Outdoor performance of a CdTe based PV generator during 5 years of operation

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***Abstract*— Together with the huge growth of the traditional crystalline silicon (Si-x) PV manufacturers, other thin-film solar cells have also emerged such as cadmium telluride (CdTe) manufacturers. They are characterized by the fact that they were created to reduce costs and by the scarcity of silicon, from which the rest of the modules are made. Despite they need more space to generate the same amount of energy as crystalline modules, their price is supposed to be much lower, and argue that they have a better performance at high temperatures. However, real comparisons between the outdoor performance of CdTe and Si-x modules have been scarcely addressed in the literature. This paper provides a comparison under real operating conditions of a CdTe photovoltaic generator versus a conventional silicon generator during 5 years of operation in a mid-latitude area, identifying the causes of the differences observed.**

Keywords— photovoltaic; solar cells, Si-x solar cells, CdTe solar cells ; thin-film solar cells

I. Introduction

Although conventional silicon (Si-x) occupies almost the entire market share of module manufacturing in the world [1–3], there is still talk of alternatives that, at a lower cost, they are an alternative to traditional silicon [4,5].

One of this thin-film technology is the cadmium telluride (CdTe), which is claimed to have the lowest photovoltaic manufacturing cost technology [6], with cell record efficiencies of 22.1% which is similar to that on Si-x [7] and with expectations of production growth [8].

According to CdTe manufacturers, apart from the low cost, its advantages are mainly related to easy processing, lower temperature coefficient and high optical absorption which makes them perform well under diffuse radiation [9–12].

However, there is a lack of studies conducted with real data comparisons between the outdoor performance of CdTe and Si-x modules at a generator level. Herein, it is shown a comparison under real operating conditions of a CdTe and a Si-x photovoltaic (PV) generator during 5 years of operation in a mid-latitude area and identifying the causes of the differences observed.

II. Methodology

A. PV test material

In this analysis, a 2250 W photovoltaic generator of commercial CdTe modules has been analysed together with a 2240 W generator composed of modules made of conventional silicon. Prior to the commission of both generators, the modules were characterized to check if there was any discrepancy between the real values and the datasheet values. On the one hand, the power of the modules were measured following the standard IEC-60891 [13]. Several measurements were made with a capacitive load measuring both radiation and temperature with a calibrated cell and then using the temperature coefficients given in the datasheet to extrapolate the measurements to standard test conditions (STC). Figure 1 shows an example of an I-V curve taken to one of the CdTe modules and extrapolated to STC.

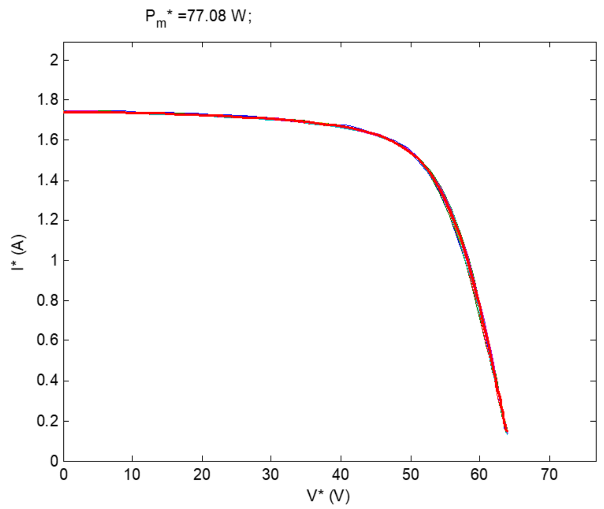

Figure 1: Example of I-V curves of a CdTe module extrapolated to STC

On the other hand, the experimental values of the temperature coefficients of the modules have also been verified following a procedure similar to the one shown in [14].

B. PV SYSTEM

The two PV generators were commissioned in February 2014 in a static 30° tilted structure South facing located at a latitude and longitude of 42º 04'N, 1º 36'W (North of Spain). Table 1 shows the general characteristics of each of the generators.

TABLE 1: SUMMARY OF ALL THE MAIN CHARACTERISTICS OF BOTH GENERATORS

Generator	Total Modules	Total Power (W)	γ (%/°C)
Si-x	14	2240	-0,45
CdTe	16	2320	-0,25

The generators are directly connected to two 2.5 kW commercial inverters, which means that since the power of the generators is always lower, they will never saturate and will not influence the analysis.

The temperature of the generators is measured with two PT100 probes and the radiation by means of crystalline silicon reference modules that have been previously calibrated by CIEMAT [15]. For the measurement of power, both in AC and DC, two wattmeters MW100 [16] are used which measure the data every second but make the recordings as 10-minute averages. Table 2 shows the uncertainties for each of the elements used.

TABLE 2: INSTALLED DATA ACQUISITION EQUIPMENT, SENSORS, AND THEIR UNCERTAINTIES.

Parameter	Manufacturer	Maximum uncertainty
Global Radiation 30º Si-x reference modules	Yingli Solar	±2% (Calibrated by CIEMAT[a])
Pt100 Temperature	Omega	B Class = ± 0.3˚C at nominal resistance (0˚C) B Class = ± 0.8˚C at nominal resistance (100˚C)
DC Active Power	Yokogawa	±(0.3% of reading + 0.2% of range)

[a]CIEMAT: Centre for Energy-Related, Environmental and Technological Research. (http://www.ciemat.es/)

The entire analysis was conducted between March 2015 and February 2020. Table 3 shows the main characteristics of the environmental conditions observed, such as broadband horizontal daily irradiation, $G_d^{BB}(0)$, and average ambient temperature during the day, T_A. showing that the location is a sunny place with high temperature variations between Summer and Winter.

TABLE 3: SUMMARY OF ALL THE MAIN CONDITIONS OF THE LOCATION

Weather	$G_d^{BB}(0)$ kW h/m²	T_A (°C)
Average	4.43	16.87
Worst month	1.22	6.29
Best month	7.88	27.05

III. RESULTS

A. Energy produced per nominal kWp referred to the Si-x generator.

Due to the fact that crystalline silicon technology has been widely known and contrasted, the Si-x generator will be taken as a reference. Figure 3 shows the monthly production per nominal kWp of the CdTe generator referred to the production obtained in the Si-x generator. Only the moments in which both generators were working correctly have been taken and the productions are expressed in percentages of one (p.u.) with respect to Si-x production. It can be seen that the production of the CdTe generator is below that of Si-x. Furthermore, it can be observed that, the differences in production vary considerably and seasonally, tending to decrease in the warm months and increase in the cold months.

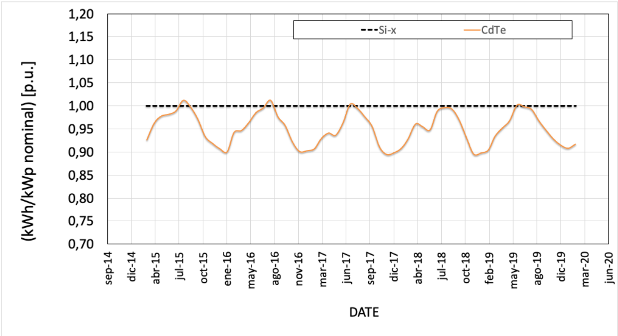

Figure 2: CdTe generator monthly energy production per nominal kWp referred to the energy produce by the Si-x generator.

The annual difference in production, per nominal kWp, between the CdTe generator and the Si-x generator is shown in Table 4. The CdTe generator has produced, on average, 4.5% less than the Si-x generator during the years under study. The following sections will analyze the reasons for this difference.

TABLE 4: DIFFERENCES IN PRODUCTION (IN %) BETWEEN THE CdTe GENERATOR AND THE Si-x GENERATOR.

Year	1	2	3	4	5	Average
%	-3.6	-4.2	-5.4	-4.6	-3.9	-4.5

B. *Real STC power.*

Figure 4 shows the measured STC power values for both the Si-x generator and the CdTe generator. The power output of CdTe modules under standard conditions shows some periodic variations over time, tending to increase in the warm months and decrease in the cold months. This fact is consistent with what has been seen in the available literature.[17–19].

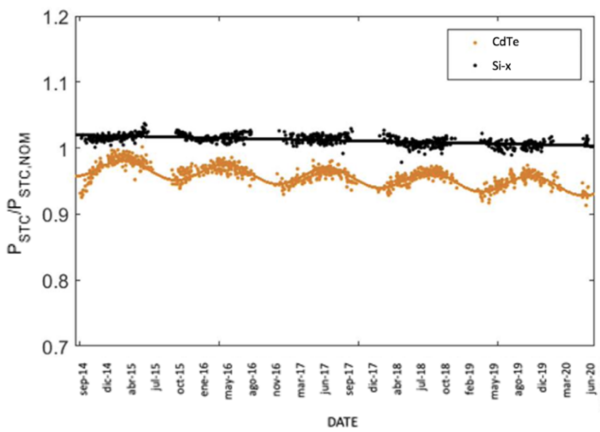

Figure 3: STC power measured in the Si-x and CdTe generators.

Table 5 shows the deviation of the power under standard test conditions from its datasheet value for both the Si-x and CdTe generators. Furthermore, the annual degradation rate has also been calculated yielding results of 0.3% per year in the reference Si-x generator and doubling this rate (0.6% per year) in the CdTe generator.

TABLE 5: STC POWER DURING THE PERIOD STUDIED

Year	Si-x	CdTe
1	1.02	0.98
2	1.02	0.97
3	1.02	0.97
4	1.01	0.96
5	1.01	0.96
Average	1.02	0.97
Average annual degradation	0.3% / year	0.6% / year

Based on these results, it can be assumed that part of the differences found in the production will be due to these differences in the real power of the generators. Table 6 summarizes the differences between both generators by differentiating which part is due to different real STC power.

TABLE 6: ANNUAL DIFFERENCES BETWEEN BOTH GENERATORS BY DIFFERENTIATING WHICH PART IS DUE TO DIFFERENT REAL STC POWER

Year	1	2	3	4	5	Average
Total difference (%)	-3.6	-4.2	-5.4	-4.6	-3.9	-4.5
Difference due to P_{STC} (%)	-5.0	-5.6	-6.2	-6.2	-6.6	-5.9

Figure 5 shows the monthly production differences between the two generators if the real STC power in both of them were equal to the datasheet power. The average value of the CdTe generator monthly productions is very close to that of the Si-x generator.

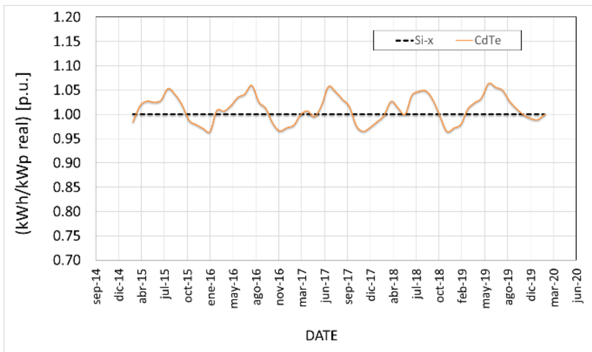

Figure 4: Monthly production if both generators have a real STC power equal to that given in the datasheet.

C. *Temperature response*

Another factor that may influence the differences found in the production between the two generators is the different behavior of the generators with respect to temperature. Thanks to the installed PT100 sensors, the average temperature differences over the entire analysis period for both generators have been analyzed. The CdTe generator heats up, on average, about 0.63 degrees less than the crystalline silicon generator, which has a positive impact on energy production. In addition, the CdTe generator has a smaller coefficient of variation of power with temperature, γ (Table 1) which means that it has a lower variation in its efficiency with the operating temperature. The efficiency of the crystalline silicon modules decreases by 0.45% for each degree that the operating temperature rises, while the efficiency of the CdTe generator only decreases by 0.25% for each degree.

Table 7 quantifies how much the losses are reduced by working with a lower temperature and having a lower γ. In particular, the temperature losses of the CdTe generator with respect to Si-x are reduced around 2.2% per year.

TABLE 7: DIFFERENCE IN ANNUAL PRODUCTION (%) OF THE CIS GENERATOR WITH RESPECT TO THE C-SI GENERATOR, DUE TO TEMPERATURE.

Year	**1**	**2**	**3**	**4**	**5**	**Average**
%	2.1	2.1	1.9	2.2	2.7	2.2

D. *Irradiance response*

Figure 7 shows the monthly production of the CdTe generator and the Si-x generator, after removing the effect of different STC power and temperature, both referred to the Si-x production. From this figure, it can be deduced that the production of the CdTe generator would be, in case of having the same STC power and the same temperature losses, practically the same in the warm months and slightly lower than that of the crystalline silicon generator during the winter months.

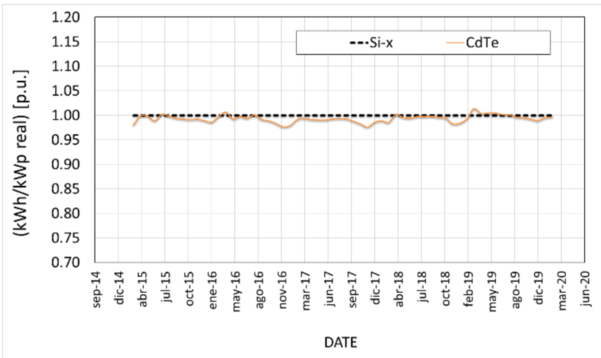

Figure 5: Monthly production if both generators have a real STC power equal to that given in the datasheet the module temperature of both generators was always 25ºC

This small difference in behavior in winter can be explained by the variation of module efficiency with the amount of incident irradiance. Figure 8 shows the variation of efficiency at 25°C with irradiance, which has been measured for the CdTe generator and the Si-x generator. It can be seen how the efficiency of the Si-x generator is slightly higher than that of the CdTe generator for irradiances between 100 W.m^{-2} and 800 W.m^{-2}.

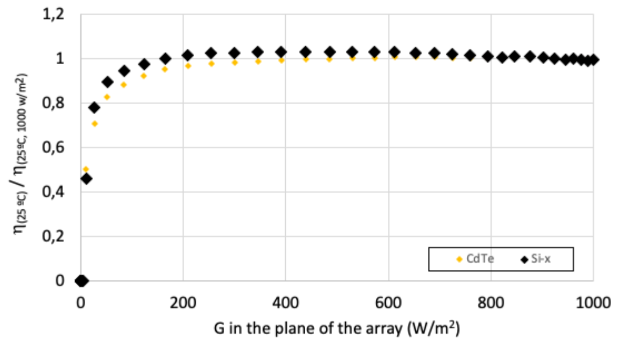

Figure 6: Efficiency variation at 25ºC with irradiance measured for the CdTe and Si-x generators.

Figure 9 shows the reduction in efficiency with radiation of the CdTe generator with respect to the Si-x generator. For irradiance values around 500 W.m^{-2}, the efficiency of the CdTe generator is 2% lower than that of the Si-x generator.

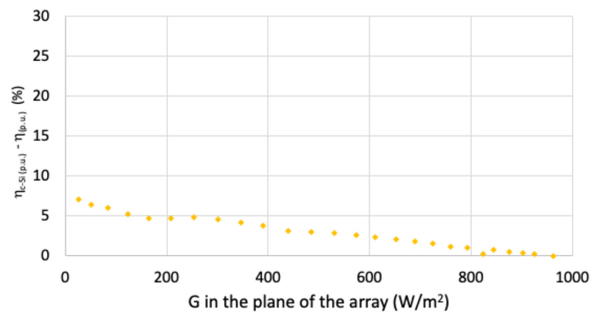

Figure 7: Reduction in efficiency with radiation of the CdTe generator with respect to the Si-x generator

Table 8 below shows that this decrease in efficiency with irradiance leads to a reduction in annual production with respect to crystalline silicon of about 0.6%.

TABLE 8: DIFFERENCES IN PRODUCTION (%) WITH RESPECT TO THE SI-X GENERATOR DUE TO THE DECREASE IN EFFICIENCY WITH IRRADIANCE.

Year	**1**	**2**	**3**	**4**	**5**	**Average**
%	-0.7	-0.7	-1.0	-0.6	0.0	-0.6

IV. CONCLUSIONS

Table 9 summarizes the main differences observed in the study over the five years analysed of a commercially available CdTe PV generator compared to a conventional crystalline silicone one under outdoor field conditions.

The CdTe generator has produced, on average, 4.7% less than the Si-x generator during the five years of the study.

Its better thermal performance has allowed it to reduce its temperature losses by 2.2% with respect to Si-x. However, this advantage is practically lost when, on the one hand, it has a worse efficiency at low irradiances, which has reduced its production by 0.6% with respect to Si-x, and, on the other hand, losses due to STC, which has reduced it by another 5.9%.

Finally, an average annual degradation ratio has been measured of 0.6% per year, which is twice the 0.3%/year measured for the Si-x generator

TABLE 9: SUMMARY OF THE DIFFERENCES BETWEEN THE CdTe and Si-x TECHNOLOGIES

Production differences per nominal kWp (%)	**P_{STC} differences (%)**	**Difference due to Tc (%)**	**Difference due to G (%)**
-4.5	-5.9	2.2	-0.6

ACKNOWLEDGMENT

This work was supported in part by the Spanish State Research Agency (AEI) under grants PID2019-111262RB-I00/AEI/10.13039/501100011033 and PID2019-110816RB-C21-I00/AEI/10.13039/501100011033.

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