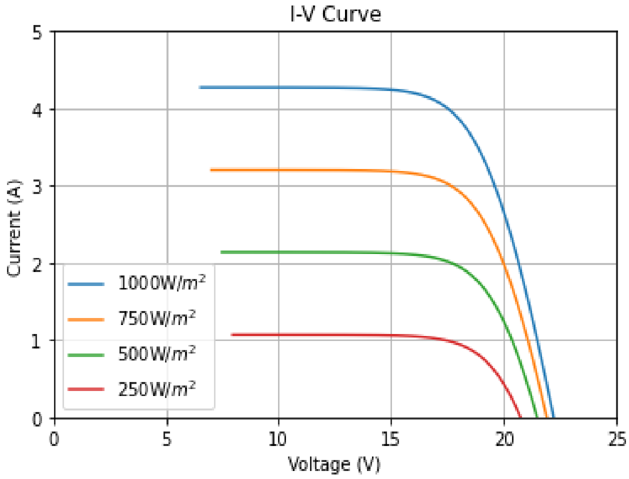

Figure 1: I-V curves of the PV panel computed using single-diode model ($T_c = 25^oC$)

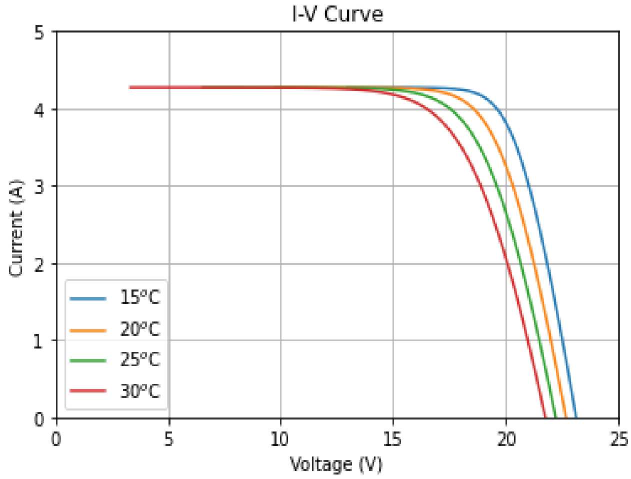

Figure 2: I-V curves of the PV panel computed using single-diode model (G = 1000W/m^2)

4.1.2 ***P-V Characteristics*** Figure 3 and 4 showcases the P-V curves for the same 37W panel used for simulation with varying irradiance and temperature. From Figure 3 it can be observed that the irradiance has a huge impact proportional impact on the PV power curve, compare to the temperature that is inversely proportional to the PV output power with minor influence that cannot be ignored.

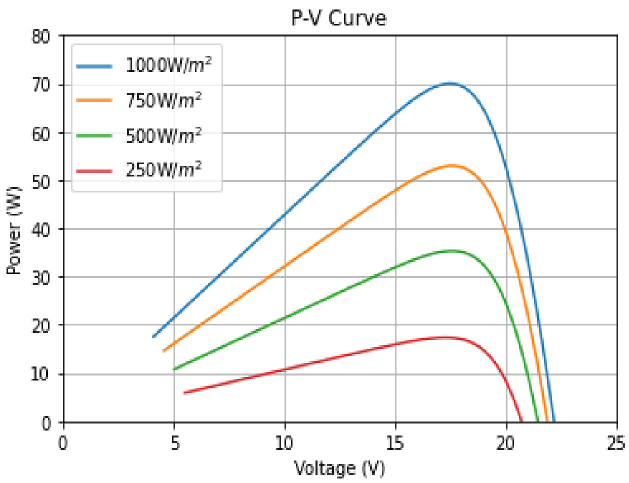

Figure 3: P-V curves of the PV panel computed using single-diode model ($T_c = 25^oC$)

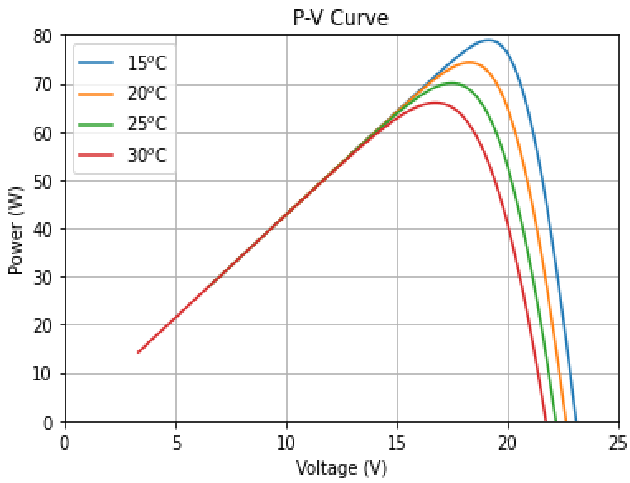

Figure 4: P-V curves of the PV panel computed using single-diode model (G = 1000W/m^2)

4.2 Models Comparison

The models will be provided with PV panels parameters at STC and will be tested with NOCT conditions (G = 800W/m^2, $T_c = 20^oC$) since PV modules datasheets provides the required characteristics for comparison under those conditions. To compare the models, 9 Trinar solar panels (320W,325W, 330W, 335W, 340W, 345W, 350W, 355W and 450W) were used.

4.2.1 ***Maximum Ouput Power*** Figure 5 showcases the maximum output power of the single-diode model (SIM Pmax), fill-factor model (FIM Pmax), maximum-power model (MPM Pmax) and the datasheet maximum power (DS Pmax) for a series of PV panels. It can observed from the figure that the maximum power calculated using the single-diode model best matches the one provided on the datasheet for all PV panels tested compared to the other models.From the figure it is further observed that the gradients line of best fit for all the models will be similar but the offset are different. Figure 6 showcases the deviation of the models maximum power compared to one provided on datasheet. The fill-factor model is found to have the average deviation/offset of 14.13W, the maximum-power model has 2.4W and single-diode model has the 0.58W.

From Figure 3 and 4 a remarkable observation was note. It can be noted that irradiance affects the slope of the P-V curve and temperature affects the offset. Since temperature affects the open-circuit voltage, that implies to rectify the fill-factor and maximum-power model, the voltage calculation using temperature needs to be rectified to eliminate the offset.

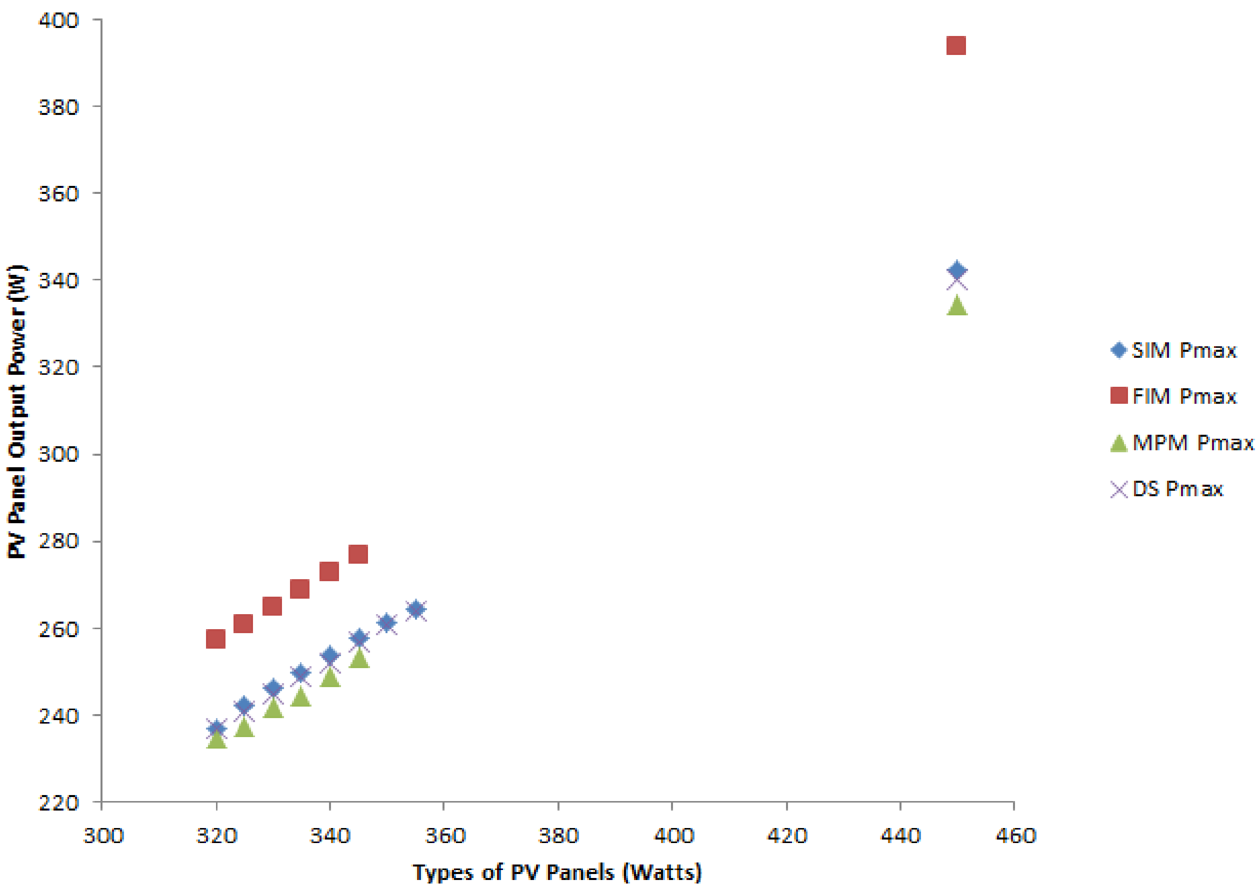

Figure 5: Maximum power output for various Trinar solar modules using all the models

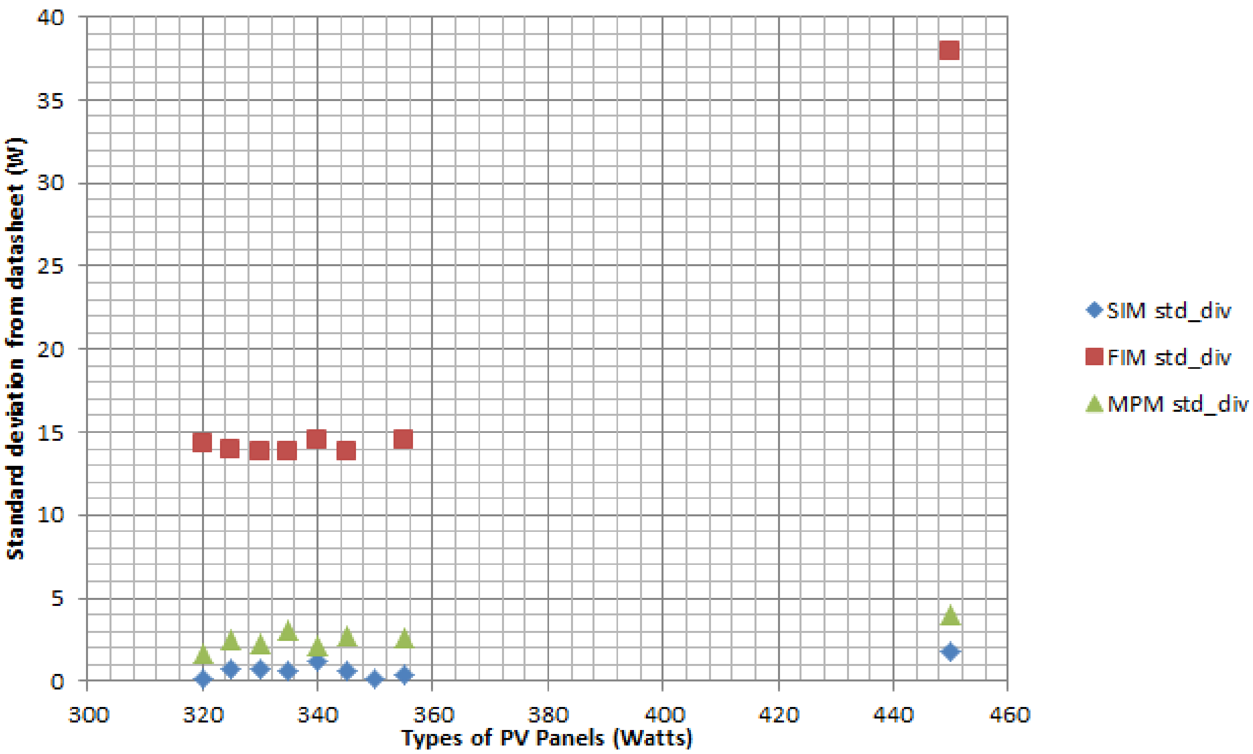

Figure 6: Standard deviation of models compared to the datasheet expected values

4.2.2 ***Single-diode model & PV's Datasheet*** Since the single diode model gives the knowledge of short-circuit current and open-circuit voltage, this data was collected for all tests with series of PV panels and compared with the values provided on the datasheets. Those results are shown on Figure 7 and 8 for short-circuit current and open-circuit voltage comparison respectively.

It is observed from Figure 7 that short-circuit current for all PV panels calculated using the single-diode model completely matches the one provided on the datasheet with negligible offset. On Figure 8 it is observed that the slope for line of best fit for both the datasheet and single-diode scatter-plots are similar with a small-offset. These results shows that the offset on maximum power comparison aforementioned was due to open-circuit voltage. This results further support remarkable observation aforementioned.

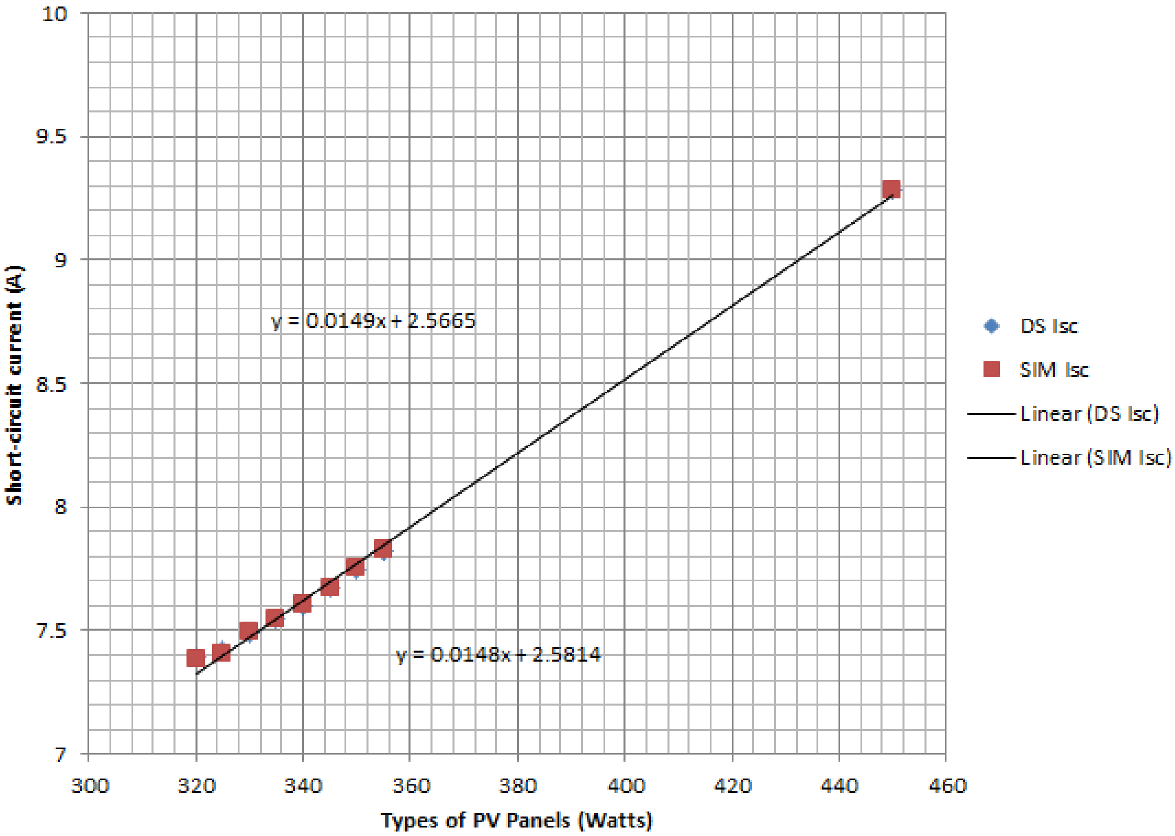

Figure 7: Standard deviation of models compared to the datasheet expected values

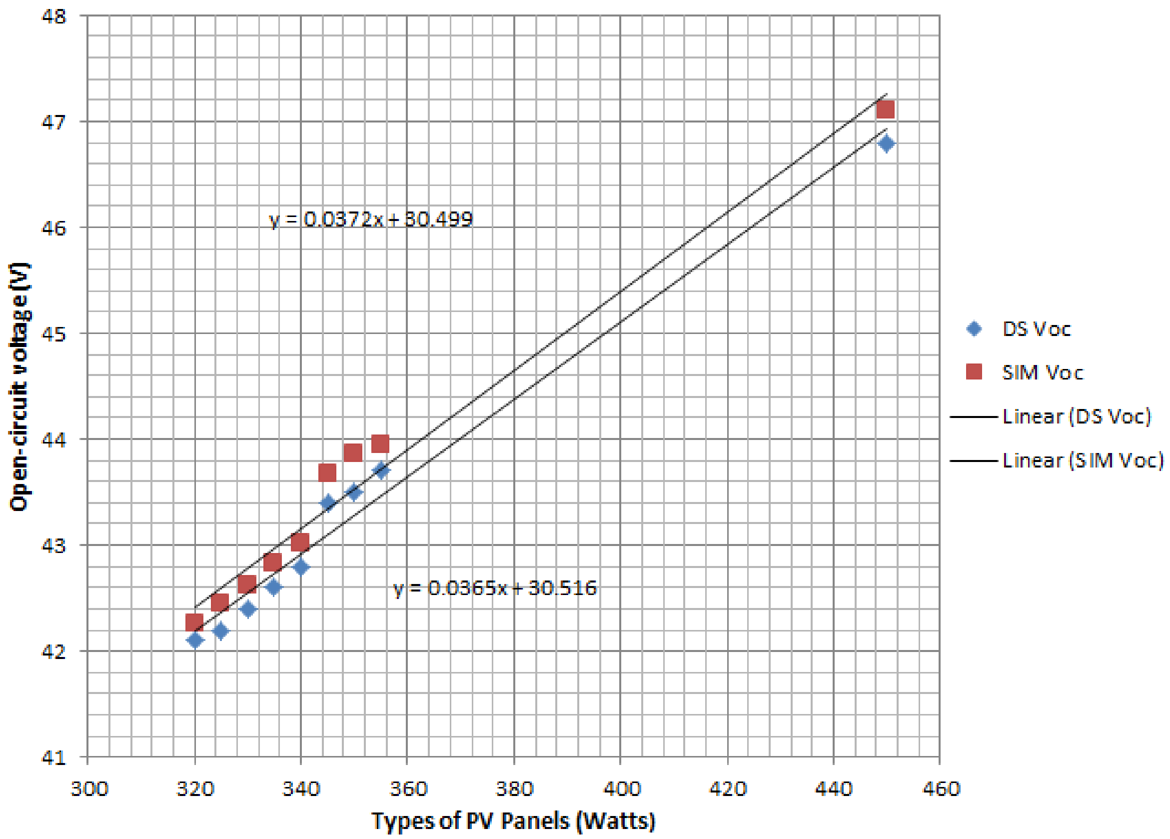

Figure 8: Maximum power output for various Trinar solar modules using all the models

4.2.3 ***Selection of Credible Model*** All the models are mathematical correct, few changes should be made to fill-factor model and maximum-power model to eliminate the constant deviation/offset from the datasheet values. The single-diode model was found have minimal offset from the true maximum power value compared to other models. The nature of the single-diode model of being analytical, allows it to be the only model in this paper to provide the P-V and I-V characteristics of a PV panel which is very useful. With all the results presented and the advantages of single-diode model stated, it is concluded that the single-diode model is more credible compared to the other presented models.

5. CONCLUSION

This report outlined the comparison of three different techniques for modelling a PV panel which include the single-diode model, the fill-factor model and the maximum power model. The comparison of the models was achieved by considering the maximum power. Using analysis from comparison it was concluded that single-diode model is more credible compared to the other two.It was recommended that the other two models can give improved results by rectifying the calculation of voltage used calculate maximum power.

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