ONE YEAR PERFORMANCE ASSESSMENT OF SLICON HETERO-JUNCTION SOLAR MODULES ON HORIZONTAL SINGLE AXIS TRACKER

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ABSTRACT: The deployment of single-axis tracker bifacial PV systems is attracting the interest of several PV operators particularly targeting the utility-scale market segment. The main driver is the lowest Levelized cost of electricity (LCOE) achievable by this solution due to the increased energy yield. This paper presents the results of one full year of monitoring data from a pilot PV system realized in the framework of the H2020 European project, GOPV. The PV pilot plant is installed in Cadarache (France) and consists of bifacial half-cell silicon heterojunction (HJT) PV modules combined with Horizontal Single Axis Trackers (HSAT), east-west sun tracking.
This work compares the monthly gain of the energy yield of the bifacial HJT technology, installed both on a tilted fixed structure and on a HSAT tracker, with a PERC monofacial technology installed on tilted fixed structure, which serves as a reference system.
The results highlight that, compared to the benchmark technology, the energy yield of the bifacial HJT on a fixed structure can achieve an average of 15% gain on annual basis, and the HJT bifacial on HSAT can exceed 35% during the summer months. This study also includes insights from the experience gathered in one year of activity on the influence of wind parameters on tracking yield.
Keywords: PV system, HJT, bifacial gain, single-axis tracker, PV monitoring

1 INTRODUCTION

In recent decades, photovoltaic (PV) technology has proved to be one of the most reliable renewable energy sources contributing to the widespread use of crystalline silicon (c-Si) photovoltaic modules in various installations. Thanks to the technological improvements, the efficiency of the solar cells has progressively increased, and new efficient technologies have rapidly taken the place of the previous ones; let's think for example how the PERC technology (passivated emitter and rear-contact) has progressively replaced the traditional AlBSF (aluminium back surface field) cell, or other improvements such as the introduction of half-cells or the adoption of larger cell sizes.
In more recent times, the bifacial technology - capable of capturing solar radiation from both surfaces (upper and lower) - is rapidly eroding the market share of monofacial technologies and it is expected that within the next 10 years it will cover a share of the global market by more than 50%, while about 20% of the single-sided module market will use bifacial cells. [1]
The main advantage of this technology consists in the greater energy obtainable for the same surface area, quantifiable with the "Bifacial Gain" index, corresponding to the additional fraction of the total energy that a bifacial photovoltaic system can provide compared to a monofacial system of the same orientation and size.
The Bifacial Gain can be further expanded if other *factors* affecting the energy performance of the bifacial modules are considered in the design phase [1], such as the albedo, the type of mounting structure (fixed or single-axis tracker), the elevation of the modules, the Ground Coverage Ratio –(GCR), the space between the PV modules on the structure and, finally, the climatic zone of the installation site.
The energy gain also depends on the bifaciality of the PV module itself, i.e., the ratio between the nominal power of the rear side of the module and that of the front side.
Typically, the bifaciality ratio is in the range of 70% to 85% for most bifacial modules currently on the market; with silicon heterojunction technology - HJT - it is possible to have up to 85% of bifacial ratio and a potential of 100% that can be reached with careful optimization. [1]
The bifacial technology, coupled with single-axis tracking structures, can increase the energy yield of PV systems, compared to a monofacial installation on fixed tilted structures. A recent study has in fact indicated the bifacial single-axis trackers is the solution with the lowest LCOE (Levelized cost of electricity) for the vast majority of potential PV sites on the planet [2]; this result, combined with the progressive decline in the prices of single-axis trackers, makes this solution suitable for the utility- scale PV systems.
Although the bifacial technology combined with tracker is already largely used in utility scale PV installations, there is scientific interest in the study of models able to estimate, with high precision, the producibility of the PV installation, taking into account the *factors* that mainly affect the energy yield of this solution. Moreover, the PV operator are also interested in finding solutions to increase the producibility of bifacial PV system, optimize the O&M measures, reducing at the same time the LCOE costs.
This paper aims to illustrate the results of one full year of performance assessment of Heterojunction (HJT) bifacial technology combined with Horizontals Solar Axis Tracker (HSAT), with respect to a standard monofacial module (PERC) mounted on a fixed tilted structure that is considered as reference in this analysis. The pilot PV system has been realized in the framework of a H2020European project, GOPV (Global Optimization of integrated PhotoVoltaic system for low electricity cost).

2 METHODS

2.1 Cadarache Solar PV system description

The PV solar system is located in Cadarache (France,

43°N) and consists of a fixed tilted structure and three horizontal single-axis trackers (HSAT).
The fixed tilted structure is south oriented while the three trackers are aligned along the north-south axis.
Both types of structure host respectively two PV technologies: the monofacial PERC and the half-cell silicon heterojunction (Bfc-HJT), the latter made within the GOPV project.
The **Table 1** summarizes the nominal power on the DC side, for each PV plant.

Table 1 PV system installed in the Cadarache pilot and the respective Nominal Power of the DC string

	Fixed		HSAT	
N. Modules	8		8	
N. Strings	1		1	
Layout	P		2P	
Technology	HJT Bfc	PERC Mfc	HJT Bfc	PERC Mfc
P_{STC}*[kW]*	2,95	2,56	2,97	2,56
Tilt	30°	30°	+/-55°	+/-55°
Elevation [m]	1	1	2,3 (*)	2,3 (*)
Albedo [avg]	0,25			
Soil Material	Gray gravel			

P – Portrait; 2P – two module in Portrait;
Bfc – Bifacial; Mfc – Monofacial
(*) average height of the tracker

Figure 1 shows the modules layout of fixed tilted structure and of horizontal single-axis trackers.

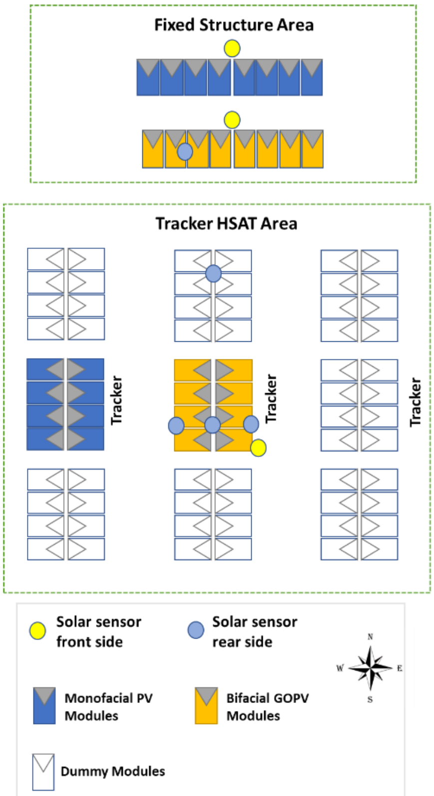


Figure 1 Modules layout of fixed tilted structure and horizontal single-axis trackers

The fixed test bench is equipped with one front side and one rear side solar sensors, as well as a sensor temperature respectively installed for each PV technology.
The tracker test bench is equipped with two front side and four rear side solar sensors, as well as a temperature respectively installed for each PV technology.

2.2 Energy Yield comparison

A comparative analysis is performed between bifacial HJT technology and monofacial PERC installed on the same fixed structure. Then a second comparison is performed between bifacial HJT on a tracker and the monofacial PERC on fixed structure (reference technology).
PV data have been collected from March 2020 to March 2022 for PV system on Fixed structure and from November 2020 to March 2022 for the PV system on tracker. All data are aggregated on a monthly basis.
In 2021, problems with the data collection occurred on all sets installed on trackers (from 10/06/2021 to 15/06/2021). For a reliable comparison analysis of the different PV systems installed, overall data (all data collected in the test period) and filtered data (removing invalid periods) are used for data analysis reported in this section. No main issues occurred in data collection of PV systems installed on Fixed.
All the evaluations have been performed considering the same time period of analysis and synchronizing all datasets: the corresponding records with invalid data were deleted from all datasets in order to avoid the underestimation or overestimation of the columns of variables unaffected by invalid values and errors.
Since, the bifacial and monofacial PV strings converge into a single inverter, the AC-side energy generation for each technology is not available. For this reason, all data and results reported in this section relate to DC data for all systems.

2.3 Performance Metrics

Two performance indicators are used for this analysis: the *Energy Yield* and the *Bifacial Gain.*
The Energy Yield represents the net DC energy output ($E_{DC,}$ [kWh])from the PV string during a period (a month), normalized to the DC rated power in STC ($P_{STC,}$ [kWp]) and it is calculated in accordance with IEC 61724-1 [3] as:

$$Y_{a,month} = \frac{E_{DC}}{P_{STC}}$$

The Bifacial Gain is defined as the additional fraction of the total energy that a bifacial PV system will produce compared to a monofacial system with the same orientation and inclination [1]it is calculated as:

$$Bg = \frac{(Y_b - Y_m)}{Y_m}$$

where Y_b and Y_m are respectively the Energy yield of bifacial and monofacial systems

3 RESULTS

3.1 Backside irradiance assessment

Figure 2 and **Figure 3** show the monthly irradiance respectively for the tilted fixed structures and the tracker structures. In both graphs, the orange bar represents the rear side irradiance contribution.
The months of February and April 2021 are particularly characterized by cloudy skies and rains, while on July 21, a failure lasting two days occurred in the front side solar

sensor of the fixed structure; this explains the lower radiation compared to previous months. (**Figure 2**)
In general, for both structures, it can be observed that the amount of rear-side radiation is less during the winter period due to fewer sunny days with clear skies, lower radiation, and lower sun elevation (winter solstice) that generate longer shadows that cover the ground. During the summer months, the rear-side radiation tends to increase.

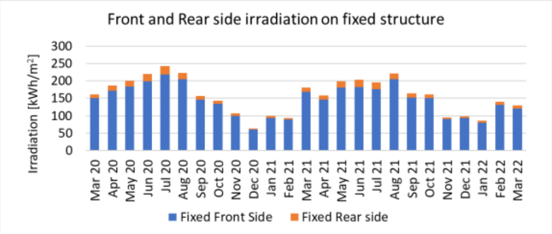


Figure 2 Front and Rear side irradiation on fixed structure

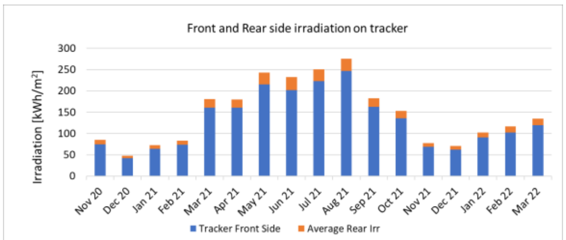
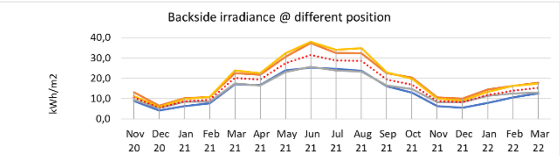


Figure 3 Front and Rear side irradiation on tracker.

Figure 4, shows the rear-side irradiation measured in the tracker where four solar sensors are installed. It can be noted that during the summer months the rear-side inhomogeneity becomes more evident between the middle and edge of the structure. The dotted red line represents the average value of the four solar sensors.



	Nov 20	Dec 20	Jan 21	Feb 21	Mar 21	Apr 21	May 21	Jun 21	Jul 21	Aug 21	Sep 21	Oct 21	Nov 21	Dec 21	Jan 22	Feb 22	Mar 22
Middle Rear Cell 3	8,8	4,1	6,3	7,5	16,9	16,5	23,9	25,2	24,6	23,6	16,0	12,8	6,3	5,4	7,8	10,5	12,5
West Rear Cell 4	13,1	6,4	10,2	10,8	22,5	21,6	30,4	37,2	32,3	32,2	22,5	20,3	10,5	10,0	14,4	16,2	17,9
Middle Rear Cell 5	9,4	5,3	8,3	8,4	17,4	16,3	23,1	25,6	23,9	23,3	16,3	14,6	8,2	8,1	11,3	12,5	13,0
East Real Cell 6	11,2	5,9	9,7	10,8	23,9	22,5	32,2	38,0	34,0	34,7	22,8	19,7	9,9	9,0	13,3	16,1	17,3
Average Rear Irr	10,6	5,4	8,6	9,4	20,2	19,3	27,4	31,5	28,7	28,4	19,4	16,9	8,7	8,1	11,7	13,8	15,2

Figure 4 Rear radiation distribution measured with four solar sensors installed on the tracker.

For the period April 21 – March 22, one full year for both installations, the cumulative rear and front irradiance captured from both structures has been acquired. For this analysis, only the measurements of the solar sensor positioned in the middle of the rear side have been used.
According to the obtained results, it can be concluded that the backside contribution is higher on the tracker than on the fixed bench during the period. In fact, the rear-side irradiance contribution is 10.4% for the tracker and 8.4% for the fixed structure (see **Figure 5**). Additionally, for the same period the effective irradiation (rear + front) on the tracking bench is 6,72% higher compared to fixed one.

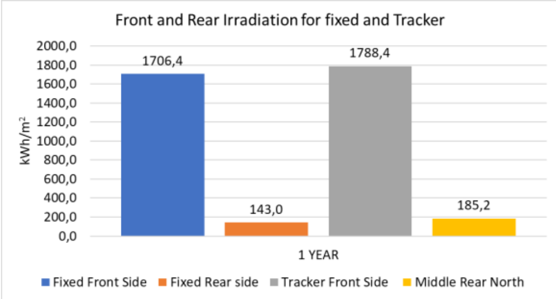


Figure 5 The cumulative rear and front irradiance for fixed and tracking structures.

3.2 Energy Yield assessment

3.2.1 Fixed structure: Bifacial vs. Monofacial

The monthly Energy Yield for fixed tilted structure is shown in **Figure 6**.

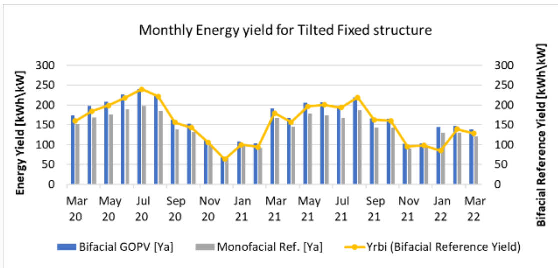


Figure 6 Bifacial HJT and monofacial PERC Energy Yield for a fixed tilted structure. The yellow solid line represents the Bifacial Reference Yield

The bifacial technology shows a better performance with respect to the monofacial reference for the whole testing period. The yellow curve of the graph represents the Bifacial Reference Yield [Y_{rbi}], calculated according to the recent standard IEC 61724-1:2021 with the irradiation measured in the plane of Array (PoA) of the fixed PV plants. The overall trend of the Bifacial Energy Yield follows the Bifacial Reference Yield.
For the fixed systems, the Bifacial Gain of GOPV bifacial with respect to the Monofacial reference technology for the period March 20 to March 22, is on average +15,1%, with the highest values obtained in summer months, toping at +21,2% in July 2020. See figure **Figure 7**

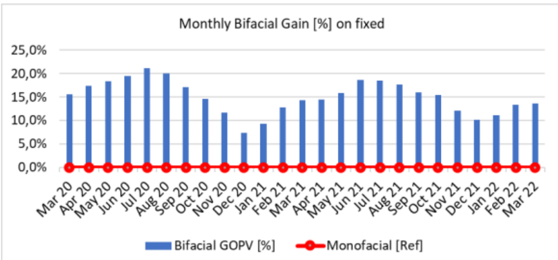


Figure 7 Monthly bifacial gain for the Bfc-HJT technology compared to the reference PERC-monofacial modules on fixed structures.

3.2.2 Tracker structure: Bifacial vs. Fixed Monofacial

Figure 8 shows the monthly energy yield gain evolution of the bifacial HJT on tracker, compared to the monofacial

PERC on tilted fixed structure, for the period November 2020 – March 2022. In general, from November to February – i.e. in the winter period - the gain is negative as the angular declination of the sun is unfavorable with respect to the horizontal plane in which the modules are located on the tracker system, while the solution on a fixed structure, with a 30 °-tilt, is less disadvantaged. The energy yield gain, starts to be positive from March to October, increasing gradually up to 35% in the summer months of June, July and August.

In general, a growing trend is observed starting from December, with the increase in the angular declination of the sun, which from the winter solstice (21 December) grows to reach its maximum value on the summer solstice (21 June). The higher gains in summer months (up to 35%), highly compensate the losses of the winter months, justifying the adoption of the tracker technology.

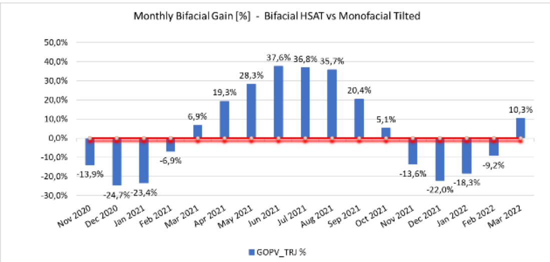


Figure 8 Evolution of the monthly bifacial gain (expressed in%) of the Bifacial tracking system compared to the Monofacial fixed structure.

It should be noted that, positive gain of tracked bifacial vs fixed bifacial is slightly delayed and starts in April.

The energy gain obtainable by the tracker has been assessed comparing the two bifacial HJT installed on fixed and tracker. As better explained in paragraph 3.2, the value of the gain of the tracker can be compromised if a threshold for the wind stow position is set on the tracker relatively low compared to the characteristics of the installation site. Especially during the winter period when the declination of the sun is more unfavorable with respect to the horizontal plan this could compromise the expected energy yield gain. Moreover, during the months of December and November some partial shading of neighboring buildings affected the energy production of the tracker.

For this reason, this assessment considers 12 clear skies days appropriately selected throughout the first year of monitoring (one day for each month), during which the production for the trackers was not affected by the stowage position for wind levels above the cutoff.

Figure 9 illustrate the energy yield of the tracker, comparing the two bifacial HJT modules installed on the fixed solution and on the tracker. From the obtained results, at Cadarache latitude it is possible to achieve a tracker energy yield gain of about 5,9 % (vs. expected ~7% of the PV model based on SAM Software, and verified with Radians ray tracing software).

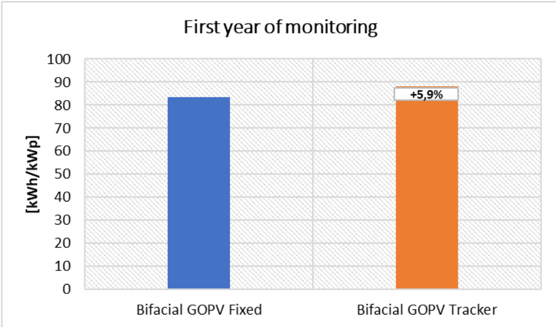


Figure 9 Energy yield gain comparing bifacial HJT installed on a tracker and on a fixed structure, performed considering one representative day per month during the first year of monitoring.

With the same methodology the gain of the GOPV solution (HJT bifacial + Tracker) respect to reference solution (monofacial PERC on tilted) has been calculated, giving a gain of 22% on annual basis.

3.3 Discussion on Tracker Operative Condition

During the monitoring period, the Bifacial tracking systems were set up with a lower wind limit than the one recommended by the tracker manufacturer, for local safety reasons due to imperfect module clamping system. This led to a lower gain than expected, since the trackers went too frequently in safety position. The wind limit recommended by the manufacturer was applied starting from the end of July 2021.

Figure 10 shows a typical day, in which for a few minutes the wind speed exceeds the limit value set for the trackers, bringing them in safety position. Net of two isolated cases (circles in orange), the power curve of the horizontal solar axis tracker system (in blue) is relatively broader than the power curve of the fixed system, thanks to the contribution of solar tracking. **Figure 11** shows another case of a windy day, with wind speed exceeding the safety limit starting from 10:30 and lasting all the day. In this case, the power curve, starting at 10:30, takes the typical shape of a fixed system. The additional power contribution is only that linked to the bifacial gain.

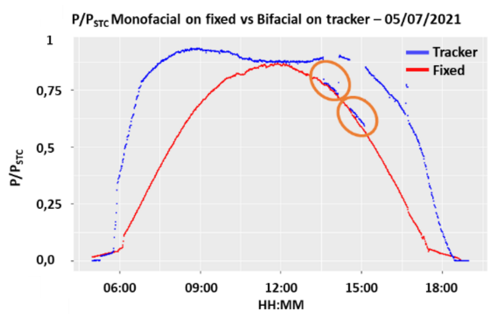


Figure 10 Power curve of a day, in which for a few minutes the wind speed exceeds the limit value set on the trackers

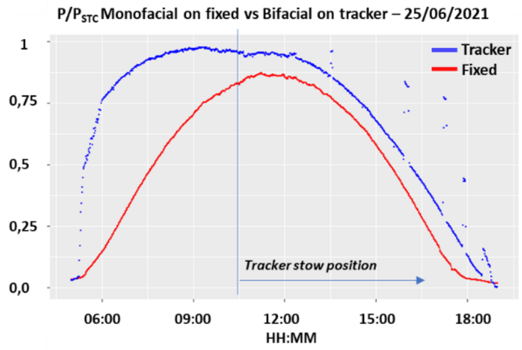


Figure 11 Power curve of a day, in which the wind speed exceeds the safety limit value set on the tracking systems starting from about 10:30; it takes the typical shape of a fixed system

4 CONCLUSION

This work illustrates the effectiveness of the GOPV solution consisting of half-cell HJT bifacial technology installed on Horizontal single axis tracker, compared to the reference solution consisting of PERC monofacial technology installed on fixed tilted structure. The analysis has been carried out with in the European GOPV project, using an **experimental PV pilot plant** installed in CEA's Cadarache, solar platform (France, 43 °,N).

The results highlights that on fixed tilted mounting structure, bifacial HJT technology improves the yearly Array Energy Yield by +15% compared to a reference monofacial PERC. Energy gain can even reach 20% in summer period..

The global GOPV solution (HJT bifacial technology + Horizontal solar axis tracker), outperforms the reference system (monofacial PERC fixed tilted) by more than 22% on an annual basis.

Therefore, the positive gains recorded from March 21 to October 21 (8 months) exceed, in absolute value, the losses of the winter period (4 months from November 2020 to February 2021). In fact, during the summer period, in the months of June, July and August, this gain have exceed the 35% of the monthly Array Energy Yield of the reference system.

Finally, when analyzing the tracker gain alone on energy yield, a +5,9% (vs. expected ~7% of the PV model) was observed compared to the same bifacial GOPV technology installed on a fixed structure. In conclusion, the results obtained in this experimental PV system demonstrated the effectiveness of combining the two technologies, Horizontal Single Axis tracker and Heterojunction silicon bifacial modules. Although the area constituted by the single-axis trackers worked for most of the annual period under disadvantageous conditions, let's think about the low wind speed limit set on trackers due to experimental constraints of the new GOPV modules, the results obtained hint at the possibility of obtaining greater energy gain, compared to the monofacial technology on fixed, in nominal condition without any extra constrain.

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