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# Accuracy of PVSyst Simulations in the Reproduction of the Yield Performance of Multicrystalline, Monocrsytalline and Monocasting Modules in Outdoor Conditions

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**Abstract.** In this study we performed field tests on three small installations consisting of 12 modules each and next to each other, all of them using exactly the same manufacturing technology for cells and modules and employing the same manufacturing equipment and raw materials. The only difference between the systems was the wafer technology used. Two of them were manufactured through the same casting technology (Direct solidification system-DSS) and the same equipment: in one of them we grew mc-Si and in the other one CM-Si (mono casting). In the third system we used traditional Czochralski monocrystalline wafers as technology. Two of the facilities (the DSS based ones) have been closely monitored for three years, and the traditional monocrystalline one for 17 months. For the three installations the performance data is shared and compared with PVsyst simulations and correlated well to each other.

**Keywords:** Silicon, Cast-Mono, Multicrystalline, Monocrystalline, Outdoor Performance, Simulation.

## 1. INTRODUCTION

On the journey to reduce the cost of solar modules several silicon growing techniques have been explored to grow the wafers the cells are based on [1]. The most utilized ones have been the multicrystalline and the monocrystalline ones, being the latter the current winner [2]. Mono casting was also employed during the last decade [3], with several GWs of modules on the field, but no data has been shared to date on the performance of those modules. This would be valuable information to assess the potential of the mono casting technology, which offers cost advantages as compared to the multi- and mono-crystalline ones.

In this study we performed field test on three small installations to compare the performance of multicrystalline, monocrystalline and mono-cast silicon PV modules, and benchmarked the monitored experimental data with PVSyst simulations [4].

# 2. EXPERIMENTAL PROCEDURE

## 2.1 Description of Installation

The generators used for this experiment consisted of 12 pieces of glass-backsheet PV modules model CS3U-P and CS3U-MS manufactured by Canadian Solar, each mounted on a typical two rows portrait fixed racking system. One of the systems used CS3U-P (P3) mc-Si modules for a total of 4.06 kWp (Array mc) while the other used CS3U-P (P5) CM-Si modules for a total of 4.5 kWp (Array CM), and the last one used CS3U-MS monocrystalline modules [1] for a total of 4.54 kWp (Array Cz). The systems were located next to each other in the Canadian Solar testing facility in Suzhou China (coordinates N 31.3 E 120.8), south oriented, 25º tilt and without shadowing, as shown in fig. 1. All the systems' modules were manufactured at the same facility and with the same equipment and technology (PERC- passivated emitter and rear cell) but for the crystal growth technology that was different on each of them as described before. Their temperature coefficients, as provided by the manufacturer, are listed in table 1.

***Table 1.*** *Temperature Coefficients*

| Temperature Coefficient | γ (Pmax) (%/ºC) | β (Voc) (%/ºC) | α (Isc) (%/ºC) |
|---|---|---|---|
| CS3U-335P(P3)(mc-Si) | -0.38 | -0.31 | 0.05 |
| CS3U-370P(P5) (CM-Si) | -0.37 | -0.29 | 0.05 |
| CS3U-390MS (Cz-Si) | -0.37 | -0.31 | 0.05 |


***Figure 1****. Field trial test general view.*

The generators were connected to the grid through a Huawei Sun 2000-10 KLT inverter of 10 kW. The equipment used for monitoring was the same in all arrays as it was for the position of the sensors (listed in table 2).

***Table 2.*** *Measurement Equipment List.*

| Equipment | Vendor | Model | Tolerance |
|---|---|---|---|
| DC Meter | GMC-I | V604s-20A | Voltage：±0.2% Current：±0.2% |
| Wind speed sensor | Met one | 034b | V<10.1m/s：±0.1m/s<br>V>10.1m/s：±1.1%*display value |
| Wind direction | Met one | 034b | ±4° |
| Rain sensor | Intell-sun | PHYL | ±4% |
| Ambient temperature sensor | Rotronic | HC2S3 | ±0.1℃@20℃；±0.3℃@-40℃ |
| Humidity sensor | Rotronic | HC2S3 | ±0.8%*display value |
| Pyranometer | Kipp & Zonen | CMP10 | Yearly instability <0.5% |

| | | | |
|---|---|---|---|
| Module temperature sensor | SUYI | PT100 | ±0.2℃@25℃ |

Before starting the monitoring campaign outdoor light soaking was performed. Detailed measured module electrical parameters under Standard Test Conditions (STC) after 120 kWh/m$^2$ outdoor exposure are shown in Table 3. The initial output power under STC is depicted as well.

***Table 3***. *Modules STC Electrical Information Summary: initial power and parameters after 120 kWh/m$^2$ outdoor exposure.*

| Array mc | SN | Initial Power （W） | Pm [W] | Vm [V] | Im [A] | Voc [V] | Isc [A] |
|---|---|---|---|---|---|---|---|
| 1 | Y1019206450004 | 337.21 | 337.0 | 38.3 | 8.79 | 46.1 | 9.26 |
| 2 | Y1019206450005 | 337.53 | 338.4 | 38.4 | 8.81 | 46.2 | 9.27 |
| 3 | Y1019206450006 | 339.01 | 337.2 | 38.4 | 8.79 | 46.1 | 9.25 |
| 4 | Y1019206450007 | 338.02 | 337.2 | 38.4 | 8.79 | 46.1 | 9.25 |
| 5 | Y1019206450008 | 338.61 | 339.0 | 38.4 | 8.83 | 46.2 | 9.3 |
| 6 | Y1019206450009 | 338.36 | 338.0 | 38.4 | 8.81 | 46.1 | 9.28 |
| 7 | Y1019206450010 | 337.00 | 339.6 | 38.4 | 8.85 | 46.1 | 9.31 |
| 8 | Y1019206450012 | 339.63 | 337.5 | 38.4 | 8.79 | 46.1 | 9.27 |
| 9 | Y1019206450013 | 338.51 | 338.5 | 38.4 | 8.81 | 46.1 | 9.28 |
| 10 | Y1019206450015 | 338.65 | 339.0 | 38.4 | 8.82 | 46.2 | 9.3 |
| 11 | Y1019206450016 | 339.02 | 338.7 | 38.4 | 8.81 | 46.2 | 9.27 |
| 12 | Y1019206450017 | 337.21 | 338.6 | 38.4 | 8.82 | 46.2 | 9.27 |
| Sum | | | 4058.7 | | | | |

| Array CM | SN | Initial Power （W） | Pm (W) | Vm (V) | Im (A) | Voc (V) | Isc (A) |
|---|---|---|---|---|---|---|---|
| 1 | Y1019206450052 | 374.25 | 375.1 | 39.4 | 9.52 | 48.1 | 10.02 |
| 2 | Y1019206450053 | 375.27 | 374.3 | 39.4 | 9.5 | 48 | 10 |
| 3 | Y1019206450054 | 373.67 | 375.3 | 39.4 | 9.52 | 48.1 | 10.02 |
| 4 | Y1019206450055 | 374.47 | 375.5 | 39.4 | 9.53 | 48.1 | 10.02 |
| 5 | Y1019206450056 | 375.13 | 375.7 | 39.4 | 9.53 | 48.1 | 10.04 |
| 6 | Y1019206450057 | 375.01 | 375.0 | 39.4 | 9.52 | 48.1 | 10.01 |
| 7 | Y1019206450058 | 372.71 | 374.5 | 39.4 | 9.51 | 48 | 10.01 |
| 8 | Y1019206450059 | 374.85 | 374.9 | 39.3 | 9.53 | 48 | 10.04 |
| 9 | Y1019206450060 | 374.58 | 373.7 | 39.4 | 9.5 | 48 | 9.99 |
| 10 | Y1019206450061 | 375.74 | 374.6 | 39.4 | 9.51 | 48.1 | 10.03 |
| 11 | Y1019206450066 | 373.89 | 372.7 | 39.3 | 9.48 | 48.1 | 9.96 |
| 12 | Y1019206450069 | 375.52 | 373.9 | 39.5 | 9.47 | 48.2 | 9.94 |
| Sum | | | 4495.2 | | | | |

| Array CZ | SN | Initial Power （W） | Pm (W) | Vm (V) | Im (A) | Voc (V) | Isc (A) |
|---|---|---|---|---|---|---|---|
| 1 | Y1019246361116 | 377.71 | 377.7 | 39.78 | 9.49 | 48.14 | 10.02 |
| 2 | Y1019246361114 | 377.99 | 378.0 | 39.89 | 9.48 | 48.15 | 10.04 |
| 3 | Y1019246361108 | 377.37 | 377.4 | 39.98 | 9.44 | 48.07 | 10.04 |
| 4 | Y1019246361121 | 377.26 | 377.3 | 39.77 | 9.49 | 48.13 | 10 |
| 5 | Y1019246361112 | 378.24 | 378.2 | 39.79 | 9.5 | 44.16 | 10.04 |
| 6 | Y1019246361111 | 378.92 | 378.9 | 39.89 | 9.5 | 48.16 | 10 |
| 7 | Y1019246361115 | 376.66 | 376.7 | 39.87 | 9.45 | 48.11 | 10.03 |
| 8 | Y1019246361113 | 378.79 | 378.8 | 39.77 | 9.52 | 48.12 | 10.04 |
| 9 | Y1019246361118 | 377.89 | 377.9 | 39.66 | 9.53 | 48.03 | 10.04 |
| 10 | Y1019246361117 | 378.06 | 378.1 | 39.76 | 9.51 | 48.12 | 10.01 |
| 11 | Y1019246361109 | 378.03 | 378.0 | 39.73 | 9.52 | 48.06 | 10.03 |
| 12 | Y1019246361110 | 379.58 | 379.6 | 39.77 | 9.54 | 48.18 | 10.05 |
| Sum | | | 4536.5 | | | | |

Arrays CM and mc were measured from 26th of July of 2019 until 19th of July of 2022 while array Cz was measured from 20th of August 2019 until 31st of December 2020. System performance (DC and AC Voltage and Current and AC Power) and ambient data (ambient and module temperature measured at 4 different points for each array, wind speed and direction, inclined plane irradiance and horizontal irradiance and rain) were measured every minute. The average monthly irradiance was 100 kWh/m$^2$ with a maximum of 163,95 kWh/m$^2$ and a minimum of 20 kWh/m$^{2.}$

# 3. RESULTS AND DISCUSSION

The energy yield of the three arrays were modelled with commercial simulation software PVSyst , and the results were compared to the measured data.

Thanks to the long testing period we can assume that the data represent any climatic condition at the location.

The modules appearance through visual inspection showed no significant aging or degradation or hot spots or any other performance phenomena at the end of the monitoring period.

A summary of PVSyst simulation inputs parameters is shown in table 3. The low light performance data were determined by taking the average values of actual laboratory test measurements of the modules used and the thermal factor that was provided by the manufacturer.

***Table 4.*** *PVSyst Input parameters*

| **Low light (W/m$^2$)** | **CS3U-335P(P3)(mc-Si)** | **CS3U-370P(P5) (CM-Si)** | **CS3U-390MS (Cz-Si)** |
|---|---|---|---|
| 200 | -4.20 | -1.30 | -3 |
| 400 | -1.70 | 0.20 | -0.8 |
| 700 | -0.40 | 0.40 | 0 |
| 800 | -0.40 | 0.20 | 0.20 |
| Thermal Loss Factor Uc (W/m$^2$K) | 30.1 | 31.7 | 31 |

Figure 2 shows the monthly energy yield of the three systems in kWh/kWp both measured and simulated. We notice that in every single month the performance of the CM-Si based system is better with an average of 1.54% higher energy yield than the mc-Si based one and of 1.00% of the Cz one. For the simulations this difference is slightly higher: 1.73% and 1.02% respectively.

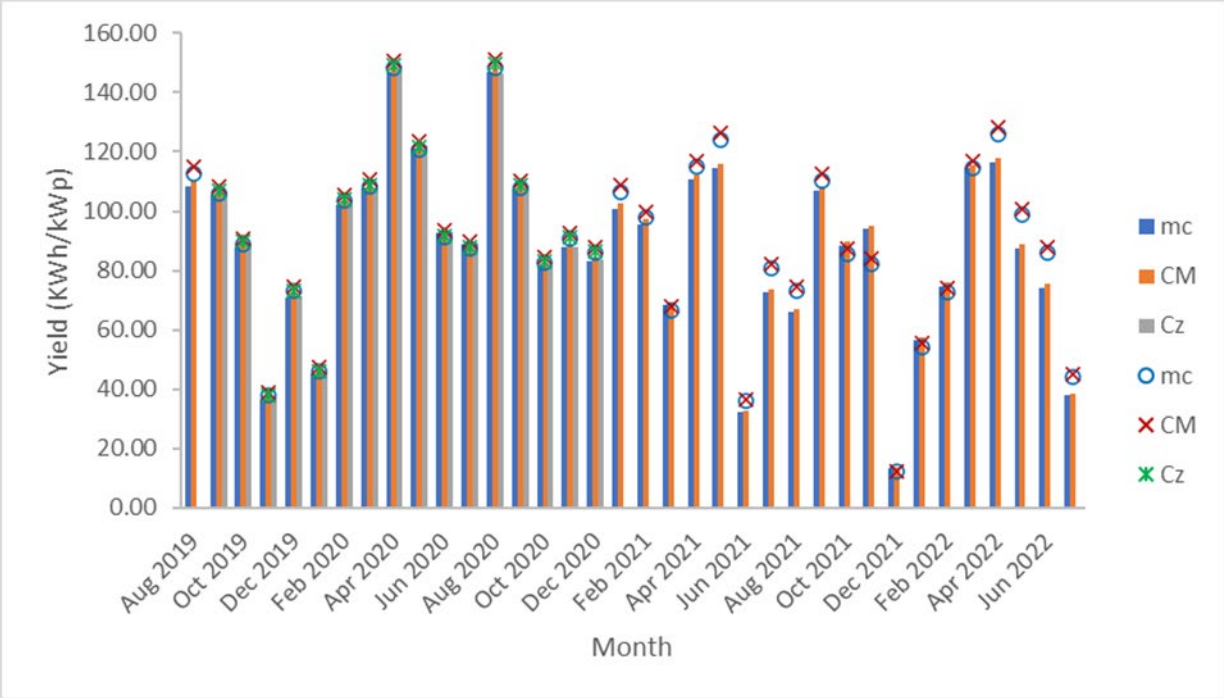


***Figure 2.*** *Measured (bars) and simulated (crosses) yield of the three arrays.*

Figure 3 shows the correlation between measured and simulated data for the three systems and as it can be noticed the CM system does not show a significant different performance than mc and Cz modules. PVSyst simulations are pretty accurate for the three modules systems:, the difference between simulated results and measured results was verified by the index of MBE/AV (Mean Bias Error over Absolute Value) and it was between 1% and 3% for the three systems, while the RMSE (Root Mean Squared Error) was between 1% to 5% that are considered reasonable errors for a simulation as reported by Freeman et al. [5].

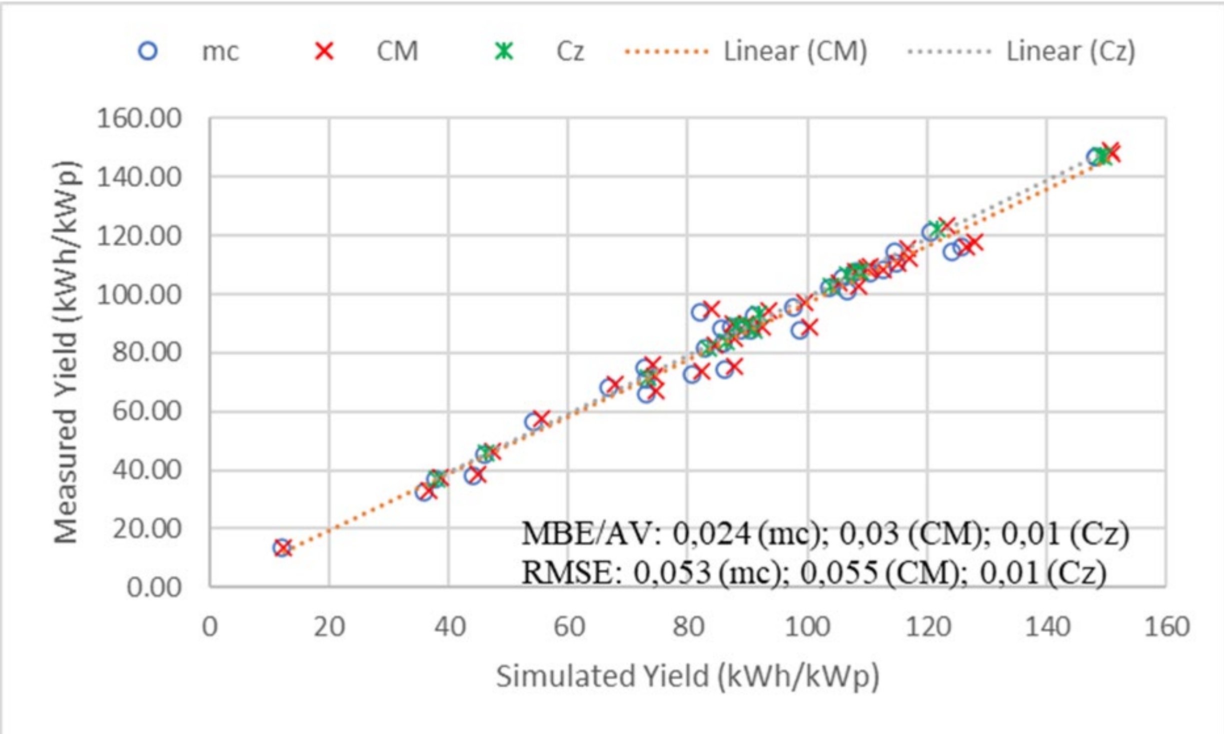


***Figure 3.*** *Measured and simulated results correlation*

There is extensive literature about the validity of simulation tools for yield performance analysis [6] and of PVSyst in particular as a valid software tool that is extensively used in science and commercial simulations. There are several parameters to pay attention to in order to obtain a simulation that represents the system properly as we managed to do in this work. Beyond the obvious accurate representation of the system on parameters such as shading, dust, etc. one of the most important variables to consider is the meteorological data base to be used. In our simulation we used a local weather station with which we could maximize the accuracy of the simulation.

# 4. CONCLUSIONS

There are several GW of mono-cast modules on the field and the results obtained from this study demonstrate that is a very valid technology that does not show signs of relevant degradation after several years of operation. The energy yield over time has been measured and simulated and compared among the three technologies, showing that the mono-cast modules simulations correlate as well as the other technologies. The behavior of these technologies in simulations and in the field is very similar among the three technologies.

It has been reported that the energy required to grow cast-mono modules is less than the one required to grow Cz-Si ones resulting in a lower carbon footprint. There are several GW of mono-cast growers that are abandoned and will be scrapped. We suggest further exploration of this technology and a better use of the equipment available in the industry to optimize the carbon footprint.

## Data availability statement

The data supporting this research will be made available to whoever showing interest in excel format, please contact the correspondence author to request the excel files.

## Author contributions

Ismael Guerrero: Conceptualization, formal analysis, investigation, methodology, visualization, writing.

Carlos del Cañizo: Funding acquisition, resources, supervisión, validation, writing review & editing.

Yuanjie Yu: Data curation, software, validation. writing review & editing.

## Competing interests

The authors declare that they have no competing interests.

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