The Influence of Sand Density on a Photovoltaic Production

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***Abstract*—Photovoltaic solar energy presents today one of the highest potential within the different renewable energy sources. In the recent decades, several technological and research advances have been contributing for the consolidation of its potential. One current research topic on photovoltaic energy is the impact analysis of dust/sediments on the panels performance. The development of models capable of predicting the performance of photovoltaic panels under the presence of dust/sediments may allow a better decision making when considering maintenance operations. In this way, this work investigates the influence of sand on the production of photovoltaic solar energy in cadmium telluride (CdTe) solar panels. Six panels of this type with different colors and transparencies were experimentally tested without and with the presence of sand. The impact of the sand is evaluated through the study of the average values of the unknown parameters of 1M5P model and of other parameters that characterize the performance of the solar cell. Based on this study, the construction of a model that allows modeling the effect of sand on these panels was introduced. With the calibration of the models, it is possible to predict the influence of the dust on the efficiency and output power of the photovoltaic panel.**

***Index Terms*—Photovoltaic Solar Energy; Cadmium Telluride; 1M5P Model; Sand Influence.**

I. Introduction

Over the past few years, the emission of greenhouse gases, constant climate change have been worrying warnings for the health of the planet and humans. The main reason for these phenomena is due to the excessive use of fossil fuels during the last decades. The use of renewable energies is the present and future solutions for the production of electricity. With the emergence of technological advances, at the end of the XIX century, it was possible to transform the energy of the sun into electricity, thanks to the invention of the solar cell [1] [2]. The enormous potential of this type of energy, combined with advances in this field of research over the last few decades, have led to the development of several studies that promote improvements in the efficiency of solar panels. There are several factors that influence the performance of a photovoltaic system, such as temperature, irradiance, humidity, dirt in the modules or energy losses in the components of the [3]. The focus of this dissertation is on the influence of dust and sediment on the production of photovoltaic solar energy.

In urban areas, the efficiency of photovoltaic production is increasingly affected by atmospheric pollution and the deposition of sediment on solar panels. In addition, photovoltaic systems will face problems with the reduction of the space available for their implementation. A possible alternative will be the installation of photovoltaic systems in deserted or uninhabitable regions whose conditions are not ideal for their operation. In places such as deserts or other arid regions, in addition to the influence of temperature, the deposition of sediments on solar panels is also one of the non-idealities of these areas. However, it is necessary to point out that there is a huge interest in installing this form of energy generation in these areas of the world, as they are the places where the best conditions for horizontal global irradiance exist. The unfavorable conditions of these regions are a motivating factor to find solutions to mitigate them. A possible solution is the creation of models that allow analyzing the impact of dirt on solar panels. Through this study, performance losses can be estimated and maintenance plans can be decided.

This dissertation intends to analyze and characterize the influence of sand on CdTe photovoltaic solar panels with different colors and transparencies. It is intended to investigate the effect of sand on parameters that characterize the performance of the solar cell and to develop an electrical model that allows modeling the effect of the introduction of sand in the production of photovoltaic solar energy.

II. State of the Art

The working principle of the solar cell is based on the photovoltaic effect which consists of the generation of electric current or voltage from the exposure of a semiconductor material to light. When the photons from the incident solar radiation have sufficient energy and reach the valence band electrons of the solar cell, electron-hole pairs are formed [4] [5]. Due to electrical field forces (p-n junction field), electrons and holes move to opposite terminals. For that reason a higher potential difference appears in the semiconductor [5].

Existing photovoltaic technology can be divided into three generations. First generation solar cells use crystalline silicon (c-Si) technology and can be of two types: monocrystalline silicon and polycrystalline silicon. Second generation cells use thin film technology applied on rigid substrates and include thin-film solar cells based on: a-Si, CdTe and CIGS [6]. Third generation cells include the most recent technologies to be created. These include organic solar cells, dye-sensitised solar cells and quantum dot cells [7] [8].

The 1M5P model is the most popular and practical model for specifying the operation of a solar cell. This model consists of a current source in parallel with a diode (p-n junction) and two resistances, one in series (R_s) and one in parallel (R_{sh}) [9] [10]. The resistance R_s helps to represent the voltage drop in the circuit to the external contacts and the resistance R_{sh} helps to describe the existing leakage currents. The Equation 1 describes this model, representing the output current as a function of the output voltage and the five unknown parameters (I_{pv}, R_s, R_{sh}, I_s and n).

$$I = I_{pv} - I_s(e^{\frac{q(V+R_sI)}{nkT}} - 1) - \frac{V + R_sI}{R_{sh}} \quad (1)$$

III. Methodology

A. Experimental Procedures

Experimental tests were carried out to obtain the characteristic I-V and P-V curves of the photovoltaic solar modules. The experiments were carried out with clean solar panels and with three different densities of sand (80 g/m^2, 160 g/m^2 e 240 g/m^2). For the study in question, six CdTe photovoltaic solar panels of different colors and transparencies of 40% (grey, orange, red and yellow) and 50% (blue and green) were used. Figure 1 shows the electrical schematic of the experiments carried out.

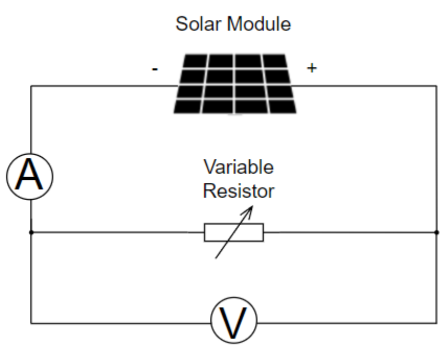

Fig. 1. Electrical schematic.

The experiments were carried out under normal operating conditions, that is, under natural radiation. It is important to mention that the tests were carried out only for a null angle of inclination of the modules in relation to the horizontal. The tests were carried out on different days and at different hours. The same experimental procedure was applied to each panel: for a given hour, incident irradiance was measured at nine locations on the panel, as well as its temperature, which was measured at just one point on the panel. After measuring the irradiance and temperature, five experimental tests are carried out for each of the following four cases: clean solar panel and solar panel with three different densities of sand (80 g/m^2, 160 g/m^2 e 240 g/m^2). Regarding the cases in which sand was introduced into the solar panel, for each test, the sand was spread randomly and as uniformly as possible. In total, 255 valid experimental tests were accounted for.

For each of the situations under analysis (no sand, $80g/m^2$, $160g/m^2$ e $240g/m^2$), the average of the experimental data obtained (current and voltage) was applied and, in this way, average I-V and P-V curves were obtained. The fit of these curves was performed with the help of MATLAB, more specifically with the cftool tool. Figure (2) shows an example of the fit of the experimental results obtained. The process in the remaining I-V and P-V curves is similar.

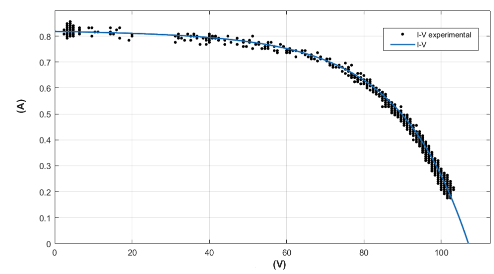

Fig. 2. Yellow CdTe - No sand ($G = 843W/m^2$).

B. Method to obtain 1M5P unknown parameters

To obtain the unknown parameters of the 1M5P model of a solar panel, the non-iterative method of Zhaoxu Song was used [11], which admits the possibility of obtaining these parameters based on characteristics of the I-V and P-V curves.

According to Zhaoxu Song [11], in the I-V characteristic curve there are three important points, the short circuit point, the open circuit point and the point of maximum power.

So, at the short-circuit point ($V = 0$;$I = I_{sc}$):

$$I_{pv} = I_{sc} + I_s(e^{\frac{R_sI_{sc}}{N_{celulas}nV_t}} - 1) + \frac{R_sI_{sc}}{R_{sh}} \quad (2)$$

At the open circuit point ($V = V_{oc}$;$I = 0$):

$$I_{pv} = I_s(e^{\frac{V_{oc}}{N_{celulas}nV_t}} - 1) + \frac{V_{oc}}{R_{sh}} \quad (3)$$

And at the point of maximum power ($V = V_{mp}$;$I = I_{mp}$):

$$I_{pv} = I_{mp} + I_s(e^{\frac{V_{mp}+R_sI_{mp}}{N_{celulas}nV_t}} - 1) + \frac{V_{mp} + R_sI_{mp}}{R_{sh}} \quad (4)$$

For the same irradiance, the left side of Equations 3 and 4 is the same, which means that the right side of both Equations is an equality:

$$I_se^{\frac{V_{oc}}{N_{celulas}nV_t}} + \frac{V_{oc} - V_{mp}}{R_{sh}} - I_{mp} - \frac{R_sI_{mp}}{R_{sh}} - I_se^{\frac{V_{mp}+R_sI_{mp}}{N_{celulas}nV_t}} = 0 \quad (5)$$

To obtain the series resistance (R_s) and the parallel resistance (R_{sh}) the Equations 6 and 7 were used, respectively. However, it should be mentioned that for the resistances R_s and R_{sh} the linearizations were applied roughly between the points [$0.9V_{oc}$;V_{oc}](V) and [0;$0.1V_{oc}$](V), respectively.

$$\frac{\partial I}{\partial V} \approx -\frac{1}{R_s} \quad (6)$$

$$\frac{\partial I}{\partial V} \approx -\frac{1}{R_{sh}} \quad (7)$$

Under the condition of the same irradiance, equating the expressions 2 and 3 and assuming the approximation $I_s e^{\frac{V_{oc}}{N_{celulas} n V_t}} >> I_s e^{\frac{R_s I_{sc}}{N_{celulas} n V_t}}$ devido a $V_{oc} >> R_s I_{sc}$, it is possible to arrive at the Expression:

$$I_s e^{\frac{V_{oc}}{N_{celulas} n V_t}} = I_{sc}(1 + \frac{R_s}{R_{sh}}) - \frac{V_{oc}}{R_{sh}} \tag{8}$$

In this way, it can be observed that the current I_s is given by the following Equation:

$$I_s = \frac{I_{sc}(1 + \frac{R_s}{R_{sh}}) - \frac{V_{oc}}{R_{sh}}}{e^{\frac{V_{oc}}{N_{celulas} n V_t}}} \tag{9}$$

By substituting the current expression I_s into the Equation 5, an equation restricted to one unknown is obtained, which in this case is the ideality factor, n. Consequently, through 9 the saturation reverse current of the diode is calculated, I_s, and from 2 the photovoltaic current, I_{pv}, is calculated.

C. Modeling the Sand Effect on Solar Panels

This model has as input parameters the unknown parameters of the 1M5P model (I_{pv}, I_s, R_s, R_{sh} e n) and as output parameters the maximum power generated (P_{max}), the efficiency (η) and the fill factor (F_F). Bearing in mind that for each panel, information was collected for different irradiances, a study was carried out on the average values of the unknown parameters of the 1M5P model, the maximum power generated, the efficiency and the fill factor. As the currents obtained have a dependence on the irradiance incident on the panel (G) it is essential to normalize the photovoltaic current and the short circuit current to the incident irradiance for the analysis of the average values of these parameters (I_{pv}/G e I_{sc}/G) [12] [5]. In this way, the results of the model's input variables were interpolated as a function of the sand density. Any variation in one of the input parameters will have an impact on the output parameters. Through the information taken from the interpolations of the input variables and considering related conditions such as incident irradiance (G), the panel temperature (T_{pv}), the open circuit voltage (V_{oc}) and the density of sand, a program was developed in MATLAB that consists of estimating the values of the fill factor (F_F), the maximum output power (P_{max}) and the efficiency (η) of any of the six photovoltaic solar panels under study.

IV. Experimental Results

In this section, the experimental mean values and the respective maximum and minimum deviations of the input parameters (unknown parameters of the 1M5P model: I_{pv}/G, n, R_s, R_{sh} and I_s) and output parameters (F_F, P_{max}/G e η) are presented. Parameters such as short circuit current (I_{sc}) and maximum output power (P_{max}) were obtained from the average I-V and P-V curves. The fill factor and efficiency were obtained from the Expressions 10 and 11, respectively.

$$F_F = \frac{P_{max}}{V_{oc} I_{sc}} \tag{10}$$

$$\eta = \frac{P_{max}}{G A_{pv}} \tag{11}$$

Where G represents the irradiance and A_{pv} represents the active area of the solar panel.

The unknown parameters of the 1M5P model were obtained through the non-iterative method mentioned above [11]. Finally, the results of the model considering the effect of sand on solar panels are presented.

A. Input Parameters (1M5P) and I_{sc}/G

In all panels, the currents show an approximately linear characteristic with increasing sand density. This behavior of the currents is due to the decrease in the capture of irradiance from the photovoltaic cells due to the shading caused by the sand. The yellow panel showed the highest ratios of I_{sc}/G and I_{pv}/G. The green and gray solar panels were the ones that suffered the greatest losses with the introduction of sand.

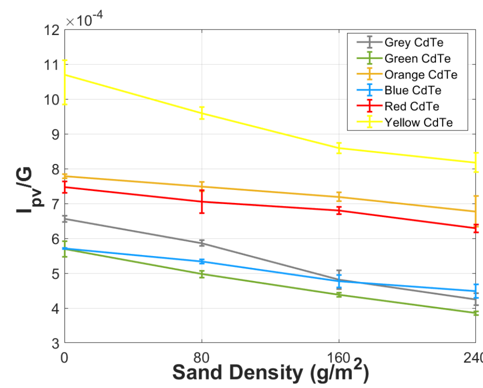

Fig. 3. Mean Values and Deviations of I_{pv}/G.

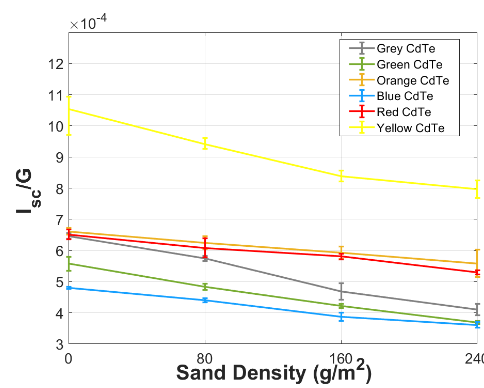

Fig. 4. Mean Values and Deviations of I_{sc}/G.

Regarding the resistances, its characteristics are approximately linear with the increase of the sand density. As the sand density increased, an increase of R_s was noted, in general, for all panels. In the blue panel the highest values of this parameter were obtained and in the yellow panel the lowest values.The grey and green panels were the most sensitive to the presence of sand in this parameter. Regarding the R_{sh} resistance, its tendency was to decrease with increasing sand density.. The yellow, grey and green panels have R_{sh} values considerably higher than the orange, blue and red panels.

The increasing of R_s resistance the and the decreasing of R_{sh} resistance with the introduction of sand makes sense because the functioning of the panels deviate from the best situation (clean panel). In the ideal situation R_s tends to zero and R_{sh} tends to infinity. The investigation by João Guilherme Santos [13] with the same panels also revealed this behavior of the resistors with the addition of sand in the panels.

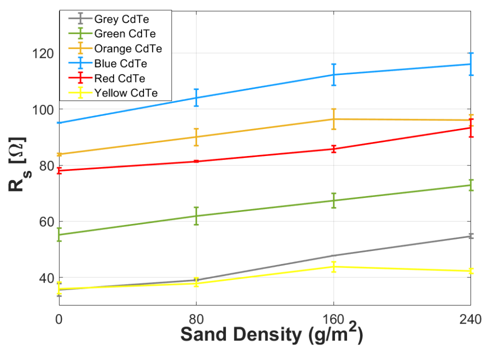

Fig. 5. Mean Values and Deviations of R_s.

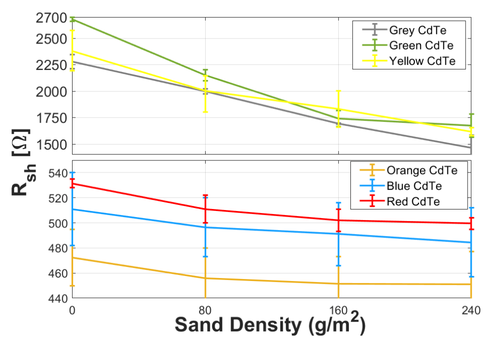

Fig. 6. Mean Values and Deviations of R_{sh}.

Cadmium telluride is a compound semiconductor, which makes it difficult to find a value for the ideality factor (n). By searching theoretical/tabled values for this parameter, it was found that they can vary between 1.5 and values close to 2 [13]–[16]. For the situation where the panel is clean, ideality factors varied between these values. With the introduction of sand in the solar panels, it was analyzed that the values of (n), in general, decrease. One of the reasons for this decrease can be explained by the increase in the temperature of the panels caused by the addition of sand. Several studies had already proven that the ideality factor (n) decreases with increasing temperature of solar cells [17]–[21].

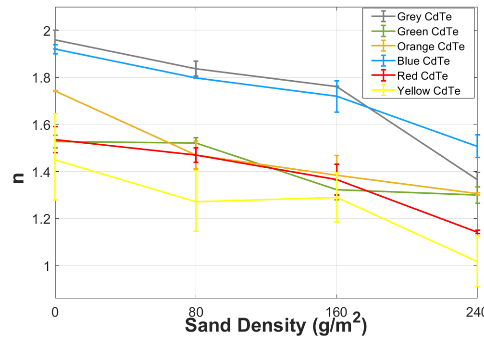

Fig. 7. Mean Values and Deviations of n.

The results of the I_s average current show that this was the parameter that suffered the greatest variations with the introduction of sand. For example, in the yellow, grey and red panels the results for the cases in which the panels are clean and with 240 g/m^2 of sand diverge by about three orders of magnitude (10^3). It was noted that as a general rule, this parameter tended to decrease with the presence of sand, and the discrepancy between the extreme cases (panel without sand and panel with 240 g/m^2) was notable. A search was made for typical values of this parameter in CdTe cells. The study by Mohammed Alaani [22] found values of I_s between orders of magnitude: 10^{-8} and 10^{-7} and the Bin Lv [23] study found values between orders of magnitude: 10^{-7} and 10^{-5}.

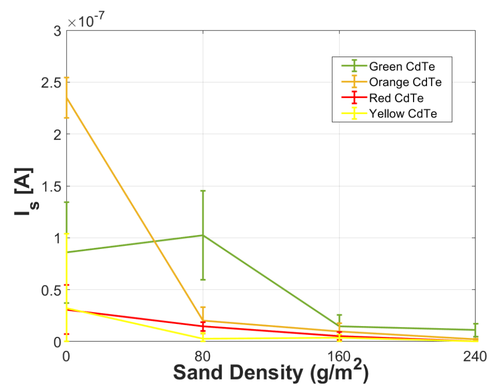

Fig. 8. Mean Values and Deviations of I_s.

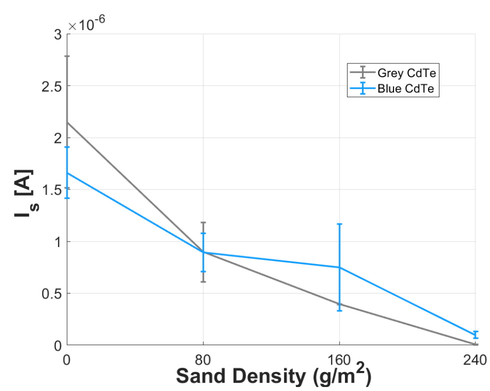

Fig. 9. Mean Values and Deviations of I_s.

B. Output Parameters (F_F, P_{max}/G e η)

Analyzing the efficiency and maximum power responses of the panels, it can be seen that the behavior was similar in all. These two parameters decrease with increasing sand density in the panels, showing an approximately linear relationship. It is necessary to highlight the results of the yellow panel since they highlight its performance in comparison with the others. The grey, green, orange and red panels performed very similarly and the blue panel showed the lowest values. The grey, green and blue panels showed the highest losses of these parameters, approximately 35%, 36% and 28% respectively.

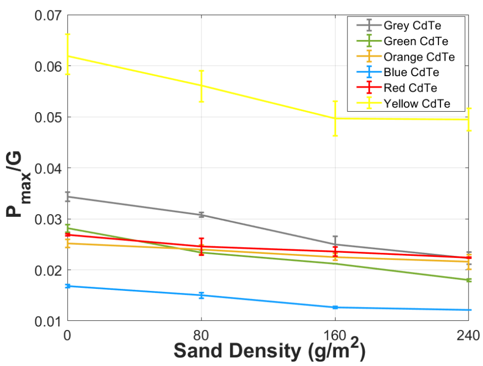

Fig. 10. Mean Values and Deviations of P_{max}/G.

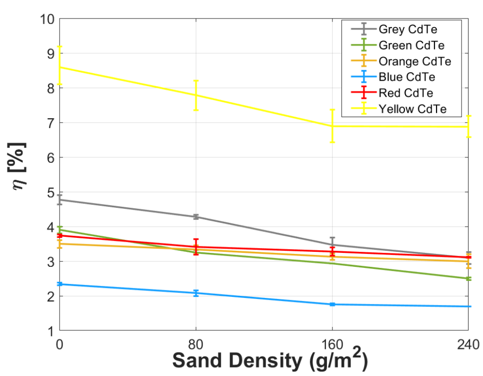

Fig. 11. Mean Values and Deviations of η.

Regarding the results of the fill factor (F_F), the differences in values of the yellow, grey and green panels in relation to the orange, blue and red panels are highlighted. The first group of panels showed higher F_F values. The variations of F_F were negligible with the introduction of sand. This can be explained by the reduced variations of the open circuit voltage V_{oc} with the addition of sand and the very similar decreases of the maximum power (P_{max}) and short circuit current (I_{sc}) at each sand density. The largest variation of this parameter was 3.54% in the red panel.

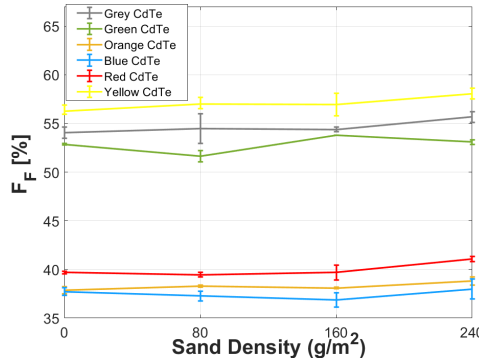

Fig. 12. Mean Values and Deviations of F_F.

C. Model Results Considering the Effect of Sand on Solar Panels

This subsection presents the comparison between the experimental results and the results of the interpolation model for the effect of sand.This model is based on a polynomial interpolation to the input parameters in order to investigate the behaviour of the output parameters, given certain conditions (panel temperature, incident irradiance, panel sand density and open circuit voltage). In Figures 13, 14, 15, 16, 17 and 18 the mean values of the model output parameters and the experimental results are present.

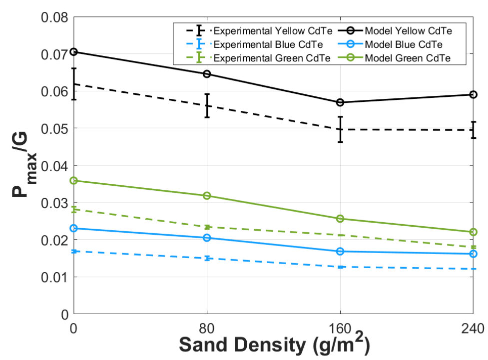

Fig. 13. Mean Values of P_{max}/G - Experimental vs Model.

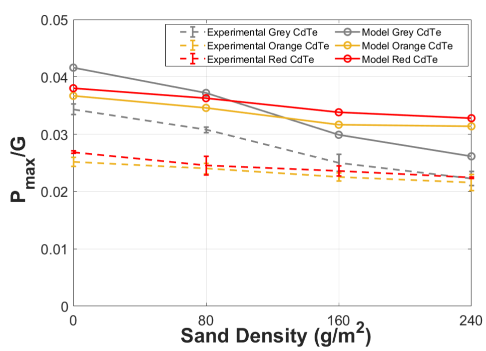

Fig. 14. Mean Values of P_{max}/G - Experimental vs Model.

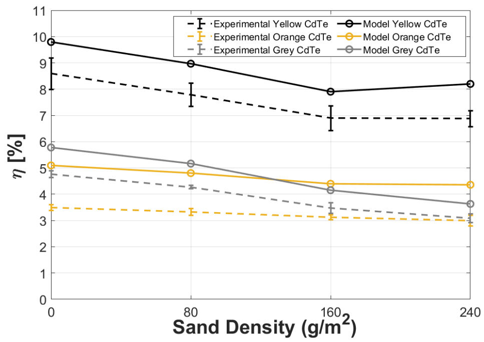

Fig. 15. Mean Values of η - Experimental vs Model.

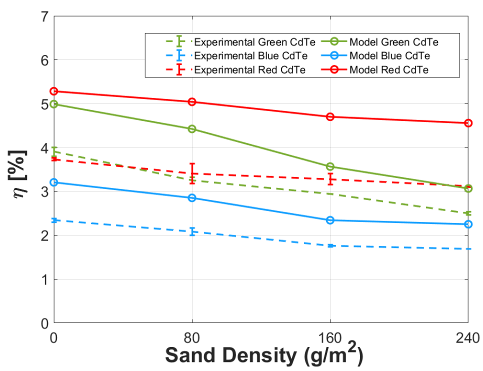

Fig. 16. Mean Values of η - Experimental vs Model.

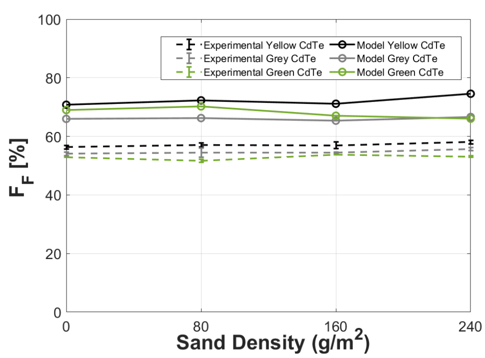

Fig. 17. Mean Values of F_F - Experimental vs Model.

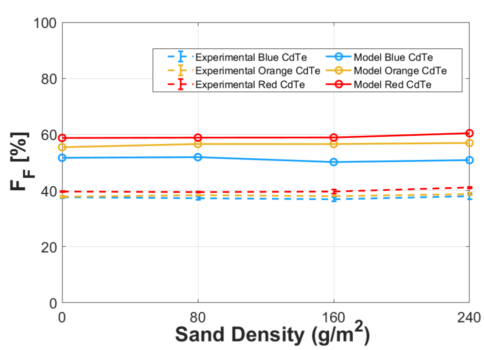

Fig. 18. Mean Values of F_F - Experimental vs Model.

Of the three parameters under analysis, the fill factor (F_F) was the one that showed the worst results. It is necessary to pay attention to the results of the maximum output power due to its direct impact on the other two parameters (η e F_F).

Based on the results of the average values of the maximum output power, it was observed that in each panel there is a very similar displacement between the experimental value and the value obtained by the model. This can be evidenced by the existence of an offset. This is evidenced by the very similar relative errors at all sand densities in a given panel.The maximum output power values obtained were always higher than the experimental results. Although the relative errors are very similar, in most results it was found that this error tends to decrease slightly with increasing sand density. In other words, this high value of the maximum power generated can be directly related to problems in the calibration of the output current.

Recalling the Expression of the output current of the 1M5P model:

$$I = I_{pv} - I_D - I_{sh} \tag{12}$$

It is possible to verify that there are several hypotheses to change the output current such as changes in the current source (I_{pv}), in the diode which works as a $p-n$ junction or in the parasitic resistances R_s and R_{sh}.

Due to the previous findings regarding the slight decrease in error with increasing sand density, in most cases, for higher sand densities, the current source may show some preponderance in the error.That is, with more sand density in the panel, the captured irradiance decreased and, consequently, the measured output current also decreased, leading to a decrease in the error source. The measured experimental irradiance is one of the parameters most susceptible to error. This parameter was always measured at the beginning of each hour of experiments and was assumed to be constant during all the tests performed during that hour. In reality, irradiance changes with the passing of the hour and therefore, in an ideal situation, irradiance should be measured in all the experimental tests carried out. There is a strong possibility that the photovoltaic current is not adjusted to the experimental conditions.

Besides the previous fact, the calibration of parasitic resistances may also be directly involved with the existence of this offset. Recalling the Expression of I_{sh}, it can be seen that this current depends on both resistances.

$$I_{sh} = \frac{V + R_s I}{R_{sh}} \tag{13}$$

Despite the discrepancy of the results, it should be noted the consistency of the model in the variations of these parameters with the increase of the sand density. Experimentally, it was found that these two parameters always decrease with increasing density of sand on the surfaces of the panels, and these decreases are different between panels. In this aspect, the model was able to follow these variations, that is, the efficiency and power losses in a congruent way.

In an attempt to improve the errors associated with the model, it was decided to increase its complexity.A little more study was carried out on the modeling of the photoelectric effect and the solar cell, and hypothesised that the model with only one diode is not sufficient to represent in the best way the functioning of the $p-n$ junction. The $p-n$ junction is not completely perfect or equal in all solar cells. That is, for a better representation of its behaviour, more exponential functions are needed to help depict the generation of electron-hole pairs and the "losses" of the $p-n$ junction (adding more diodes in parallel). The greater the number of unknown parameters of a model (achieved by adding more diodes), the more correct and closer to reality the model is.

Given this idea, in order to find the best possible model, an example of the orange panel was analyzed with the 2D7P model. No progress was made in the optimization of parameters with sand, however the intention was the future and the possibility of finding more reliable and robust models for this type of modeling. Figure 19 shows the experimental I-V and P-V curves, with the 1M5P model and with the two-diode and seven-parameter model (2D7P) of a case (without sand and with an irradiance of $G = 865W/m^2$) of the orange panel. It can be seen that the 1M5P model revealed difficulties in following the experimental curves and, in contrast, the model with two diodes improved the accuracy of the curves.

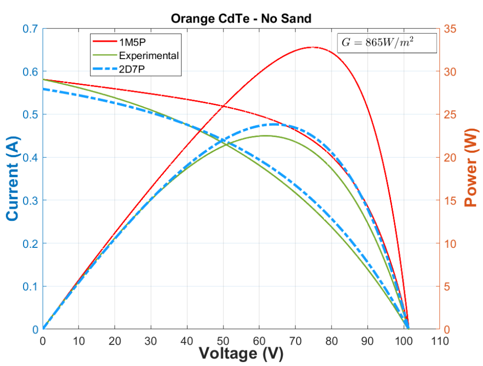

Fig. 19. Example of experimental curve vs 1M5P vs 2D7P.

In Table I are the relative errors of the parameters P_{max}, η and F_F of the 1M5P model and the 2D7P model for the orange panel example under analysis.

TABLE I
RELATIVE ERRORS OF P_{max}, η AND F_F OF THE 1M5P MODEL AND THE 2D7P MODEL FOR A SPECIFIC CASE OF ORANGE CDTE.

		Relative Errors	
		1M5P Model	2D7P Model
Orange CdTe **No sand** $G = 865W/m^2$	P_{max}	45.75%	5.87%
	η	45.75%	5.87%
	F_F	45.77%	10.10%

For future work, a valid hypothesis would be to do exactly the same methodology presented, but instead of following the 1M5P model, proceed to the implementation of the 2D7P model. The greatest difficulty will be the extraction of the unknown parameters of this model through an accurate method.

V. CONCLUSIONS

In this dissertation, the focus is on the analysis and characterisation of the influence of sand on CdTe photovoltaic solar panels. In this investigation six CdTe panels with different colours and transparencies of 40% (yellow, grey, orange and red) and 50% (green and blue) were used. This study also starts the development of a model that allows modelling the effect of sand on the solar panels under study.

Based on the results of the panels under normal operating conditions and the study of average values it was found that the efficiencies and maximum output powers generated by these panels are relatively low. The yellow panel was the one that showed the best performance, its highest recorded efficiency value was 9.19% while of the remaining panels the highest value was 4.9% (in the grey panel). One of the reasons affecting the efficiency values is related to the 40% and 50% transparencies of the panels under study.

With the introduction of sand in the solar panels, it was observed that its temperature increased, and this phenomenon is related to the physical properties of the sand, namely the small specific heat. Sand, in addition to preventing solar cells from capturing solar radiation, also influences the temperature of the panel, which ends up having a negative impact on the maximum output power (P_{max}) and efficiency (η) of the panels.

It was concluded that parameters such as the maximum output power (P_{max}), efficiency (η) and short-circuit current (I_{sc}) suffered decreases, showing an approximately linear relationship with the sand density in all panels.

Contrary to parameters like those analysed above (P_{max}, η and I_{sc}), the open circuit voltage (V_{oc}) showed insignificant changes with the addition of sand in the solar panels. The largest variation of this parameter with the introduction of sand was 4.7%, in the blue solar panel.

The variations of F_F were also insignificant in all solar panels with the introduction of sand.

With the increase of the sand density in the solar panels it was found that, in general, the resistance R_s increased and the resistance R_{sh} decreased, evidencing the deterioration of the panels behaviour in relation to the best case (clean panel).

Regarding the ideality factor (n), it was not possible to find with precision and certainty a theoretical/tabulated value for cadmium telluride. However, several studies indicated that this value would be between 1.5 and values close to 2. The average values of n obtained (when the panel is clean) were around the above values. With the addition of sand in the solar panels it was analysed that the values of (n), in general, decreased.

Regarding the model results. In the average values of the maximum output power, it was found the presence of a possible offset. The values obtained by the model were always higher than the experimental ones.

The incident irradiance measured experimentally is one of the most error-prone factors in this investigation. This parameter was measured always at the beginning of each hour of experiments and was assumed to be constant during all the tests performed during that hour. This is one of the causes of the mismatch of the photovoltaic current to the experimental conditions. On the other hand, the calibration of the parasitic resistances can also be one of the factors influencing this offset due to its impact on the output current expression.

The model with only one diode proved not to be sufficient in representing the operation of the $p-n$ junction. In this way, a brief study was carried out with the 2D7P model for an orange panel situation (Figure 19 and Table I) and the improvements were evident compared to the 1M5P model.

Finally, despite the differences of the results by the model in comparison with the experimental results, the consistency of the model in following the losses of P_{max}/G and η as a function of the increase of the sand density in the panels is highlighted.

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