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Comparative Study of Solar PV Power Plant Dimensionnement Connected to Network Based on Monofacial and Bifacial Modules

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Abstract: This article presents the results of comparative study of two PV solar modules technologies, namely monofacial and bifacial. This study main objective is to identify conditions and parameters that make it possible to obtain better energy and economic efficiency from one or other of two technologies. The study reason lies in revival observed on bifacial module in recent years where all the major manufacturers of PV solar panels are developing them where in a few years, this technology risks being at the same price as the monofacial solar panel with better efficiency. Economic indicator used is energy levelized cost (LCOE) which is function technology type, energy productivity, annual investment and operation cost. To achieve this, a 3.685 MWc solar PV power plant was dimensioned and simulated under Matlab for a 3.5 ha site with a 2,320,740,602 FCFA budget for monofacial installation, against 1,925,188,640 FCFA for 2.73 MWc bifacial installation. The LCOE comparative analysis of two technologies calculated over a period of 25 years, showed that plant with bifacial panels is more beneficial if bifacial gain is greater than 9 %. It has further been found that it is possible to gain up to 40 % of invested cost if bifacial gain reaches 45 %. Finally, a loss of about 10 % of invested cost could be recorded if bifacial gain is less than 9 %.

Key words: Solar PV power plant, Sizing, Monofacial panels, Bifacial panels, LCOE.

Nomenclature

α	Solar Elevation [°C]
β	Panel Inclination [°C]
δ	Solar Declination [°C]
GCR	Ground Coverage Ratio [-]
LCOE	Levelized Cost of Energy [FCFA/KWh]
CAPEX	Capital Expenditure [FCFA]
OPEX	Operating and Maintenance Expenditure [FCFA]
r	Discount Rate [%]
T	Temperature Limit [°C]
Tstc	Temperature under Standard Test Conditions [°C]
R	Minimum distance between two panels [m]
Qt	Annual Energy Production [KWh]
d1	Monofacial Panel Degradation Rate [%]
d2	Bifacial Panel Degradation Rate [%]
Gi	Bifacial Current Gain [%]
g	Bifacial Gain [%]

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1. Introduction

Currently, photovoltaic solar energy has become a mature technology ready to be deployed on a terawatt scale and contribute to short-term emissions reduction

[1]. Due to its advantages, it has attracted increasing attention in the field of energy production. One particularly interesting factor is the modular nature of PV, also known as “granular” [2]. Furthermore, new models of solar modules have emerged: bifacial photovoltaic modules. These modules generate energy from both their front and back sides, simultaneously utilizing the reflected light from the back, thereby offering higher output power compared to monofacial PV modules. Energy efficiency can significantly increase with the collection of energy from the back side, which depends heavily on the climate and system configuration [3, 4]. The essential parameters to consider in the system are the distance between two rows of panels, the inclination and height of the panels, and the albedo of the underlying surface.

According to several manufacturers, bifacial modules represent the future of photovoltaics. Chinese panel manufacturer LONGi Solar believes that we are entering a new era of photovoltaics, an era where high-efficiency modules dominate. “Bifacial modules are the future of the industry” said Hongbin Fang, Technical Director of LONGi Solar [5]. “They have inherited all the advantages of mono PERC modules. We believe that bifacial PERC modules provide the best approach to reducing the cost of photovoltaic energy” [5].

Unfortunately, there are no projects in Benin or the sub-region that utilize these bifacial PV modules. It is therefore necessary to examine the comparison between monofacial and bifacial modules based on the design of a photovoltaic power plant to serve as a decision-making tool for stakeholders in the field. Several studies have been dedicated to the performance analysis of bifacial modules [6-8]. In this article, we will present the effect of bifacial gain on the cost of electricity derived from bifacial modules, and we will examine the conditions under which they will be more productive and cost-effective than monofacial modules. The obtained results will also serve as a decision-making tool for professionals in this sector.

2. Matériels et méThodes

2.1 Site Selection

For this study, we carefully selected a suitable site in the Seme Krake locality of Benin, with consideration given to its proximity to the distribution substation. The chosen site is an expansive and unobstructed area spanning 3.5 hectares, located in the village of Sèmè Okoun within the municipality of Sèmè Kpodji. Its geographical coordinates are approximately 6.38 °N latitude and 2.62 °E longitude, with an elevation of 55 meters above sea level. The study site is depicted in Fig. 1.

2.2 Components Selection

To develop the study, the selection and sizing of the necessary components for the installation of a grid-connected PV solar power plant were carried out for each of the two technologies. The selection of these components was made from a functional standpoint, as the study specifically focused on efficiency by applying methods that streamline the work process. In this regard, the two chosen photovoltaic panels are manufactured by Canadian Solar, with a peak power of 455 W. The sizing of each technology is based on the available surface area but using different methods for calculating the minimum distance between two panels. Calculating this distance requires knowledge of several parameters, such as the horizontal or vertical arrangement and the

Fig. 1 Site selection.

production of each technology. The recommended arrangement is the one that accommodates more panels, i.e., the one with higher power output. In our case, the vertical arrangement is deemed optimal, and the monofacial installation will require more panels, specifically 8,100 compared to 6,000 for the bifacial installation. Figs. 2 and 3 illustrate the principle of calculating the inter-panel distance.

Taking into account a safety distance of ds (in our case, ds = 30 cm), the Eq. (1) enables the calculation of the spacing between the beginning of one panel and the beginning of the subsequent panel.

$$R = \frac{h}{tan\ \alpha} + L.cos\beta + d_s \qquad (1)$$

$$Where\ \alpha = 90° - L + \delta$$

The bifacial installation has the particularity of having panels that absorb energy from both sides. For this reason, the principle of calculating the inter-panel distance is different. It should ensure the avoidance of

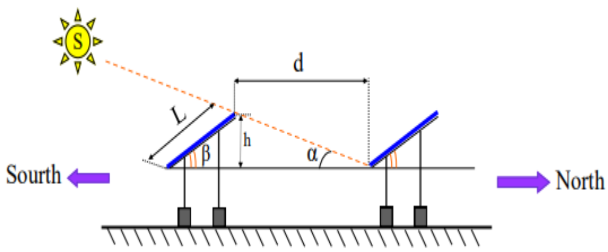

Fig. 2 Inter-panel Distance for Monofacial Panels.

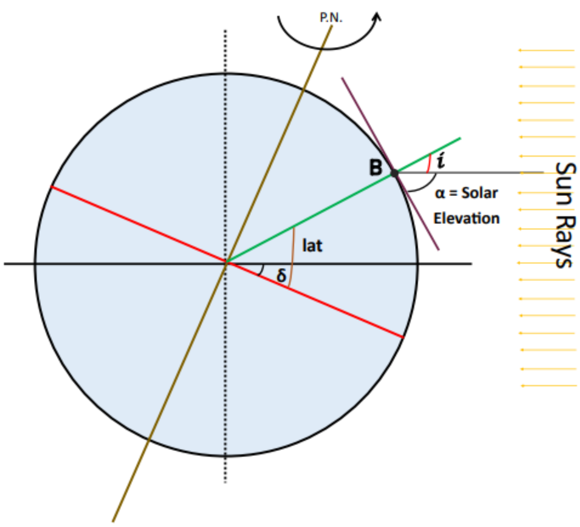

Fig. 3 Solar Elevation [9].

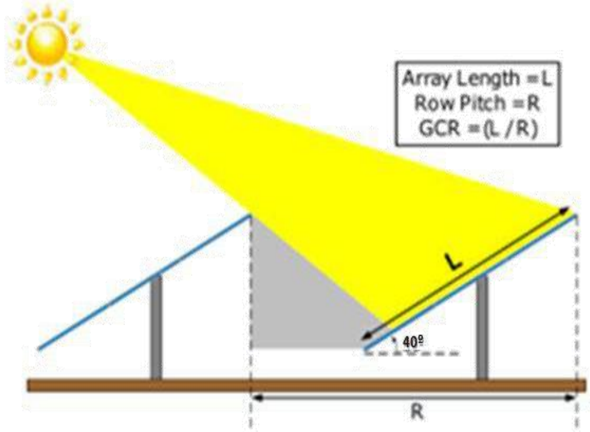

Fig. 4 Distance between bifacial panels (GCR concept) [10].

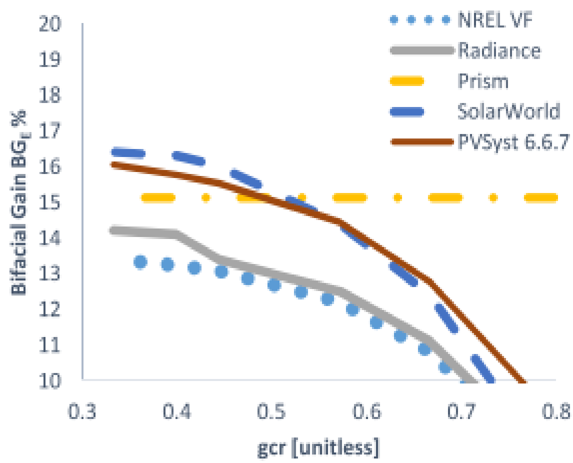

Fig. 5 Relationship between GCR and bifacial gain [11].

shading on the panels while maintaining optimal operation on both sides. To achieve this, the ground coverage ratio (GCR) is defined, which is the ratio between the panel length and the distance between rows of panels [12]. Its optimal value is determined based on Fig. 5. In our case, we have chosen GCR = 0.55.

$$R = \frac{L}{GCR} \qquad (1)$$

Regarding the selection of the inverter, a preliminary calculation of the voltage limits was performed based on the operating temperature using Eq. 3.

$$V_x\ (T) = V_x + (T - T_{stc}) * \left(\frac{Temp\ Coef}{100} * V_x \right) \qquad (2)$$

Where:

V_x: the maximum voltage or open-circuit voltage of the module in volts

T: the maximum temperature in ℃. The recommended range is typically -10 ℃ to 70 ℃.

T_{stc}: the temperature under standard test conditions, which is 25 ℃.

Temp Coef: the temperature coefficient of efficiency loss. Depending on the manufacturer, it is usually between: -0.3%/℃ to -0.5%/℃.

After the current, voltage, and power sizing, the Ingecon SUN Power B Series 1600TL B615 central inverter was chosen, which is compatible with both the monofacial and bifacial installations. The accurate quantification of solar cables was achieved through the use of Xrelais software for designing the layout. It was observed that the monofacial installation requires a greater number of cables compared to the bifacial installation.

Considering the criticality of system protection for its long-term performance, protective measures were taken into account when selecting all system components. The junction box serves as a key element in this protection, housing fuses for overcurrent protection and surge protectors for atmospheric overvoltage protection.

Furthermore, an impact assessment of the bifacial gain on the levelized cost of electricity (LCOE) was conducted using a Matlab program incorporating various variables. The LCOE, which determines the electricity's cost, is generally calculated using Eq. 4 [13].

$$\text{LCOE} = \frac{CAPEX + \sum_{t=1}^{N}[\frac{\text{OPEX}}{(1+r)^t}]}{\sum_{t=1}^{N}[\frac{Q_t}{(1+r)^t}]} \quad (1)$$

Its application to both systems yields the following equations for the monofacial and bifacial LCOE, respectively.

$$LCOE_{MoFa} = \frac{CAPEX_{MoFa} + \sum_{t=1}^{N}[\frac{OPEX_{MoFa}}{(1+r)^t}]}{\sum_{t=1}^{N}[\frac{Q_t(1-d1)}{(1+r)^t}]} \quad (2)$$

$$LCOE_{BiFa} = \frac{CAPEX_{BiFa} + \sum_{t=1}^{N}[\frac{OPEX_{BiFa}}{(1+r)^t}]}{\sum_{t=1}^{N}[\frac{Q_t(1-d2)(1+g)}{(1+r)^t}]} \quad (3)$$

The variables involved in the simulations are as follows:

t = [1: 25]: the number of years of operation

r = [2: 26]: the discount rate

d1 = 0.55%: the degradation rate of the monofacial system

d2 = 0.45%: the degradation rate of the bifacial system

g = [0:48]: the bifacial gain in percentage

2.3 Methods for Determining the Electrical Parameters of Bifacial Solar Modules

The bifacial gain, which is a crucial variable for our study, is illustrated in Fig. 6.

The various electrical parameters of bifacial solar modules are determined by the Eq. [14].

The current gain of bifacial photovoltaic modules is obtained using Eq. 7.

$$G_i = \alpha \ x \ \frac{Isc_{rear}}{Isc_{front}} \quad (7)$$

α: The reflection coefficient is related to the operating conditions of the modules, including geographic location, surface conditions of the ground, module tilt angles, weather/season, etc. The standard for standard test conditions suitable for the application of double-sided photovoltaic modules recommends a uniform value of 0.1 [14].

Iscrear: The short-circuit current at the back of the bifacial photovoltaic module, in amperes (A).

Iscfront: The short-circuit current at the front of the bifacial photovoltaic module, in amperes (A).

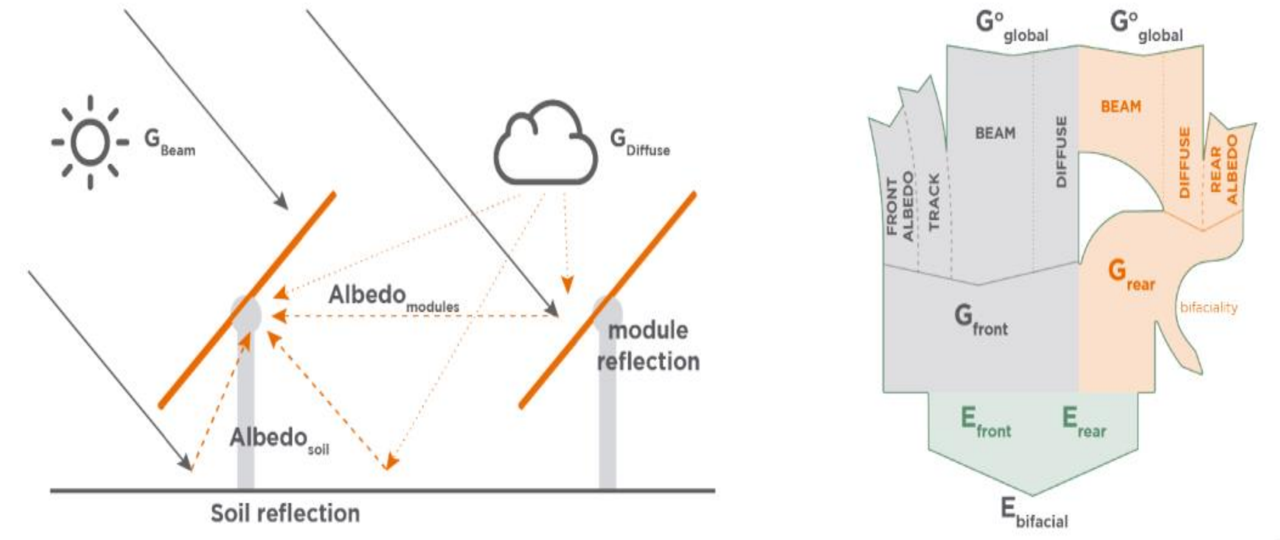

Fig. 6 Parameters for the production of bifacial modules.

The open-circuit voltage Voc of bifacial photovoltaic modules is obtained by Eq. 8:

$$Voc_{Bifa} = Voc + \beta \quad (8)$$

Voc: The open-circuit voltage on the front side of the bifacial photovoltaic module, in volts (V).

β: The voltage correction factor. It is calculated according to Eq. 9.

$$\beta = \frac{NkT}{Aq} ln\, ln\, (1+\alpha) \quad (9)$$

N: the number of equivalent cells in series of the modules.

K: the Boltzmann constant, in joules per Kelvin (J/K).

T: the temperature, in Kelvin (K).

A: the ideality factor of the PV module, with a recommended value of 1.2.

q: the charge of an electron, measured in coulombs (C).

The short-circuit current Isc_{BiFa} and the maximum power point current Im_{BiFa} of bifacial photovoltaic modules are given by Eqs. 10 and 11:

$$Isc_{BiFa} = Isc_{front}\ (1 + G_i) \quad (10)$$

$$Im_{BiFa} = Im_{front}\ (1 + G_i) \quad (11)$$

Isc_{front}: The short-circuit current on the front side of the bifacial photovoltaic module, in amperes (A);

Im_{front}: The maximum power point current on the front side of the bifacial photovoltaic module, in amperes (A).

The maximum power point voltage Vm_{BiFa} of the bifacial photovoltaic modules is given by:

$$Vm_{BiFa} = Vm_{front} + \beta - R_s Im_{front} \quad (12)$$

Vm_{front}: The maximum power point voltage on the front side of the bifacial photovoltaic module, in volts (V).

R_s: The equivalent series resistance of the bifacial photovoltaic modules under standard test conditions (STC), in ohms (Ω).

The fill factor of the bifacial photovoltaic modules FF_{BiFa}. is represented by:

$$FF_{BiFa} = \frac{[Vm_{front} + \beta - R_s\ Im_{front}]x\ Im_{front}\ (1+G_i)}{[Voc_{front} + \beta]\ x\ Isc_{front}\ (1 + G_i)} \quad (13)$$

The maximum power output *Pmax* of the bifacial photovoltaic modules is determined by Eq. 14:

$$Pmax_{BiFa} = Voc_{BiFa}\ x\ Isc_{BiFa}\ x\ FF_{BiFa} \quad (4)$$

3. Results

We have developed a Matlab program for our study to simulate the behavior of the LCOE based on the bifacial gain and assess the financial impact of utilizing the rear-side energy contribution in a bifacial photovoltaic project. It is important to emphasize the significance of the LCOE in determining the cost of energy in a PV project. Accurate calculation of the LCOE is crucial for informed decision-making, as a project with an energy selling price lower than the LCOE would result in financial losses. Therefore, precise determination of the LCOE is essential, particularly considering the varying scenarios influenced by external factors that directly affect the gross income and introduce uncertainty into project evaluation.

By analyzing the results, as depicted in Figs. 7 and 8, we observe the LCOE trends for both technologies and the sensitivity of the LCOE to the bifacial gain. Initially, the PV plant with monofacial modules is cheaper than the bifacial option by approximately 300 FCFA/kWh for the first few years. However, from the 7 th year onwards, the bifacial option becomes more cost-effective and maintains this advantage throughout the remaining years. The bifacial gain plays a key role in achieving the reduced $LCOE_{BiFa}$ cost, as higher gain values result in cheaper electricity LCOE from the PV plant. On average, considering a discount rate variation from 2 % to 26 %, the $LCOE_{Mono}$ is determined to be 83.49 FCFA/kWh, while the $LCOE_{BiFa}$ is 72.44 FCFA/kWh.

Furthermore, it is crucial to assess the price disparity between the two technologies to understand the financial implications that the bifacial gain could bring when utilizing bifacial PV modules. The obtained results are presented in Figs. 9 and 10, highlighting three notable observations:

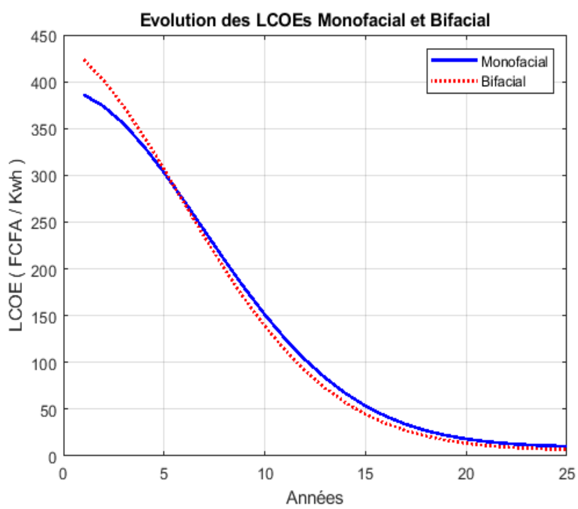

Fig. 7 Comparison of LCOE between the two technologies.

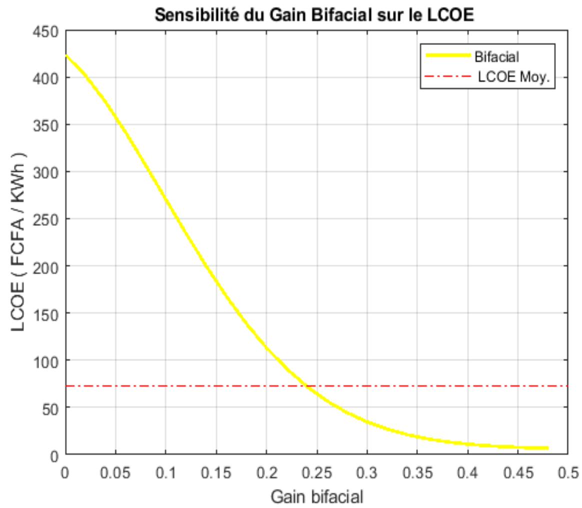

Fig. 8 Sensitivity of bifacial gain on LCOE.

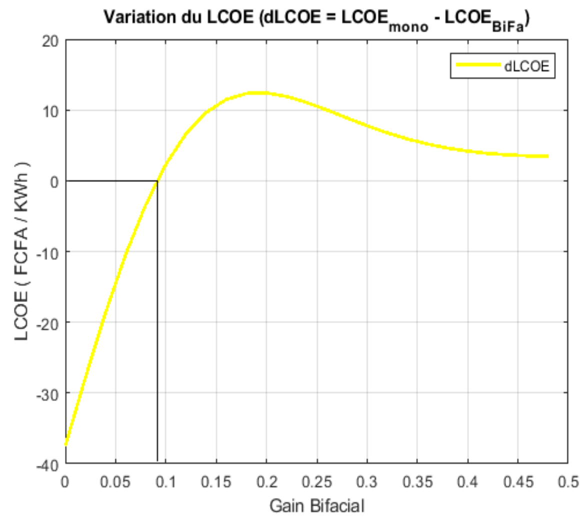

Fig. 9 Comparison of additional gains.

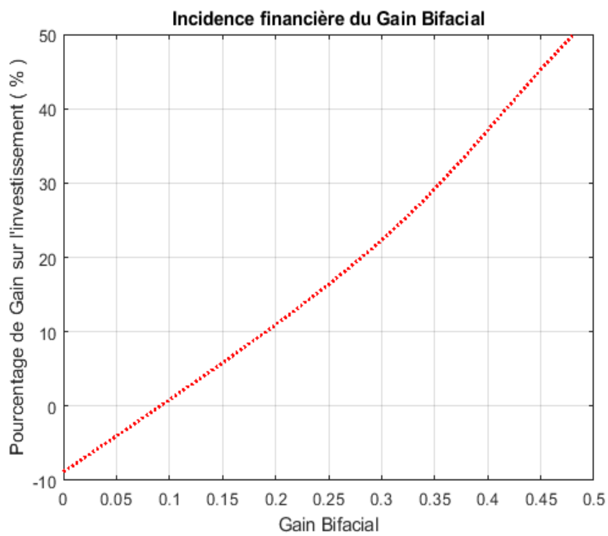

Fig. 10 Financial impact of bifacial gain.

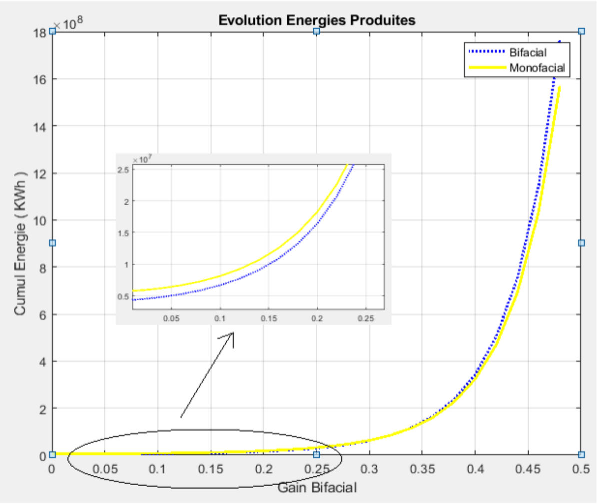

Fig. 11 Comparison of the energy generated.

- When the bifacial gain is equal to or less than 9%, the PV plant with monofacial modules is more profitable than the bifacial modules. Installing bifacial modules under these conditions would result in a loss of up to 38 FCFA/kWh, equivalent to an 8% loss of the total invested cost over the plant's lifespan.
- The PV plant with bifacial modules becomes profitable when the bifacial gain exceeds 9%, offering the potential to save over 40% of the investment cost if the bifacial gain reaches 45%.
- The optimal difference between the two LCOEs is achieved when the bifacial gain ranges between 15% and 25%.

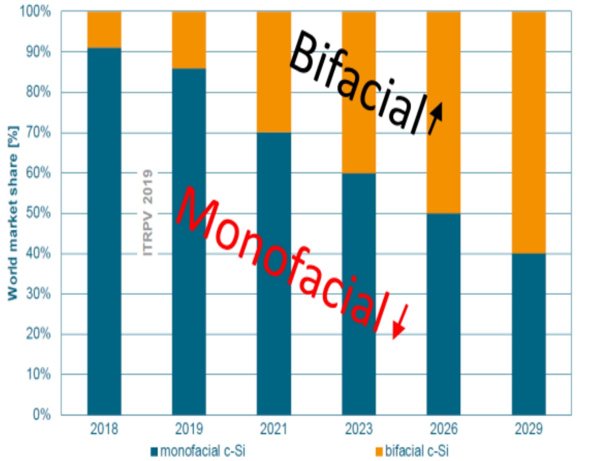

Fig. 12 Market share of photovoltaic modules (Source: ITRPV).

Additionally, comparing the two technologies in terms of energy output, Fig. 11 demonstrates that, despite a difference of 2,100 panels between monofacial and bifacial modules for the same surface area, the cumulative energy production of the bifacial modules surpasses that of the monofacial modules when the bifacial gain exceeds 30%. Specifically, the monofacial installation produces 1.57 GWh, while the bifacial installation produces 1.765 GWh.

4. Discussions

As we have seen, bifacial modules can effectively increase energy production and reduce the system's LCOE starting from a bifacial gain of 9%, offering incomparable advantages compared to traditional monofacial modules. Furthermore, the economic appeal of bifacial technology largely depends on the bifacial gain, which represents the rear-side irradiation efficiency. Scott Stephens, Director of Technology Development at Clearway Energy, stated, "While bifacial technology may cost more than a monofacial PV system, bifacial technology easily outperforms with a 10 % bifacial gain" [15]. Additionally, the HSAT (Horizontal Single Axis Tracking) bifacial installation has gained significant attention in recent years due to the combination of both technologies leading to the lowest possible LCOE (Levelized Cost of Electricity) [16].

Therefore, the bifacial gain is a crucial parameter for achieving optimal system performance. This parameter also depends on factors such as module height, row spacing, tilt angle, and ground albedo. According to the International Photovoltaic Technology Development Blueprint (ITRPV), the market share of bifacial modules will continue to increase each year over the next decade, representing nearly 70% by 2030 [16]. Hence, it is important to understand the technical specifications of this technology.

For any photovoltaic installation project, feasibility studies comparing the two technologies should be conducted to adopt the most reliable and cost-effective technology. Bifacial technology is likely to become predominant, with monofacial technology primarily used for residential applications, while bifacial technology is preferred for medium and large-scale photovoltaic projects.

Based on the obtained results, we recommend four basic principles for the installation of bifacial PV modules:

- They should be arranged according to the optimal tilt angle of 2 °.
- The higher the module installation height, the greater the energy production, but the installation height should not exceed 2 meters to ensure suitable wind load on the support structure.
- A study of the geographic location for module installation should consider site-specific reflection conditions.
- The support structure for bifacial PV modules should avoid obstructing the rear side of the module to allow for optimal configuration and maximize energy production gain.

5. Conclusion

In summary, future electricity production business owners will have a range of options when it comes to installing a PV plant. In the past, the choice was between polycrystalline and monocrystalline solar modules, which depended on the processing method. However, there is now an additional choice between monofacial and bifacial modules. Through the study of a case, we have understood that the offer presented by bifacial technology is economically compelling, provided that the various selection and sizing criteria are respected to achieve a bifacial gain of at least 9%. The critical value for the bifacial gain is 9%, as below this value, we could lose up to 8% of the invested cost, which amounts to 38 FCFA/kWh if bifacial modules were installed. Conversely, if the bifacial gain exceeds 9%, we can gain up to 40% of the invested capital. We hope that the results of this work will significantly contribute to understanding and decision-making between these two PV module technologies.

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