# Analysis of a CIS based PV generator versus a multi-crystalline generator under outdoor long-term exposure

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***Abstract*— The worldwide growth of the PV market has been almost exponential during the last years. Together with conventional crystalline (c-Si) PV modules, "new" commercially available PV technologies such as copper indium selenide (CIS) based solar cells have appeared achieving a similar efficiency comparable to c-Si at similar production cost. In addition to the use of cheaper materials, CIS solar cells manufacturers claim some enhancements such as lower temperature coefficient or higher absorption of diffuse light that achieve to reduce the cost of electrical energy. Although several papers deal with this topic, little is known about real comparisons between CIS technology and conventional crystalline at a PV generator level with real test conditions. This paper analyses the in-field performance and degradation of a commercially available CIS solar based PV generator compared to a conventional c-Si one during four years of operation attributing the differences observed to the possible factors that can influence in both technologies.**

***Keywords*— solar energy; CIS based solar cells, c-Si solar cells, comparison, thin-film solar cells**

## I. Introduction

Despite conventional crystalline silicon (c-Si) solar cells monopolize the market more than 92% [1–4], both the continuous development and enhancement of thin film solar cells (TFSC) make that they are repeatedly being proposed as an alternative to conventional crystalline silicon [5–11].

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

Particularly, copper indium (gallium) selenide CI(G)S based solar cells have received worldwide attention since they have achieved 22.8% efficiency which is similar to c-Si solar cells [2,12] being proposed as an alternative to crystalline silicon.

TFSC manufacturers claim that they are able to produce more energy in principle possible by:

- Lower temperature coefficient.
- Good performance under lower and diffuse light.

However, there are some studies [3] which show that not always or, at least, it is not so clear that these enhancements in TFSC are true. Other studies try to clarify the behaviour of these technologies [4-10] but there are higher uncertainties in module parameters and there is no conclusive outcome to their performance compared to c-Si. Our work provides experimental data with some evidence in terms of energy yield that show some doubts about the expected behaviour of CIS technology.

## II. Experimental

### A. Test material

In this study, a commercially available CIS PV generator of 2320 W and a 2240 W conventional c-Si generator have been analysed. In a first approach, two modules of each generator, which is approximately the 10% of the modules, were characterized. According to IEC-60891 [11], the power of these samples was measured under real conditions and then extrapolated to standard test conditions (STC) before being installed at a PV plant. Following the methodology explained in [13], different measurements were taken with a capacitive load while measuring, at the same time, radiation and cell temperature with a calibrated cell. In an endeavour to avoid any misrepresentations between measurements, all of them were taken as close to STC as possible. To assure that, irradiance ($G$) was higher than 800 W.m$^{-2}$, wind speed lower than 5m/s and close to the solar noon restricting the air mass (AM) around to 1.5. Afterwards, datasheet temperature coefficient of the maximum power ($P_{MAX}$) was used to extrapolate measurements to STC. In addition, the experimental value of this coefficient was obtained before installing the modules outdoors.

The method followed to obtain the temperature coefficient of the maximum ($\gamma$) power consists of exposing the PV panels that were initially stored at ambient temperature to the sun. As soon as the PV module temperature started to rise, several IV measurements were taken. Trying to minimize uncertainty, measurements were taken when irradiance was near to 1000 W.m$^{-2}$, and by considering only moments with wind speed below 1m/s. Then, the maximum continuous power ($P_{M,DC}$) value is corrected to $G$=1000 W.m$^{-2}$ by the following equation (1):

$$P_{M,DC}^{1000} = P_{M,DC} \cdot \frac{1000}{G} \qquad (1)$$

Being $P_{M,DC}^{1000}$ the corresponding $P_{M,DC}$ values for $G$=1000 W.m$^{-2}$.

The value obtained is plotted versus cell temperature ($Tc$) and fitted to a line whose slope (in %) is just the temperature coefficient of the maximum power value, $\gamma$. Figure 1 shows this exercise for the CIS modules. The linearity observed in the corrected value denotes the validity of the process. Moreover, the characterization shows that the experimental value of γ, was very similar to that given by the manufacturer.

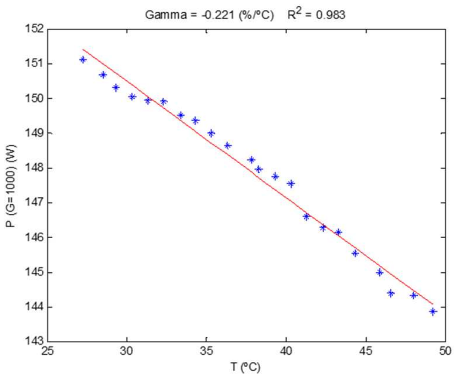



Figure 1: value of the temperature coefficient of the maximum power for the CIS manufacturer

## B. Installation

Once all the sample modules were characterized, they were deployed outdoors at a 30º tilted generator in March 2015. The location chosen was the North of Spain, particularly 42º 04'N, 1º 36'W.

Table 1 shows a summary of both generators and its characteristics.

TABLE 1: SUMMARY OF ALL THE GENERATORS MOUNTED IN THE EXPERIMENTAL

| Generator | Parallel Modules | Series Modules | Total Modules | Total Power (W) | γ (%/°C) |
|---|---|---|---|---|---|
| *c-Si* | 1 | 14 | 14 | 2240 | -0,45 |
| CIS | 4 | 4 | 16 | 2320 | -0,31 |

Both generators were connected to a 2.5 kW commercial inverter. Since the rated power of both generators is less than 2.4 kW, inverters will never limit the power delivered by the generators and will have no influence when making comparisons between manufacturers.

To measure the operating conditions of the generators, two c-Si reference modules were placed in the structure to measure the global radiation in the plane of the array. Both reference modules were calibrated by the CIEMAT [14].In addition, two Pt100 were also installed in each generator, which allow to measure the temperature of the same. Two MW100 ("Yokogawa") wattmeters are used to measure both DC and AC power of the generators. Data are measured every second but recorded as 10 minutes averages by the recorder MW100 [14].

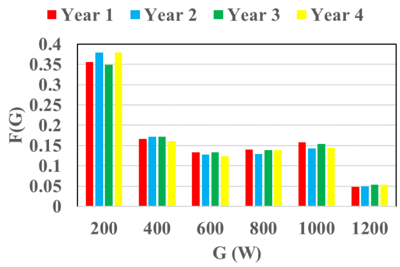
Table 2 shows the maximum uncertainty of each sensor used, acquired from the manufacturer datasheets.

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

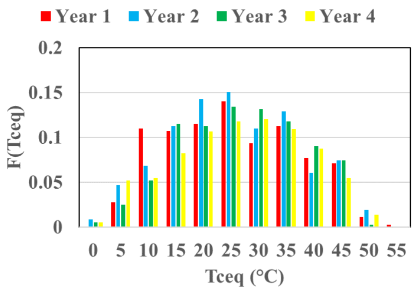
| Parameter | Manufacturer | Maximum uncertainty |
|---|---|---|
| DC Active Power | Yokogawa | ±(0.3% of reading + 0.2% of range) |
| Pt100 Temperature | Omega | B Class = ± 0.3˚C at nominal resistance (0˚C)<br>B Class = ± 0.8˚C at nominal resistance (100˚C) |
| Global Radiation 30º Si-x reference modules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

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

Figure 2 shows the main operating conditions in terms of daily irradiation in the plane of the array, $G$, and the c-Si equivalent PV module temperature, $T_{M,EQ,}$ which is defined as the average of the module temperature weighted by irradiance.




(a)




(b)

Figure 2: evolution of radiation (a) and equivalent temperature (b) along the operation time

## III. RESULTS

### *A. Energy produced per nominal kWp. Difference from crystalline silicon.*

Figure 3 shows the monthly production, per nominal (kWp), of the CIS generator referring to the production obtained in the c-Si generator. It is observed how the production is around 10% higher than that obtained with c-Si without large fluctuations with respect to the average value. It is worth mentioning that the gaps that appear in the figure correspond to a lack of data due to a malfunctioning of the datalogger.

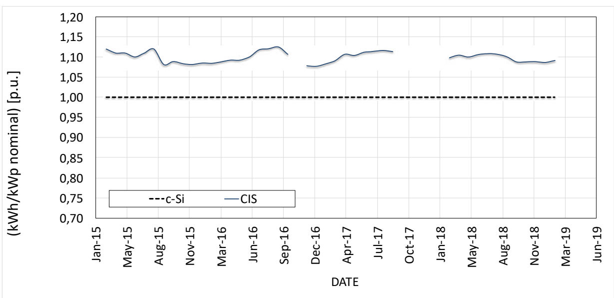



Figure 3: monthly energy produced per nominal kWp referred to the energy produce by the c-Si generator

The annual production difference, per nominal kWp, between the CIS generator and the c-Si one is shown in Table 3. The CIS generator has had an average annual production around 10% higher than that the c-Si generator in a fairly stable manner throughout the four years of study.

TABLE 3: PRODUCTION DIFFERENCE PER NOMINAL KWP (IN%) BETWEEN THE CIS GENERATOR AND THE REFERENCE C-SI GENERATOR.

| Year | 1 | 2 | 3 | 4 | Average |
|---|---|---|---|---|---|
| % | 9.1 | 9.8 | 10.9 | 9.9 | 9.9 |

### *B. Real STC power. Difference with respect to the nameplate power.*

Figure 4 shows the evolution of the STC power of both the CIS and c-Si generators over the 4 years for which data is available. STC power measurements were obtained from the wattmeter data [13]. There is no seasonal degradation, so the STC power has been modelled with a line with a slope equal to 0.3% / year.

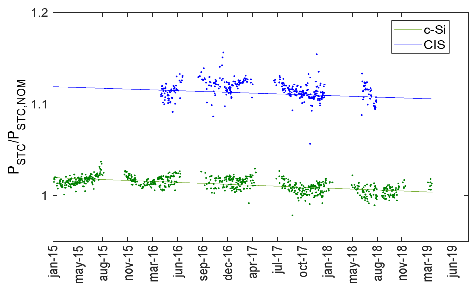



Figure 4: STC power measured for both the CIS and c-Si generators.

The average annual deviation of the STC power from the datasheet value measured in both generators is shown in Table 4. In addition, the table includes the annual degradation rate of the CIS generator, which, at 0.3% per year, turns out to be the same as that of crystalline silicon.

TABLE 4: AVERAGE STC POWER.

| Year | c-Si | CIS |
|---|---|---|
| 1 | 1.01 | 1.12 |
| 2 | 1.02 | 1.12 |
| 3 | 1.01 | 1.11 |
| 4 | 1.01 | 1.11 |
| Average | 1.02 | 1.11 |
| Average annual degradation | 0.3% / year | 0.3% / year |

It is surprising that STC power of the CIS generator was initially 12% above the data sheet value. In the c-Si generator, on the other hand, an STC power was around 1% higher than the datasheet value. From these values, it can be assumed that the difference in real STC power will be the main cause of the deviations observed in production. This fact can be observed in Table 5 where the differences in total annual production between the two technologies and the differences due to the difference in STC power are shown.

TABLE 5: ANNUAL PRODUCTION DIFFERENCES OF THE CIS GENERATOR COMPARED TO THE C-SI GENERATOR DUE TO STC POWER

| Year | 1 | 2 | 3 | 4 | Average |
|---|---|---|---|---|---|
| Total difference (%) | 9.1 | 9.8 | 10.9 | 9.9 | 9.9 |
| Difference due to $P_{STC}$ (%) | 8.8 | 9.1 | 10.7 | 9.7 | 9.6 |

Therefore, if the STC power of both generators were equal to the datasheet value, the annual production differences between the CIS generator and the c-Si generator would be only around 0.3%. In monthly production, no great differences have been observed either, as shown in Figure 5, in which the monthly productions of the two generators are represented if in both generators the STC power were equal to that given by the datasheet and referred to the monthly production of the c-Si. It can be seen from this figure that the CIS generator output is slightly higher in summer and slightly lower in winter.

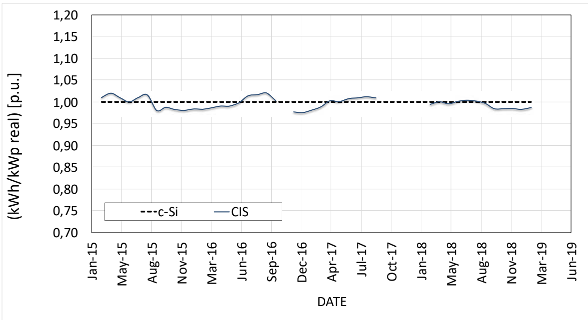



Figure 5: Monthly production that would there have been in case bot the generators had a real STC power equal to that of the datasheet.

## C. *Behavior against temperature.*

Figure 6 shows the evolution of the temperature of both the CIS and c-Si generator on two sunny days, one with wind and the other without wind. As can be seen, on windy days, the temperature of the generators is quite similar with differences of less than one degree. However, on days when there is no wind, the temperature of the CIS generator is 7 °C above that of the c-Si generator.

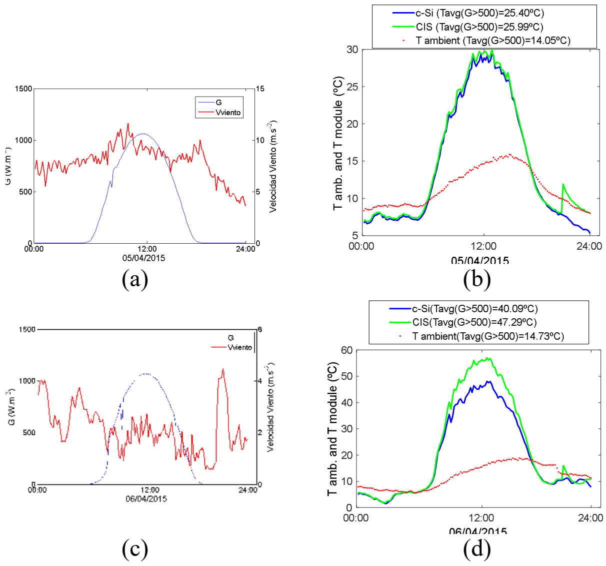



Figure 6: Evolution of the temperature of the CIS and c-Si generators on two sunny days, one with wind (a, b) and the other without wind (c, d).

In Table 6, the average temperatures over a year are shown, taking only the moments in which, the radiation is greater than 500 $W.m^{-2}$, together with the difference in temperature with respect to c-Si. As can be seen, the CIS generator temperature is, on average, around 2.6 °C above the c-Si generator, a fact that has a negative impact on temperature losses.

TABLE 6: AVERAGE TEMPERATURES THROUGHOUT A YEAR, TAKING ONLY THE MOMENTS IN WHICH, THE RADIATION IS GREATER THAN 500 $W.M^{-2}$, TOGETHER WITH THE TEMPERATURE DIFFERENCE WITH RESPECT TO THE C-SI GENERATOR.

| Technology | c-Si | CIS | Ambient Temperature |
|---|---|---|---|
| $T_{average}$ G> 500 (ºC) | 32.82 | 35.44 | 16.10 |
| Difference (ºC) | 0 | 2.60 | - |

On the other hand, the CIS generator presents a lower variation in its efficiency with operating temperature, as reflected in its coefficient of variation of power with temperature, $\gamma$ (Table 7). The efficiency of crystalline silicon modules is reduced by 0.45% for each degree that the operating temperature rises, while, in the CIS generator, the efficiency is only reduced by around 0.3% for each degree. It should be noted that, as can be seen in TABLE 7, the experimental value that was measured for these coefficients is similar to that provided by the manufacturer in their datasheets.

TABLE 7: COEFFICIENT OF VARIATION OF POWER WITH TEMPERATURE.

| Technology | γ Experimental value (% /° C) | γ Datasheet value (% /° C) |
|---|---|---|
| CIS | -0.27 | -0.31 |
| c-Si | -0.5 | -0.45 |

As can be seen inTable 8, where the production differences due to temperature losses are shown, the positive fact of having a lower γ, has a greater influence than the negative fact of working with higher temperature, so that, finally, the losses due to temperature in the CIS technology are 1% lower than those of the c-Si generator. When evaluating the data in this table, it must be considered that, during a significant part of the last year analysed (year 5), the data from the temperature sensors of the CIS generator were lost and the temperature could not be calculated. This fact probably justifies the difference compared to the rest of the years.

TABLE 8: DIFFERENCE IN ANNUAL PRODUCTION (%) OF THE CIS GENERATOR WITH RESPECT TO THE C-SI GENERATOR, DUE TO TEMPERATURE.

| Year | 1 | 2 | 3 | 5 | Average |
|---|---|---|---|---|---|
| % | 1.0 | 1.0 | 1.7 | 0.6 | 1.1 |

*D. Behavior against irradiance value.*

In Figure *7*, the monthly production of the CIS and c-Si generators is shown, removing the effects of different STC power and temperature losses, and referencing them to the monthly production of the c-Si generator. Comparing this figure with Figure 5, it can be seen that, by removing the effect of the better behaviour of the CIS generator with temperature, its production would be the same in the summer months and slightly lower in the winter months.

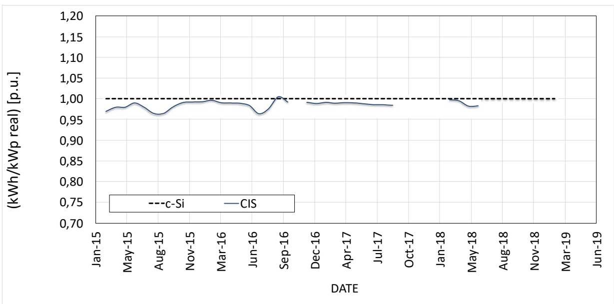



Figure 7: Monthly production of both the CIS and c-Si generators, referred to that of the latter, which would be had if the module temperature of both generators was always 25ºC and both had an STC power equal to the datasheet.

Figure *8* shows that the CIS generator presents a variation in efficiency at 25 °C with the irradiance slightly lower than that of the c-Si generator for radiations below 800 $W.m^{-2}$.

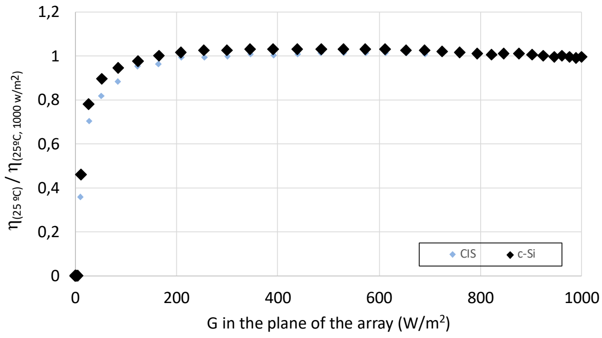



Figure 8: Efficiency variation at 25ºC with irradiance that has been measured for both the CIS and c-Si generators.

Figure *9* represents the decrease in efficiency suffered by the CIS generator with respect to the crystalline silicon generator, expressed in %. It can be seen that, with irradiance values around 600 $W.m^{-2}$ the efficiency of the CIS generator is around 1.5% lower.

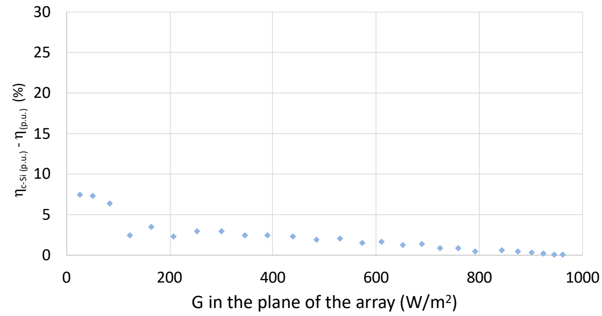



Figure 9: Decrease in the efficiency suffered by the CIS generators with respect to the crystalline silicon generator.

In Table 9, the production differences due to efficiency are shown as a function of irradiance. As can be seen, the deviations are not stable over the four years. This is probably due to the lack of data availability, especially during the first and last year. Therefore, it is most likely that the losses due to this factor will be around 0.9%, a value obtained as an average of the four years for which data are available.

TABLE 9: ANNUAL PRODUCTION DIFFERENCE (%) WITH RESPECT TO THE CRYSTALLINE SILICON GENERATOR DUE TO THE DECREASE IN EFFICIENCY WITH IRRADIANCE.

| Year | 1 | 2 | 3 | 4 | Average |
|---|---|---|---|---|---|
| Difference due to G (%) | -1.5 | -0.7 | -0.9 | -0.4 | -0.9 |

## IV. Conclusions

A currently commercially available CIS PV generator has been analysed and compared to a conventional crystalline silicone one under field conditions over the course of 4 years. They have been compared in terms of energy attributing the differences observed to the possible factors that can influence in both technologies.

The CIS generator has produced, on average, in the four years of study, 9.9% more than c-Si generator. As it has been presented, the CIS technology presents a coefficient of variation of power with temperature lower than that of c-Si, 0.31%/°C compared to 0.45% / ° C. However, the CIS module temperature has been, on average, 2.6 ° C above that of c-Si, which has limited the gain due to having a better coefficient at 1.1%. In addition, the CIS generator showed a slightly worse behaviour at low irradiance than c-Si, which has resulted in a 0.9% loss in production.

In this way, it can be stated that the difference between the production of the CIS technology and that of crystalline silicon is mainly due to the difference in STC power. In other words, a generator of this technology would produce 0.3% more than a crystalline silicon generator that had the same STC power. Since in this test the CIS generator presented a real STC power 11% higher than the datasheet value and the c-Si generator was 1% higher than the same, the difference in production has been 10%, which corresponds with the difference in actual STC power.

Table 10 shows a summary of the main differences observed in the study over the four years analysed.

TABLE 10: CIS VS. C-SI TECHNOLOGY SUMMARY

| **Production differences per nominal kWp (%)** | **$P_{STC}$ differences (%)** | **Difference due to Tc (%)** | **Difference due to G (%)** |
|---|---|---|---|
| 9.9 | 9.6 | 1.1 | -0.9 |

## References


[1] Research and Markets, Global Thin-Film Module Market - Forecasts from 2020 to 2025, 2020. https://www.researchandmarkets.com/reports/5174311/global-thin-film-module-market-forecasts-from?utm_source=GNOM&utm_medium=PressRelease&utm_code=zh9vbb&utm_campaign=1470965+-+Global+Thin-Film+Module+Market+(2020+to+2025)+-+Players+Include+United+Solar+Ov.

[2] J. Ramanujam, U.P. Singh, Copper indium gallium selenide based solar cells - A review, Energy Environ. Sci. 10 (2017) 1306–1319. https://doi.org/10.1039/c7ee00826k.

[3] Fraunhofer, Photovoltaic Report, (2016). https://doi.org/26.05.2014.

[4] Kristin Seyboth, F. Sverrisson, F. Appavou, A. Brown, B. Epp, A. Leidreiter, C. Lins, E. Musolino, H.E. Murdock, K. Petrichenko, T.C. Farrell, T.T. Krader, A. Tsakiris, J.L. Sawin, J. Skeen, B. Sovacool, Renewables 2016 Global Status Report, 2016. https://doi.org/ISBN 978-3-9818107-0-7.

[5] S. Hegedus, Thin Film Solar Modules: The Low Cost, High Throughput and Versatile Alternative to Si Wafers, Prog. Photovolt Res. Appl. 14 (2006) 393–411. https://doi.org/10.1002/pip.

[6] P. Mints, The commercialization of thin film technologies: Past, present and future, in: Photovolt. Spec. Conf. (PVSC), 2010 35th IEEE, 2010: pp. 2400–2404.

[7] D.L. Taesoo, U.E. Abasifreke, A review of thin film solar cell technologies and challenges, Renew. Sustain. Energy Rev. (2016) 0–1. https://doi.org/10.1016/j.rser.2016.12.028.

[8] M. Powalla, B. Dimmler, Scaling up issues of CIGS solar cells, Thin Solid Films. 361 (2000) 540–546. https://doi.org/10.1016/S0040-6090(99)00849-4.

[9] B. Dimmler, M. Powalla, H.W. Schock, CIS-based thin-film photovoltaic modules: potential and prospects, Prog. Photovoltaics Res. Appl. 10 (2002) 149–157. https://doi.org/10.1002/pip.413.

[10] S. Kim, J.Y. Song, D. Kim, J. Hong, I.J. Cho, Y.H. Kim, J.U. Jeong, M.S. Yoon, S.J. Ahn, W.K. Chung, T.K. Nam, S. Cho, Effect of novel double treatment on the properties of CdTe solar cells, Energy Reports. 7 (2021) 1396–1403. https://doi.org/10.1016/j.egyr.2021.02.070.

[11] M. Green, E. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, X. Hao, Solar cell efficiency tables (version 57), Prog. Photovoltaics Res. Appl. 29 (2021) 3–15. https://doi.org/10.1002/pip.3371.

[12] N.E.I. Boukortt, S. Patanè, Y.M. Abdulraheem, Numerical investigation of CIGS thin-film solar cells, Sol. Energy. 204 (2020) 440–447. https://doi.org/10.1016/j.solener.2020.05.021.

[13] F. Martínez-Moreno, E. Lorenzo, J. Muñoz, R. Moretón, On the testing of large PV arrays, Prog. Photovoltaics Res. Appl. (2011). https://doi.org/10.1002/pip.

[14] CIEMAT, No Title, Cent. Energy-Related, Environ. Technol. Res. Spain. (n.d.). https://www.ciemat.es/.