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TRABAJO TEÓRICO EXPERIMENTAL

Marginal contribution of factors to energy gains of bifacial modules

Contribución marginal de factores a las ganancias de energía de los paneles bifaciales

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ABSTRACT/RESUMEN

The introduction of bifacial panels in large-scale generation is relatively recent in the world. Studies carried out in other countries, by both academics and manufacturers, list several factors that influence the radiation reaching the back of the panel: the albedo, the elevation of the module, the distance between rows or trackers, the mounting structure of the module on the back and others. The authors performed 321 simulations of three sites with different latitudes, using fixed-tilt system (SAF) and horizontal single-axis tracking system (HSAT), and obtained six multiple linear regression equations. From them, the influence of the main factors affecting the generation in the SAF and HSAT systems with bifacial modules was quantified. The coefficients found for the different factors could be useful for future projects in Cuba, mainly because the available terrestrial surface is not unlimited.

Keywords: albedo, bifacial module, fixed tilt, solar tracking.

La introducción de paneles bifaciales en la generación a gran escala es relativamente reciente en el mundo. En los estudios realizados en otros países, tanto por académicos como por fabricantes, se listan varios factores que influyen en la radiación que llega al reverso del panel: el albedo, la elevación del módulo, la distancia entre filas o seguidores, la estructura de montaje del módulo en el reverso y otros. Los autores realizaron 321 simulaciones de tres sitios con diferentes latitudes, usando el sistema de ángulo fijo (SAF) y el de seguimiento sobre un eje horizontal (HSAT), y obtuvieron seis ecuaciones de regresión lineal múltiple. A partir de ellas se cuantificó la influencia de los principales factores ese que afectan la generación en los sistemas SAF y HSAT con paneles bifaciales. Los coeficientes hallados para los diferentes factores podrían ser útiles para futuros proyectos en Cuba, sobre todo porque la superficie terrestre disponible no es ilimitada.

***Palabras clave**: albedo, paneles bifaciales, ángulo fijo, seguimiento solar.*

INTRODUCTION

Bifacial modules can increase the energy generation in relation to monofacial ones [1]. That increase depends on the specific characteristics of the site, the layout and the technological system, among other factors. The decreasing production cost of bifacial modules has determined that its proportion in the world market of modules has been growing since 2018. Some theoretical studies have been carried out and others based on empirical results, but due to the complexity of factors affecting bifacial gains in generation, more research is needed, mainly in large-scale photovoltaic parks.

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Yusufoglua U.A., Leea T.H. y Pletzer T.M [2], carried out a test with a tilted module (SAF) towards the South in Oslo (latitude 60^0) and Cairo (latitude 30.1^0). They concluded that with an albedo value of 0,2 and a module elevation (space between the module and the ground) of 2 meters, in both cities, the optimum tilt for bifacial modules is slightly higher than that of monofacial ones. However, when the albedo increases to 0,5 this difference between optimal tilts is significantly reduced. In addition, they observed that with the optimal tilts and different albedos, the energy production is more sensitive to the elevation in Cairo. Any albedo increases augments energy gains at both latitudes.

LG Electronics, in its Bifacial Design Guide, lists the main factors affecting the bifacial generation in SAF: albedo, elevation, distance between the beginning of the first row and the beginning of the next (pitch), the shading by the module mounting structure on the backside of modules, and the number of rows (the lesser rows number, the higher the energy gain). That paper shows the results of simulations, using, PVsyst of six sites around the world with SAF and with single axis tracking system (SAT). These simulations were performed with combinations of albedos (15%, 30%, 50%, 70% and 85%) and elevations (0,3 m, 0,5 m, 0,8 m, 1 m and 1,5 m) for SAF, and axis heights from ground (1 m, 1,5 m, 2 m, 2,5 m and 3 m) for SAT.

Stein J.S, Riley D., Lave M., *et al.* [3], after conducting field tests with small SAF, conclude that total energy production seems to be maximized when the orientation of bifacial panels is the same as that of monofacial ones.

Guerrero-Pérez J. and Chaouki-Almagro S. [4], define that the main factors affecting the bifacial gains in tracking systems are the albedo, the distance between axes (pitch), the height of the axis and the mounting structure of the module. They refer that during September, October and November 2018 at BITEC (Bifacial Tracker Evaluation Center, United States) facilities, albedo was measured for three types of surfaces: seasonal soil, gravel and a white cover. The energy output of two Jolywood JW-D72N-355 bifacial modules located on a bifacial tracker was measured for each albedo condition with a 10-meter distance between axes. With albedos of 19%, 32% and 63% the energy gains were 7,9%, 11,9% and 19,2%, respectively, taking as a reference the generation of monofacial modules.

H. Park, S. Chang, S. Park and W. Kyoung Kim[5], evaluated the outdoor performance of modules and string systems was evaluated for two different albedo (ground reflection) conditions, (21% and 79%) in Gumi-Si, South Korea. In the first set of tests, output of the bifacial PV system was compared with the monofacial PV system installed on a grey concrete floor with an albedo of ~21% for approximately one year (June 2016–May 2017). In the second test, the gain of the bifacial PV system installed on a white membrane floor with an albedo of ~79% was evaluated for approximately ten months (November 2016–August 2017). During the second test, the energy production by an equivalent monofacial module installed on a horizontal solar tracker was also monitored. An increase of the ground albedo to 79% improved the bifacial gain to 33.3%. During the same period, the horizontal single-axis tracker yielded an energy gain of 15.8%.

I. Adolfsson, K. Boman and S.Ekbring [6],compared the energy gains of two roof parks in Upsala and Enköping. A bifacial PV module with frame, installed in Uppsala with a “normalized” tilt angle of 15°, results in 5.2% and 3.6% higher power output during summer and winter conditions, respectively, compared to a traditional monofacial module (with frame). The corresponding value for the frameless, more tilted and elevated bifacial PV module, installed in Enköping, Sweden, resulted in a 58% and 68% higher power output during summer and winter conditions, respectively, given the conditions of the study. The result of this study, therefore, indicates that a bifacial PV system is more advantageous than a traditional monofacial PV system in a Nordic climate.

Sun X., Ryyan Khan M., Deline C. et al [7], introduce another element that is the azimuth in the case of bifacial SAF. According to their conclusions, derived from simulations, when the latitude of the site is lower than the critical latitude Lat_{cri} the East-West orientation produces more electricity under the assumptions of absence of shading by nearby objects and infinite size of the terrain, and viceversa. They warn, however, that the regression equations found are for ideal conditions, and results may change under practical conditions. Equation (1).

$$Lat_0 = \frac{E}{H} .\left(44 .R_A - 62\right) + 37 \ . \ R_A + 12 \tag{1}$$

$$Si\, Lat_0 \leq 0,\ Lat_{cri} = 0^0 \quad y\, si\, Lat_0 > 0, Lat_{cri} = Lat_0$$

Where:

R_A: Albedo (fraction)
E: Module elevation (m)
H: Receiving band width (m)

Guari Borrull M.[8], calculated the percentage contribution of the most important factors in the dispersion of energy gains for SAF with bifacial modules. She carries out simulations with PVsyst for a 766 kWp park in Germany. This is a useful approach as it takes into account the interdependence between various factors, and the analysis is more comprehensive. However, the measure of the relative contribution by the variance or the sum of the squares, although valid, has some limitations as it depends on the absolute ranges that have been taken for the variations of each factor. In addition, it does not allow to distinguish the sign of the contributions nor to evaluate the absolute impact of each factor. According her study, the relative contribution of factors on the variance were: albedo (54,47%), tilt (33,79%) and ground coverage ratio (14,07%). Unexpectedly, the contribution of the elevation was negligible (0,67%).

J. E. Castillo-Aguilella and P.S. Hauser [9], developed an empirical model for SAF. Seven bifacial test conditions, one in New Yorkand six in Arizona, were realized; these results were show as a function of three factors: the module elevation, tilt angle, and the ground albedo. Foreach of these variables, the bifacial energy yield increasedas each of variables was increased. Five of the experimental conditions presented ran for at least a year and the one in NY for 2.5 years. The following equation was obtained by a best-fit algorithm. Equation (2).

$$Total\,Bificial\,Energy\,Yield\left(\%\right)=0,317\;.\theta+12,145\;.h+0,1414\;.\alpha+100\% \qquad (2)$$

Where:

Total Bifacial Energy Yield (%): Total bifacial energy yield of the bifacial module, when compared to an equivalent STC rated monofacial one.
θ: Tilt angle (degrees)
h: Elevation of module (meters)
α: Albedo (%)

According these authors, that model could be used under for prediction under the following conditions: systems in which the Bifacial Ratio (BR) is larger than 70%, the minimum module elevation varies from 0,15 m to 0,8 m, the module tilt angle varies from7,5 ° to 35 °, in which the ground albedo (α) varies from 10 % to 90 %, in which the latitude range is from 21 to51 degrees from the equator, and systems which use non-hybrid bifacial cell technology.

For Cuba, this issue is relatively new. Almost all papers reviewed mention or sort out some factors. One of them measures comprehensively the variations of energy due to influential factors, using the variance as a criterion. As explained before, it has some limitations. The last one developed an empirical model to estimate the bifacial gain taking into account the albedo, the elevation and the tilt angle. This approach is much closer to the method used by the authors of the present paper, who have tried to quantify the marginal influence of the most important factors explaining the energy gains of bifacial modules in the Cuban latitude range, both for SAF and HSAT, using a multiple linear regression model.

MATERIALS AND METHODS

The authors have reviewed the international literature on the factors that influence the radiation and generation gains of the bifacial modules. Meteorological databases of the Centro de Física de la Atmósfera from three different sites were used in the analysis. Performing 321 simulations using the PVsyst software, for both SAF and HSAT derived the regression equations that allowed quantifying the marginal contributions of these factors for the sites with both technologies.

Sites and meteorological databases from the Centro de Física de la Atmósfera

Two sites in extreme latitudes of Cuba and one in the middle latitude were selected (figure 1). The monthly average data of horizontal global radiation and daily temperature, according to the latitude and longitude of each location in Cuba, were obtained from the Excel book "Interp" (table 1). This file is one of the results of the project "Determination of the distribution of solar radiation on the national territory from the information provided by the heliographic network", from the Centro de Física de la Atmósfera, Instituto de Meteorología de Cuba.

Fig. 1. Selected sites.

Three sites were selected: in the west, in the center and in the east, two of them with extreme latitudes and one in the middle latitude of Cuba.

Table 1. Radiation and temperature of sites

	Site in La Habana		Site in Sancti Spíritus		Site in Guantánamo	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
	23.10	-82.34	21.57	-79.21	19.94	-75.1
	Daily horizontal solar radiation kWh/m^2.d	Daily temperature^{0}C	Daily horizontal solar radiation kWh/m^2.d	Daily temperature ^{0}C	Daily horizontal solar radiation kWh/m^2.d	Daily temperature ^{0}C
January	4,24	26,9	4,20	27,6	4,18	28,8
February	4,93	27,6	5,02	28,2	5,03	29,1
March	5,55	28,7	5,66	29,0	5,58	29,9
April	6,56	30,5	6,53	30,3	5,84	30,8
May	6,29	31,4	6,28	31,1	5,89	31,3
June	5,94	31,6	6,37	31,6	6,01	31,9
July	6,27	32,6	6,61	32,4	6,37	32,7
August	6,08	32,6	6,43	32,3	6,49	32,9
September	5,51	32,0	5,76	31,5	5,85	32,1
October	4,70	30,6	5,01	30,8	4,73	31,3
November	4,04	28,8	4,28	29,5	4,31	30,0
December	3,57	27,4	3,83	28,8	3,75	29,2
Average	**5,25**	**30,1**	**5,52**	**30,3**	**5,39**	**30,9**

Design of the experiment: site selection and factor ranges

The main objective of this work is to obtain the marginal contribution of the factors affecting the generation with the use of bifacial modules in SAF and HSAT systems, or what is equal, the determination of the sensitivity of energy to the main factors that affect it. The details of the design of the experiment are described below.

Factors to be evaluated for the SAF:

- I: Tilt of modules
- Nf: Number of rows
- Df: Distance between the beginning of the previous row and the beginning of the next one in meters
- E: Ground elevation of the lowest part of the module in meters
- Ra: Albedo in fraction or %

The energy produced by the SAF will be referred as Gsaf (in MWh). The following ranges will be used for the variation of the factors:

I: variation between 15 and 23 degrees, optimal tilt range for monofacial modules. An inclination greater than 23^0 is not recommended due to the risk of strong winds.

Nf: variation between 10 and 30 rows.

Df: variation between 4,9 and 6,7 meters. Lower limit: Average minimum distance of the three sites to avoid shading in the winter solstice at 8:00 AM (solar time) with 15^0 tilt. Upper limit: 1,05 m more than the average minimum distance of the three sites to avoid shading in the winter solstice at 8:00 AM (solar time) with 23^0.

E: 0,4 and 1,2 meters (practical reasons)

Ra: 20 and 60% (practical reasons)

To evaluate the orientation of the panels and to calculate Lat_0, equation (1), will be used an elevation 0 m; 3,37 receiving band width and albedo 0,5. The resulting critical latitude was 30.5º.

According to the above data, if the latitude of the selected sites is less than 30.5^0, the East-West orientation would maximize the generation. To test this, we performed a simulation with PVsyst, as recommended Sun X., Ryyan Khan M., Deline C. et al [7],with real critical magnitudes (table 2), but with nearby shading of modules.

Table2. Calculation of generation with North-South and East-West orientation

				Optimal tilt according to simulations			Generation with Azimuth		
	Latitude	Df	Nf		E	Ra	0^0	-90^0	Gsaf -90^0/Gsaf 0^0
La Habana	23.10	7	8	23^0	0	0,50	1 670	1 559	93,4%
Sancti Spíritus	21.57	7	8	23^0	0	0,50	1 795	1 698	94,6%
Guantánamo	19.94	7	8	22^0	0	0,50	1 727	1 675	95,3%

Although it is true that, with the reduction of latitude, the relative difference in generation seems to decrease, under real conditions, with the North-South orientation energy is maximized in all three cases. Hence, an azimuth of 0^0 will be taken as a reference for the realization of our experiment.

The ranges of the distance between the beginning of the previous row and the beginning of the next one, were calculated with the application "Calculation of tilt and hour" (original name in Spanish “Cálculo de ángulo y hora”), available at the Empresa de Fuentes Renovables de Energía, and developed by the authors of this text (table 3).

Table3. Calculation of minimum distances with angles of $15^0$and 23^0

Site	Latitude	Solar time	Receiving band width	Tilt	Df	Tilt	Df
La Habana	23.10	8 AM	3,37 m	15^0	5,05 m	23^0	5,82 m
Sancti Spíritus	21.57				4,94 m		5,64 m
Guantánamo	19.94				4,82 m		5,47 m

From this information, a range of between 4,9 and 6,7 meters will be used for Df in simulations.

Factors to be evaluated for the HSAT system:

- Nc: Number of solar tracking columns
- De: Distance between axes of the parallel trackers in meters (pitch)
- J: Height of the tracker axis from the ground in meters
- Ra: Albedo in fraction or %

The energy produced by the HSAT systems will be referred as Ghsat. The following ranges will be used for the factor variation:

Nc: variation between 15 and 40 columns.

De: variation between 4,6 and 5,8 meters. Lower limit: Average minimum distance of the three sites to avoid shading in the winter solstice at 8:00 AM (solar time). Upper limit: 1,20 m more than the average minimum distance to avoid shading in the winter solstice at 8:00 AM.

J: variation between 0,4 and 1,2 metros (practical reasons)

Ra: variation between 20 and 60%. (practical reasons)

The ranges of the distance between axes of the parallel trackers were calculated with the same application "Distance rows and columns". View table 4.

Table 4. Calculation of minimum distance between axes with angle of 45^0

Site	Latitude	Solar time	Receiving band width	Maximum angle of inclination of the panels during the tracking	De
La Habana	23.10	8 AM	1,67 m	45^0	4,76 m
Sancti Spíritus	21.57				4,57 m
Guantánamo	19.94				4,40 m

From this information, a range of between 4,6 and 5,8 meters will be used in simulations.

Design of the experiment: technological parameters for SAF

PVsyst V6.8.1 was used for the simulations. Two LR6-60 BP 320 M Bifacial modules from Longi Solar in portrait position was used. The width of the receiver band is 3,37 m. There are no minor light obstruction losses on the back of the panel due to the mounting structures. The horizon profile will be PVsyst's own. Simulations of the three sites was carried out with a 1000 kWp farm with 30 inverters (figure 2).

Design of the experiment: technological parameters for HSAT

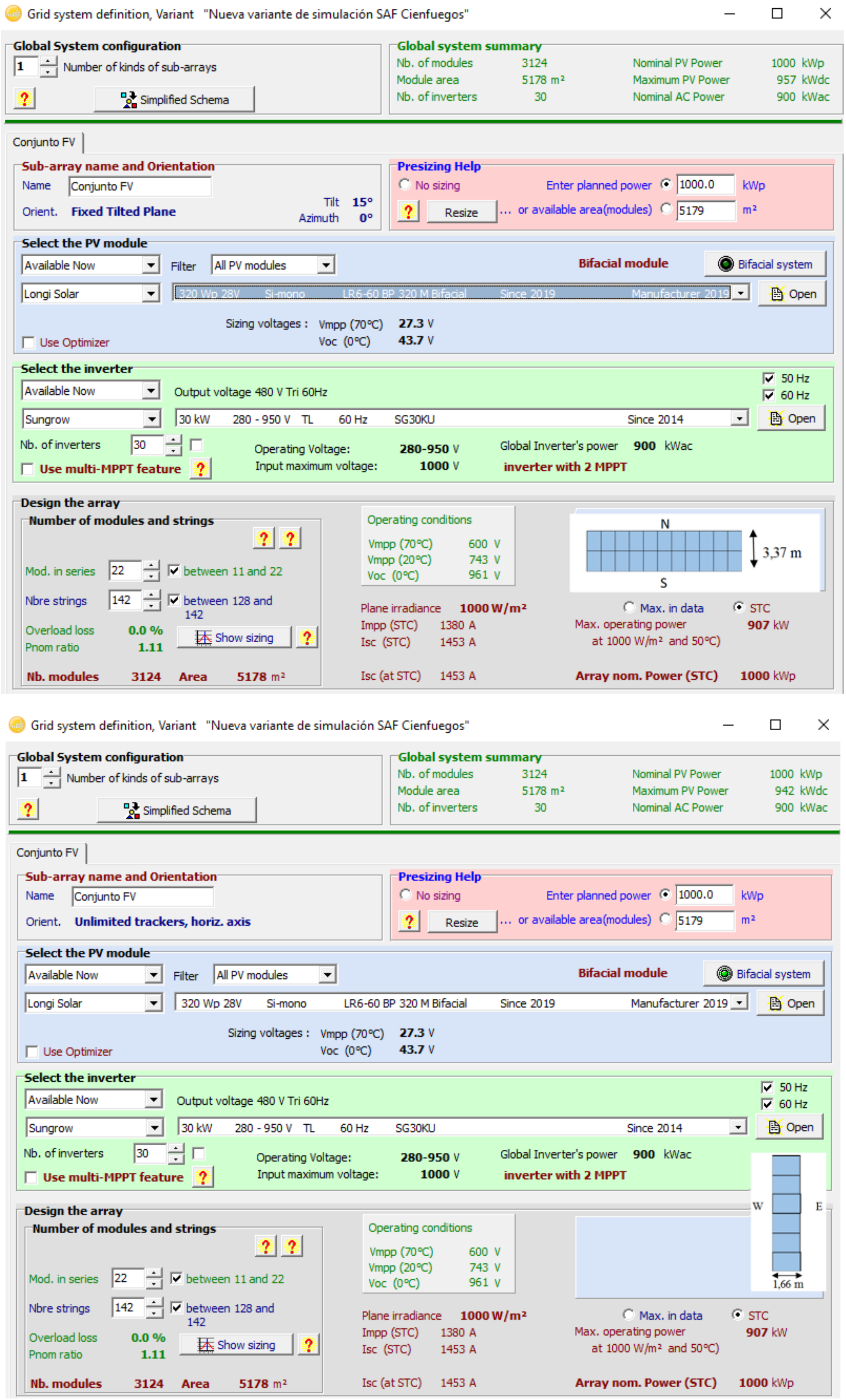
PVsyst V6.8.1 was also used. One LR6-60 BP 320 M Bifacial module from Longi Solar was used in "portrait" mode (figure 2). The width of the receiving band is 1.66 m. There are no shadows from nearby objects, and no minor light obstruction losses on the back of the panel due to the mounting structures. The horizon profile will be PVsyst's own. Simulations of the three sites was carried out with a 1 000 kWp farm with 30 inverters (figure2).

Design of the experiment: samples with randomized factor values

In order to achieve a comprehensive assessment of the marginal contribution of each factor to the generation in its interaction with the others, tables were prepared for the generation of random numbers for each of the factors listed in tables 5 and 9. The resulting samples were taken and entered into PVsyst. A partial view of generated random numbers for SAF with limits is shown in table 5, as an example. For each of the six regression analyses different random number series were used.

Table5. Random numbers (an example)

Sample number	Limits for random numbers				
	15-23	10-30	4,9-6,7	0,4-1,2	0,2-0,6
	I	**Nf**	**Df**	**E**	**Ra**
1	16	21	5,9	0,8	56%
2	23	26	5,4	0,6	24%
3	20	14	5,9	0,4	32%
4	19	21	5,9	0,5	57%
5	17	16	5,2	1,2	51%
6	19	30	6,1	0,9	22%
7	16	22	5,5	0,9	40%
8	16	26	5,7	0,7	60%
9	23	30	5,6	0,7	52%
10	21	23	6,1	0,7	23%



Grid system definition, Variant "Nueva variante de simulación SAF Cienfuegos"

Global System configuration
1 Number of kinds of sub-arrays
Simplified Schema

Global system summary
Nb. of modules 3124 — Nominal PV Power 1000 kWp
Module area 5178 m² — Maximum PV Power 957 kWdc
Nb. of inverters 30 — Nominal AC Power 900 kWac

Conjunto FV

Sub-array name and Orientation
Name: Conjunto FV
Orient.: **Fixed Tilted Plane** — Tilt **15°**, Azimuth **0°**

Presizing Help
○ No sizing — Enter planned power ● 1000.0 kWp
Resize … or available area(modules) ○ 5179 m²

Select the PV module
Available Now — Filter: All PV modules — **Bifacial module** — Bifacial system
Longi Solar — 320 Wp 28V Si-mono LR6-60 BP 320 M Bifacial Since 2019 Manufacturer 2019 — Open
Sizing voltages : Vmpp (70°C) **27.3** V; Voc (0°C) **43.7** V
☐ Use Optimizer

Select the inverter
Available Now — Output voltage 480 V Tri 60Hz — ☑ 50 Hz ☑ 60 Hz
Sungrow — 30 kW 280 - 950 V TL 60 Hz SG30KU Since 2014 — Open
Nb. of inverters 30 ☐ — Operating Voltage: **280-950** V — Global Inverter's power **900** kWac
☐ **Use multi-MPPT feature** — Input maximum voltage: **1000** V — **inverter with 2 MPPT**

Design the array
Number of modules and strings
Mod. in series 22 ☑ between 11 and 22
Nbre strings 142 ☑ between 128 and 142
Overload loss **0.0 %**
Pnom ratio **1.11** — Show sizing
Nb. modules 3124 Area 5178 m²

Operating conditions
Vmpp (70°C) 600 V
Vmpp (20°C) 743 V
Voc (0°C) 961 V
Plane irradiance **1000 W/m²**
Impp (STC) 1380 A
Isc (STC) 1453 A
Isc (at STC) 1453 A

○ Max. in data ● STC
Max. operating power **907** kW at 1000 W/m² and 50°C)
Array nom. Power (STC) 1000 kWp

Grid system definition, Variant "Nueva variante de simulación SAF Cienfuegos"

Global System configuration
1 Number of kinds of sub-arrays
Simplified Schema

Global system summary
Nb. of modules 3124 — Nominal PV Power 1000 kWp
Module area 5178 m² — Maximum PV Power 942 kWdc
Nb. of inverters 30 — Nominal AC Power 900 kWac

Conjunto FV

Sub-array name and Orientation
Name: Conjunto FV
Orient.: **Unlimited trackers, horiz. axis**

Presizing Help
○ No sizing — Enter planned power ● 1000.0 kWp
Resize … or available area(modules) ○ 5179 m²

Select the PV module
Available Now — Filter: All PV modules — **Bifacial module** — Bifacial system
Longi Solar — 320 Wp 28V Si-mono LR6-60 BP 320 M Bifacial Since 2019 Manufacturer 2019 — Open
Sizing voltages : Vmpp (70°C) **27.3** V; Voc (0°C) **43.7** V
☐ Use Optimizer

Select the inverter
Available Now — Output voltage 480 V Tri 60Hz — ☑ 50 Hz ☑ 60 Hz
Sungrow — 30 kW 280 - 950 V TL 60 Hz SG30KU Since 2014 — Open
Nb. of inverters 30 ☐ — Operating Voltage: **280-950** V — Global Inverter's power **900** kWac
☐ **Use multi-MPPT feature** — Input maximum voltage: **1000** V — **inverter with 2 MPPT**

Design the array
Number of modules and strings
Mod. in series 22 ☑ between 11 and 22
Nbre strings 142 ☑ between 128 and 142
Overload loss **0.0 %**
Pnom ratio **1.11** — Show sizing
Nb. modules 3124 Area 5178 m²

Operating conditions
Vmpp (70°C) 600 V
Vmpp (20°C) 743 V
Voc (0°C) 961 V
Plane irradiance **1000 W/m²**
Impp (STC) 1380 A
Isc (STC) 1453 A
Isc (at STC) 1453 A

○ Max. in data ● STC
Max. operating power **907** kW at 1000 W/m² and 50°C)
Array nom. Power (STC) 1000 kWp

Fig. 2. SAF y HSAT configuration.

Results of Multiple Linear Regressions

Fifty or more samples were taken for each site according to the SAF or HSAT system. 321 simulations were performed, one for each sample, with a significance level of 5%. In some cases, several regressions had to be performed to eliminate variables whose relationship with energy was not statistically significant. The results of the final multiple linear regressions are show in table 6.

Table 6. Multiple linear regressions results (α=0,05)

SAF						
Data of sites	La Habana		Sancti Spíritus		Guantánamo	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
	23,10	-82,34	21,57	-79,21	19,94	-75,1
Statistical concepts	Final regression coefficients					
Constant (C SAF)	1 407,47		1 544,96		1 491,76	
(I) Tilt	-		-0,62		-1,22	
(Nf) Number of rows	-		-		-	
(Df) Distance between the beginning of the previous row and the beginning of the next one (m)	22,68		23,64		23,16	
(E) Elevation (m)	52,82		54,30		53,08	
(Ra) Albedo (%)	283,86		294,89		290,22	
Number of samples	56		56		56	
Estimation error	3,67		3,81		3,74	
R^2	99,10		99,12		99,13	
R^2 adjusted	99,05		99,05		99,06	
R^2 prediction	98,94		98,91		98,93	
Durbin-Watson statistic	2,01737 > Du (1.683)		2,12651 > Du (1.72461)		1,87781 > Du (1.72461)	
Comments	I and Nf have no significant relation with Gsaf (P>0,05).		Nf has no significant relation with Gsaf (P>0,05).		Nf has no significant relation with Gsaf (P>0,05).	
HSAT						
Data of sites	La Habana		Sancti Spíritus		Guantánamo	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
	23.10	-82.34	21.57	-79.21	19.94	-75.1
Statistical concepts	Final regression coefficients					
Constant (C HSAT)	1 689,03		1 843,91		1 759,98	
(Nc) Number of tracker columns	-		-0,08		-0,10	
(De) Distance between axes of parallel trackers (m)	32,27		36,80		39,13	
(J) Height of the tracker axis from the ground (m)	44,33		43,71		41,95	
(Ra) Albedo (%)	447,60		454,37		448,38	
Number of samples	51		51		51	
Estimation error	3,15		1,96		1,91	
R^2	99,72		99,90		99,90	
R^2 adjusted	99,70		99,89		99,89	
R^2 prediction	99,67		99,88		99,88	
Durbin-Watson statistic	1,81601 > Du (1.67538)		2,34894 > Du (1.72179)		2,21703> Du (1.72179)	
Comments	Nc has no significant relation with Ghsat (P>0,05).		-		-	

DISCUSSION OF RESULTS

R^2 was more than 99% in all regressions. The estimation error, in the worst case, is only 3,81 MWh. The following assumptions of the multiple linear regression model were fulfilled: homoscedasticity, normality in the distribution of random disturbances, no correlation according to the Durbin-Watson test and no collinearity among variables.

Therefore, these regression models are suitable for explaining the marginal factor contribution to energy gains in the three sites. The regression equations, for purposes of prediction, are only valid within the ranges of the independent variables (limits).

The resulting regression equations for SAF system were. View equations (3-8):

La Habana: $$Gsaf = 1\,407{,}47 + 22{,}68 \cdot Df + 52{,}82 \cdot E + 283{,}86 \cdot Ra \quad (3)$$

Sancti Spíritus: $$Gsaf = 1\,544{,}96 + 23{,}64 \cdot Df + 54{,}30 \cdot E + 294{,}89 \cdot Ra - 0{,}62 \cdot I \quad (4)$$

Guantánamo: $$Gsaf = 1\,491{,}76 + 23{,}16 \cdot Df + 53{,}08 \cdot E + 290{,}22 \cdot Ra - 1{,}22 \cdot I \quad (5)$$

For HSAT system the regression equations are:

La Habana: $$Ghsat = 1\,689{,}03 + 32{,}27 \cdot De + 44{,}33 \cdot J + 447{,}60 \cdot Ra \quad (6)$$

Sancti Spíritus: $$Ghsat = 1\,843{,}91 + 36{,}80 \cdot De + 43{,}71 \cdot J + 454{,}37 \cdot Ra - 0{,}08 \cdot Nc \quad (7)$$

Guantánamo: $$Ghsat = 1\,759{,}98 + 39{,}13 \cdot De + 41{,}95 \cdot J + 448{,}38 \cdot Ra - 0{,}10 \cdot Nc \quad (8)$$

The partial derivative of Gsaf or Ghsat regarding each factor is the own coefficient associated to each one, and it can be interpreted as the marginal contribution of each factor to the generation.

For SAF:

- The main factor that contributes to the generation is the albedo.
- The second factor is the elevation of modules.
- The third one is the distance between the beginning of the previous row and the beginning of the next one.
- The inclination only contributes marginally in Sancti Spíritus and Guantánamo, sites of lower latitude. These coefficients are negative and relatively negligible. However, these results found in conjunction with the rest of the factors, contradict to some extent the statement of other studies suggesting that the optimal tilt for bifacial modules is slightly greater than that for monofacial ones [2] & [7].

The average marginal contribution in the three sites of variables Df, E and Ra for the SAF is shown below (table 7).

Table 7. Average marginal contribution and standard deviation for SAF

Factor	Average	Standard deviation	% S. Deviation/Average
Df	23,16	0,48	2,1%
E	53,40	0,79	1,5%
Ra	289,66	5,54	1,9%

Hence, on average, with an increase in the albedo by only 0,08 (8%), an energy increase of 23,2 MWh should be expected. To obtain the same energy gain, the elevation of the modules should be increased by 0,43 meters or the distance between the beginning of previous row and the beginning of next one should be extended by 1,0 meters.

For HSAT:

- The factor that contributes most marginally to the generation is the albedo.
- The second factor is the height of the axis from the ground.
- The third one is the distance between axes of the parallel trackers.
- The number of tracker columns only marginally contributes in Sancti Spíritus and Guantánamo, sites of lower latitude, in a relatively small magnitude.

The average marginal contribution in the three sites of variables Df, E, and Ra for the HSAT is shown below (table 8).

Table 8. Average marginal contribution and standard deviation for HSAT

Factor	Average	Standard deviation	% S. Deviation/Average
De	36,07	3,49	9,7%
J	43,33	1,23	2,8%
Ra	450,12	3,71	0,8%

On average, with a 0,08 (8%) increase in albedo; the energy would increase by 36 MWh. To obtain this gain in generation, the elevation of the axis should be increased by 0,8 meters or the distance between axes of trackers should be extended by 1,1 meters.

Other relationships between regression coefficients

In addition to the observations mentioned above, the ratios between the different regressions coefficients allow to analyze others (table 9).

Table 9. Relations between coefficients and data

		Habana	Sancti Spíritus	Guantánamo	Average
Daily horizontal solar radiation		5,25	5,52	5,39	-
Constant (C SAF)		1 407,47	1 544,96	1 491,76	-
Constant (C HSAT)		1 689,03	1 843,91	1 759,98	-
SAF	E (m)	52,82	54,30	53,08	53,40
	Df (m)	22,68	23,64	23,16	23,16
	E/Df	**2,33**	**2,30**	**2,29**	**2,31**
	Ra	283,86	294,89	290,22	289,66
HSAT	J (m)	44,33	43,71	41,95	43,33
	De (m)	32,27	36,80	39,13	36,07
	J/De	**1,37**	**1.19**	**1,07**	**1,20**
	Ra	447,60	454,37	448,38	450,12
Ra HSAT/Ra SAF		**1,58**	**1,54**	**1,54**	**1,55**
J HSAT/ E SAF		**0,84**	**0,80**	**0,79**	**0,81**
De HSAT/Df SAF		**1,42**	**1,55**	**1,69**	**1,56**

- The marginal contribution of the albedo (Ra) is greater as the global radiation is higher in both systems.
- The higher daily horizontal radiation the greater the regression constants (C SAF and C HSAT).
- The higher daily horizontal radiation the greater contributions of module elevation (E) and row spacing (Df) in SAF.
- The marginal contribution of module elevation (E) is higher than the contribution of row distance (Df) in SAF. The same happens for the elevation of the axis (J) and the distance between axes (De) in HSAT.
- The marginal contribution of module elevation regarding row distance contribution in SAF is greater than the marginal contribution of axis elevation respect to the contribution of distance between the axes in HSAT (E/Df versus J/De).
- The marginal contribution of albedo to energy gains is, on average, 1,55 times higher in HSAT than in SAF (Ra HSAT/Ra SAF).
- The contribution of axis elevation in HSAT is less than the contribution of module elevation in SAF (J HSAT/E SAF)
- The contribution of distance between axes in HSAT is greater than the contribution of row spacing in SAF (De HSAT/Df SAF)
- It seems that, as the latitude decreases,
    - the ratios (E/Df) in SAF and (J/De) in HSAT diminish,
    - the ratio (J HSAT/E SAF) reduces and
    - the ratio (De HSAT/Df SAF) increases.

CONCLUSIONS

The authors have analyzed the marginal contribution of each factor associated with the energy gains from the use of bifacial panels with SAF and HSAT technologies in Cuba. One of the findings has been that, marginally, albedo and module elevation or axis elevation, depending on the technology, are more important than the distance between rows or the distance between axes, depending on the system. Moreover, the higher daily horizontal radiation the greater the regression constants (C SAF and C HSAT).

Then, under land restrictions, other alternatives can be taken to raise the generation. Also, derived from this work, the energy gains due to higher albedo levels are much higher in HSAT technology, so it should be given priority to install tracking system in sites with higher levels of radiation and albedo.

The authors recommend field research to identify those areas with higher albedo (lighter grounds) and its seasonal behavior. This depends not only on the first layer (grass, for example), but also on the type of ground [10]. On the other hand, investments with ground-covering materials could be economically evaluated to augment artificially the albedo. The maintenance of grass at a low height in solar farms is a necessary condition to take fully advantage of this factor.

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INTEREST CONFLICT

The authors declare that there are no conflicts of interest.

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