THE ULTIMATE GUIDEBOOK FOR BIFACIAL SYSTEM DESIGN

Trinasolar

EXECUTIVE SUMMARY

In the coming years, bifacial technology will dominate the global solar panel industry. Market share is already above 70% in the utility-scale segment. This guidebook provides a clear view of the successful implementation of bifacial technology, maximizing system performance and minimizing Levelized Cost of Energy (LCoE).

There are some particular challenges associated with bifacial technology. One is related to calculating additional power output from the module's rear side, which is much more complex than the front side. The concept of **"Bifacial Gain"** is the most common approach in the industry to model the energy generated by the rear side of the module. The energy generated by the rear module side is calculated as a fraction of the energy produced by the front side of the module.

Starting with basic principles of this technology, this guidebook takes a closer look at the impact of bifacial technology on key system components: modules, mounting systems (including trackers), and inverters. Modules and mounting structures are the critical components affected by a bifacial PV plant. At Trina Solar, we are able to supply both of them, focusing more on a bifacial system (system level) than on individual components. This is critical to providing our customers with compatible, reliable, and optimized systems in terms of LCoE performance.

Our **modules** have a dual glass configuration instead of a transparent backsheet. We can assure that it is a more reliable and robust solution.

On **mounting structures**, the irradiation on the back of the bifacial module (and therefore the power generation) is impacted by many factors, including height and size of torque tube, purlin height, and central gap.

It is also affected by **smart tracking algorithms/technology**. With the penetration of bifacial modules, the tracking angle changes from a monofacial approach.

Apart from components, the performance of a bifacial PV plant highly depends on **installation parameters** such as **albedo**, the distance between module rows (**pitch**), **module height**, and the **shading** created by the torque tube (or other mounting system components). Based on components and previous system parameters, **bifacial gain can vary from 5% up to 30%**. Therefore, **energy production/yield can be increased up to 10% compared to a monofacial configuration**.

Bifacial modules are mature technology. At Trina Solar, we are optimizing it, having run several field tests and case studies to measure real improvements of this technology at different geographical locations, as detailed in this guidebook.

Following our field tests and case studies, we can say that in general, in locations with good irradiance conditions, a bifacial PV module plus a tracker is the optimal combination for maximizing the IRR of the PV plant. In countries with poorer irradiance conditions, a bifacial module with a fixed tilt structure can contribute to better LCoE for the PV plant.

In terms of sensitivity, it has become evident that greater albedo, mounting height and module spacing lead to greater energy production.

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1. INTRODUCTION

Bifacial technology for solar panels has existed nearly as long as solar panels themselves, but its higher costs meant it was used less frequently until 2018.However, beginning in 2019, advances in solar panel technology resolved these technical issues at the cell/module level. As a result, PERC cells are now more compatible with bifacial technology at a lower cost. As the most prominent solar cell technology, PERC has brought the solar industry's attention (from promoters, IPPs, and EPCs to tracker and inverter suppliers) to bifacial technology.

As many cell producers upgraded their PERC manufacturing processes in 2019, some started considering the next step. Encouraged by China's Top Runner program and stimulated by the U.S. Section 201 exemption, leading cell suppliers began targeting the growing demand for bifacial modules (and bifacial technology) in the following years. Nowadays, most leading cell makers have upgraded most (if not all) of their production lines to bifacial.

Global shipments of bifacial modules in 2019 were less than 9% of total module shipments. Bifacial was still a niche product at the time, and the market competition was highly consolidated among leading module suppliers worldwide. However, despite the global COVID-19 pandemic, in 2020, bifacial modules grew to 21% of the global market share of module shipments, as illustrated in Figure 1. Forecasts for 2021 and the following years show a clear growth trend for bifacial modules, predicting market shares above 50% globally as of 2023. Additionally, the bifacial module market share for utility-scale (ground-mounted) installations is expected to exceed 70% worldwide.

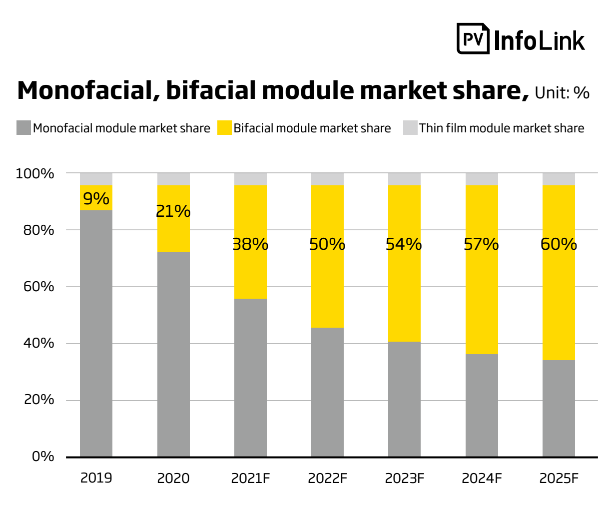


Figure 1. Monofacial vs bifacial market share worldwide

Trina Solar started shipping bifacial modules in 2015. Currently, Trina Solar's cumulative shipments of bifacial solar PV modules have reached more than 20 GW worldwide across seven main regions.

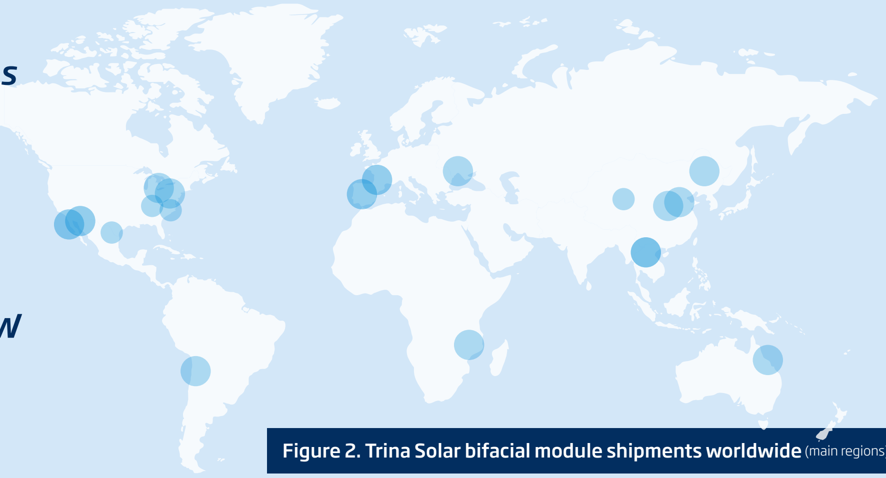


Figure 2. Trina Solar bifacial module shipments worldwide (main regions)

2. BIFACIAL TECHNOLOGY.
Principles and Basics

The power output of a bifacial module can be expressed as the sum of the energy generated by the module front and rear sides:

$$E_{bifacial} = E_{front} + E_{rear}$$

This simple formula has confused the industry for years. In monofacial modules, energy can be accurately forecasted as the front side accounts for all the energy. However, in bifacial modules, the energy output also depends on the irradiance on the rear side of the module and the energy forecasting process is more complex than in monofacial ones.

Bifacial gain, Bifaciality and Bifacial Ratio

The **"Bifacial Gain"** concept is the most common approach in the industry to model the energy generated by the rear side of the module ($\mathbf{E}_{rear}$) as a fraction of the energy produced by the front side of the module ($\mathbf{E}_{front}$).

It is worth explaining that the power conversion efficiency in a module is different on the rear side than on the front side. On the other hand, the incident light that reaches the front side of a module generates a different behavior than light reaching the rear side.

Based on previous considerations, two new definitions take relevance:

- **Module Bifaciality:**
  The ratio of the energy conversion efficiencies of a module's rear and front sides. Bifaciality is an intrinsic module feature.
- **Bifacial ratio:**
  The ratio of the irradiation that reaches the rear side of a module ($\mathbf{G}_{rear}$) to the irradiation that reaches the front side ($\mathbf{G}_{front}$).

$$Bifacial\ Gain = E_{rear} / E_{front}$$

$$Bifacial\ Ratio = G_{rear} / G_{front}$$

$$Bifaciality = Bifacial\ Gain / Bifacial\ Ratio$$

Using these definitions, the energy generated by a bifacial module ($\mathbf{E}_{bifacial}$) is related to the energy generated by the front side of a module ($\mathbf{E}_{front}$), as follows:

$$E_{bifacial} = E_{front} \times (1 + Bifacial\ Gain)$$

$$E_{bifacial} = E_{front} \times (1 + Bifacial\ Ratio \times Bifaciality)$$

According to above equations, bifacial gain could be increased by:

- ***Using modules with higher bifaciality***
- ***Positioning the modules to maximize the irradiation on the rear side***

Increasing energy generated by the rear side

In order to increase the energy output of the rear side of a module, it is necessary to understand main factors that can optimize the irradiation on the rear of the module. As Figure 3 shows, irradiation on the rear side ($\mathbf{G_{rear}}$) consists of two main terms:

- **Diffuse irradiation.**

  It is the amount of radiation received per unit area by a surface that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere. Basically, it is the illumination that comes from clouds and the blue sky. This energy accounts for about 15% of the global radiation on clear sunny days. However, on cloudy days, radiation is dispersed by the clouds, and therefore direct radiation percentage is very low, whereas diffuse radiation accounts for a much higher percentage.

$$G_{rear} = G_{diffuse} + G_{reflected}$$

- **Reflected irradiation.**

  It is the amount of radiation reflected by the earth or other surfaces.

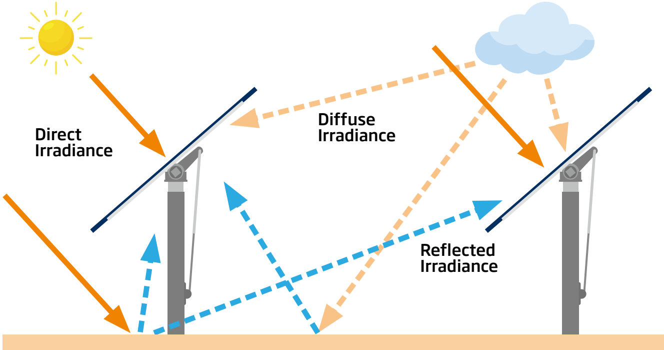


Figure 3. Basic G_{rear} irradiance sources

The amount of incident irradiation that is reflected by a surface depends on the reflection coefficient, known as **albedo**. As described in section 4.1., accurate estimations of albedo radiation involve complex boundary conditions, such as ground surface properties and the distribution of radiation reaching the ground, which might change depending on the location and the time.

Next are main PV plant (system) factors and parameters that can influence (and therefore maximize) energy generated by the rear side of a module.

(a) Albedo
(b) Distance between module rows (pitch)
(c) Module height
(d) Shading on the rear side of the module

Chapter 4 of this guidebook describes in detail the main effects of the above parameters on bifacial gain. Still, the reader can intuitively understand the influence of each one on bifacial gain as per Figure 4.

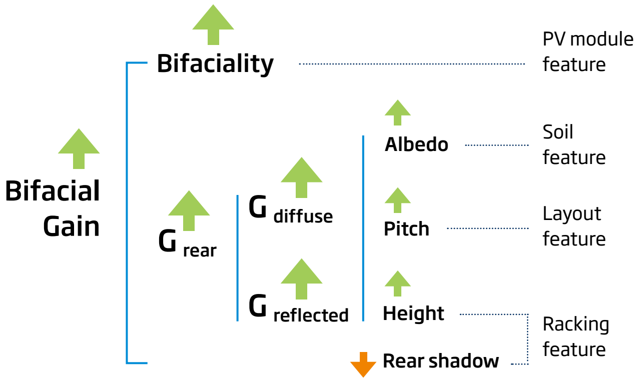


Figure 4. Basic factors affecting bifacial gain

3. BIFACIAL PV PLANT. Main Components

3.1. Bifacial module

A bifacial module can generate electricity from its front and rear sides. Unlike standard monofacial silicon PV cells that collect energy from only their front side, the bifacial cells have an open back side. This enables the collection of a substantial amount of reflected light available from the ground, rooftops, clouds, and atmosphere.

At the architectural module level, the bifacial concept requires us to replace the standard solid backsheets with either glass or a transparent backsheet. Double glass encapsulation provides additional protection to embedded solar cells due to its excellent reliability and durability. Most manufacturers use this option.

In addition to increased power output, this technology provides all the advantages of glass-glass, including lower potential induced degradation (PID); in the case of n-type cells, higher resistance and a higher tolerance for harsh environments.

However, the most important elements of bifacial technology are the cell type and the processes for making the rear side of the cell receptive to sunlight absorption (similar to its front side utilizing light resources to the greatest extent, as shown in Figure 5).

The traditional cell back surface is an aluminum back surface field, which blocks light absorption on the back. Optimizing bifacial cells requires adopting a bifacial alkali texturization process to guarantee the same light-trapping structure on both sides. The back surface must also adopt a grid line pattern similar to the front surface of the cell instead of the traditional back surface field pattern to ensure it can also absorb light for power generation.

Different cell types and technologies have different bifaciality rates (as illustrated in Figure 6), which defines the ratio of the front-side efficiency over the rear-side efficiency. N-type cell technologies such as HJT and TOPCon have the highest bifaciality, reaching up to 90% (compared with PERC at 70%).

Nevertheless, PERC cell technology is becoming a larger share of the bifacial market. Current tests and developments have shown an improvement of up to 80% in the bifaciality rate of PERC bifacial modules (PERC+).

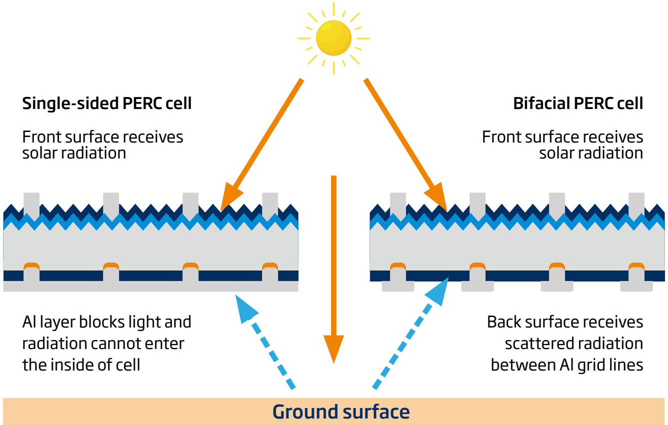
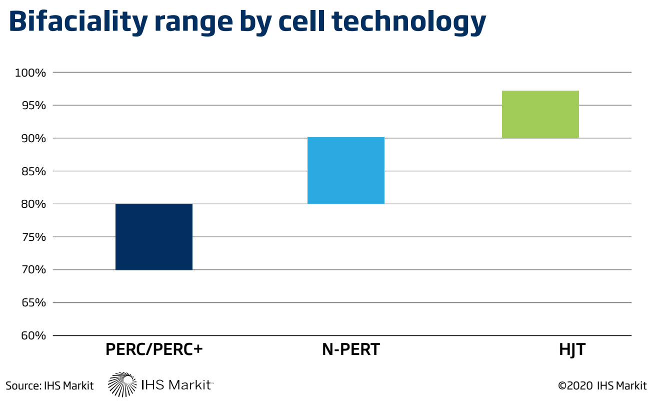


Figure 5. Cell Structure for monofacial and bifacial configurations



Source: IHS Markit

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Figure 6. Bifaciality by different cell technologies

3.1.1. Bifacial module materials: Glass-glass vs transparent backsheet

Bifacial glass technology is the preferred material among manufacturers for the rear side cover of the modules. Some key advantages of the glass-glass structure are:

- **Better light transmittance**
- **Less degradation**
- **Zero risk of water permeability**
- **Weather ability**
- **Corrosion resistance**
- **Abrasion resistance**

Glass-glass modules can also be frameless, which helps eliminate the cost of an extruded aluminum frame. However, glass-glass models with frames have a lower risk of breakage. As a result, most glass-glass modules come with frames in place.

Compared with standard glass backsheet technology, framed modules with two layers of glass are heavier. Therefore, transparent backsheets are a solution for a lighter bifacial module. A more lightweight module means less cost on transportation, labor, and trackers whenever applicable.

Due to their better reliability, glass-glass bifacial configurations have a larger portion of the worldwide bifacial module market share. Glass shortages, weight concerns for larger format modules, and decreasing prices for transparent backsheets have caused some manufacturers to switch to a glass-transparent backsheet structure. However, bifacial product forecasts this year show glass-transparent backsheet as representing only 20% of the total market share. Projections also show these shares reducing even more in the following years once the main components shortage is resolved (as seen in Figure 7).

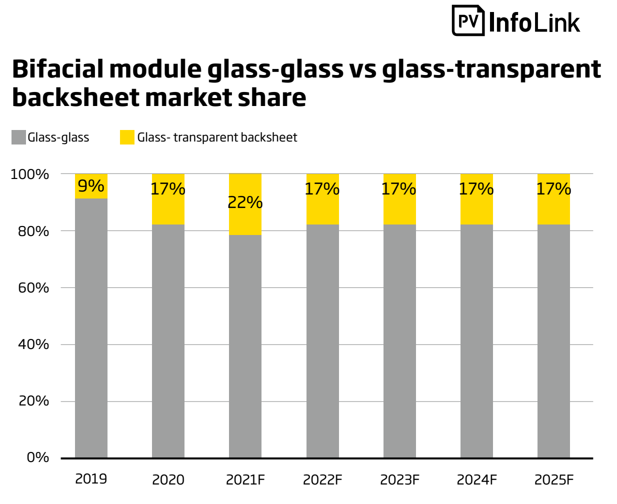


Figure 7. Glass- glass vs glass-transparent backsheet bifacial modules global market share

3.1.2. Trina Solar bet on glass-glass configuration for the bifacial module

With the rapid development of the PV industry, leading companies, research institutes, and institutions of higher education are devoted to module design and process-specific production optimization to reduce module cost and improve module quality. The life cycle of PV modules in general is primarily dependent on backsheets, and their current life expectancy is 25–30 years.

With customers' increasingly urgent need for high quality, high power, long-life products, breakthroughs in the current module structure can be challenging. However, Trina Solar has made such a breakthrough by abandoning the backsheet and developing the brand-new dual glass module.

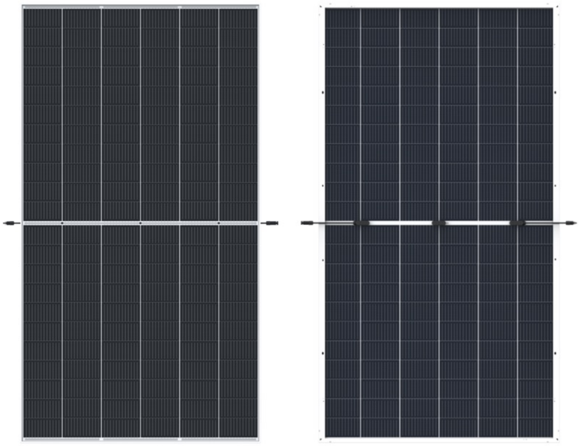


Figure 8. Trina Solar Vertex TSM-DEG21C.20 (670 W) framed dual-glass bifacial module

Our dual glass modules use the same internal circuit connection as a traditional glass-backsheet module but feature heat-strengthened glass on both sides. We produce the back glass with a unique drilling technique that ensures the reliability of both the junction box installation and the module. Compared with traditional modules, our dual glass modules replace the organic backsheet with inorganic back glass to extend life expectancy.

From this point of view, the structural design of our dual-glass modules overcomes problems such as the outdoor degradation-induced material aging and the power attenuation that frequently affects traditional backsheets. In addition, our design avoids distinctive weak points in thin-film modules, such as low efficiency and high vulnerability. Moreover, the thin-film module can only use annealed glass as front glass, resulting in cracks during production and operation due to insufficient strength. This also affects its efficiency.

Figure 9. Dual glass module structure (layers)

Trina Solar was the first company to obtain IEC61215/IEC61730-1 and 2, UL61730, IEC 1500 V/ UL100V, UL, and TUV RH Class A fire certifications for a dual glass product. Furthermore, our tested modules passed 192h PID resistance tests under 85% RH 85°C and 1500V system voltage, having shown excellent resistance to PID and snail trails.

Our analysis identified the following benefits for glass-glass configuration bifacial modules:

- ### Resistance to salt spray, acids and alkalis

  The polymer backsheet that traditional modules use is made from plastic with poor resistance to acid and corrosion. Prolonged exposure to air may bring about yellowing, cracking, degradation and chalking, etc. In contrast, the glass found in our dual glass modules is a kind of inorganic material with relatively superior weather resistance, which considerably improves the module's reliability.

- ### Zero moisture penetration

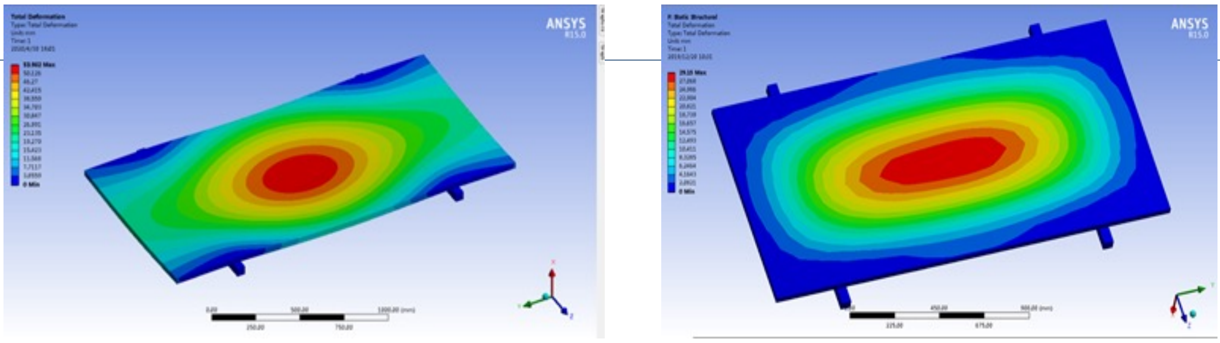
  Normally, moisture could penetrate traditional polymer backsheet modules. Long-term moisture penetration may cause various degrees of damage to cells. However, since moisture cannot penetrate glass, our glass design can better protect cells and extend their life expectancy.

- ### Comprehensively reduce invisible cell cracking

  Our dual-glass structure constitutes a sandwich-like design with a strong resistance to shock and vibration that ensures module safety during production, transport, and installation and prevents new invisible cell cracking.

- ### More excellent mechanical load ability

  Thanks to improvements in module stiffness and the better support of dual-glass design, the deformation of our dual-glass modules is much lower than that of traditional modules with frames under the same mechanical load (according to FEM simulation analysis in Figure 10).



Monofacial backsheet framed panel; the deformation may reach up to 50mm for a large format module

Bifacial dual glass framed panel; the deformation is less than 30mm for the same large format module

Figure 10. Module deformation (FEM simulation) for dual glass vs glass-backsheet configuration

3.2. Tracker and mounting structure

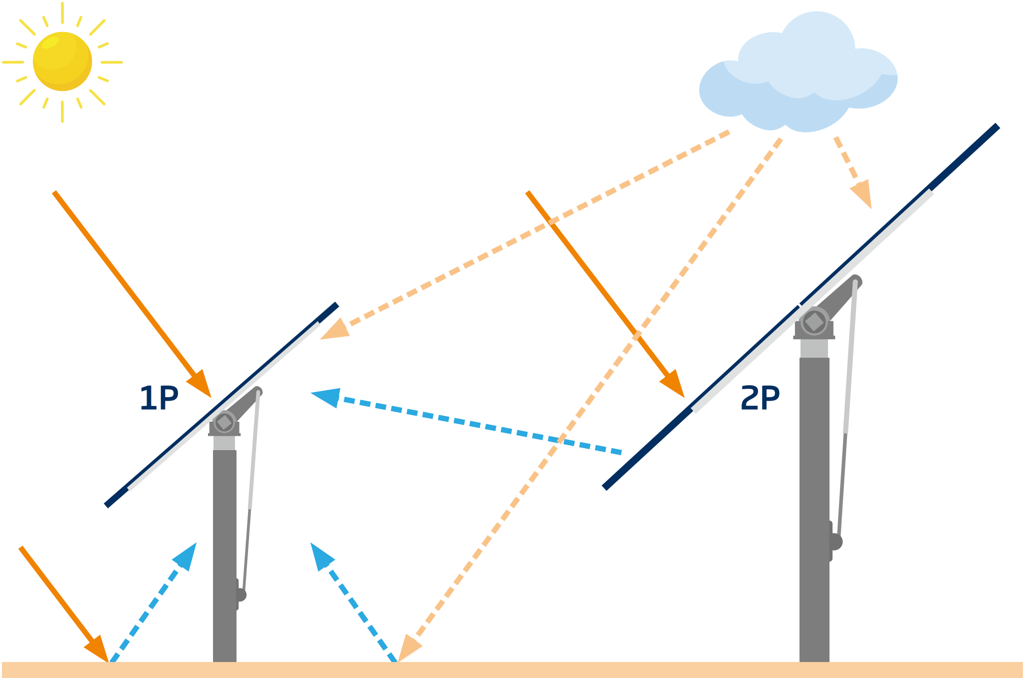


Figure 11. Back irradiation sources for 1P and 2P tracker configurations

As shown in Figure 11, the irradiation on the back of the bifacial module when mounted on trackers mainly includes two aspects: **reflected irradiation and diffuse irradiation**. The reflected irradiation consists of the reflection from the rear-row modules and the reflected irradiation from the ground. In terms of tracker structure, the amount of irradiation on the back of the bifacial module involves many factors, including:

- **Torque tube height and size**
- **Purlin height**
- **Central gap**

The power generation of trackers is proportional to the torque tube height, purlin height, and central gap. Smart tracking algorithms/technology also affect the trackers' power generation.

3.2.1. 1P tracker configuration

As Figure 12 (left) shows, the difference in power generation in the 1P (=one module in portrait mounting) tracker increases as the height of the purlin increases (for the same torque tube size). However, as the torque tube size increases (for the same purlin height), the difference in power generation decreases.

As the torque tube height increases (Figure 12, right), the difference in power generation and power generation increases as well.

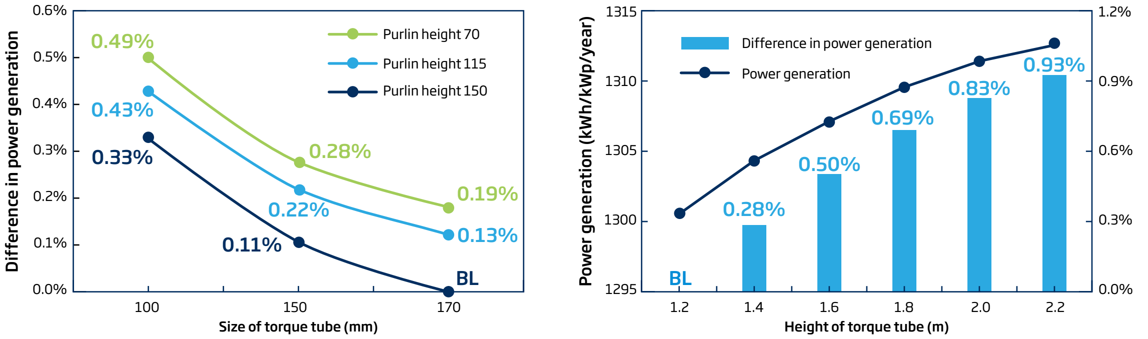


Figure 12. Influence of 1P tracker design / structure on power generation

The tracker's main parameters optimize the energy generation, especially for bifacial modules, and ensure the tracker's safety and stability. As shown in Figure 13, reasonable design safety guidelines for the 1P tracker product configuration might result in a purlin height of 65 millimeters, a torque tube size of 120 millimeters, and a torque tube height of 1.2–1.95 meters.

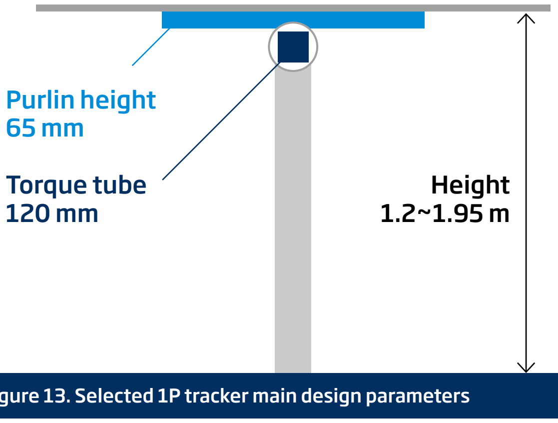


Figure 13. Selected 1P tracker main design parameters

3.2.2. 2P tracker configuration

The difference in power generation in the 2P (=two modules in portrait mounting) tracker is proportional to the height of the purlin (Figure 14, left) and torque tube height (Figure 14, right). The difference in power generation is inversely proportional to the size of the torque tube (Figure 14, left).

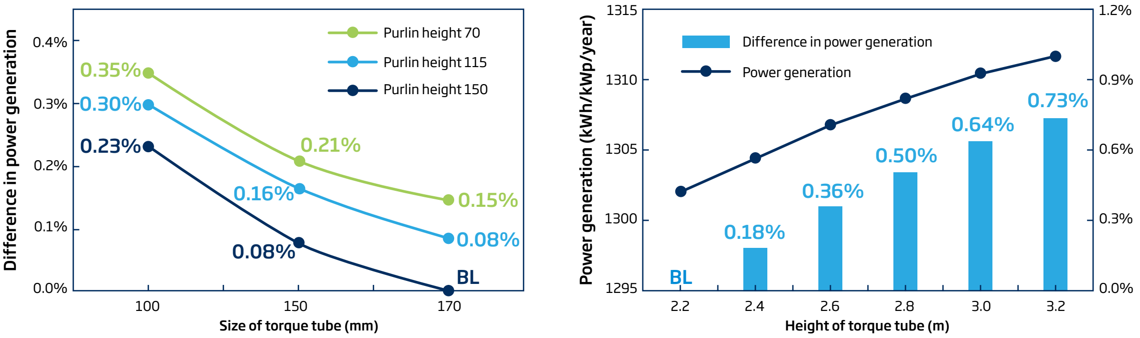
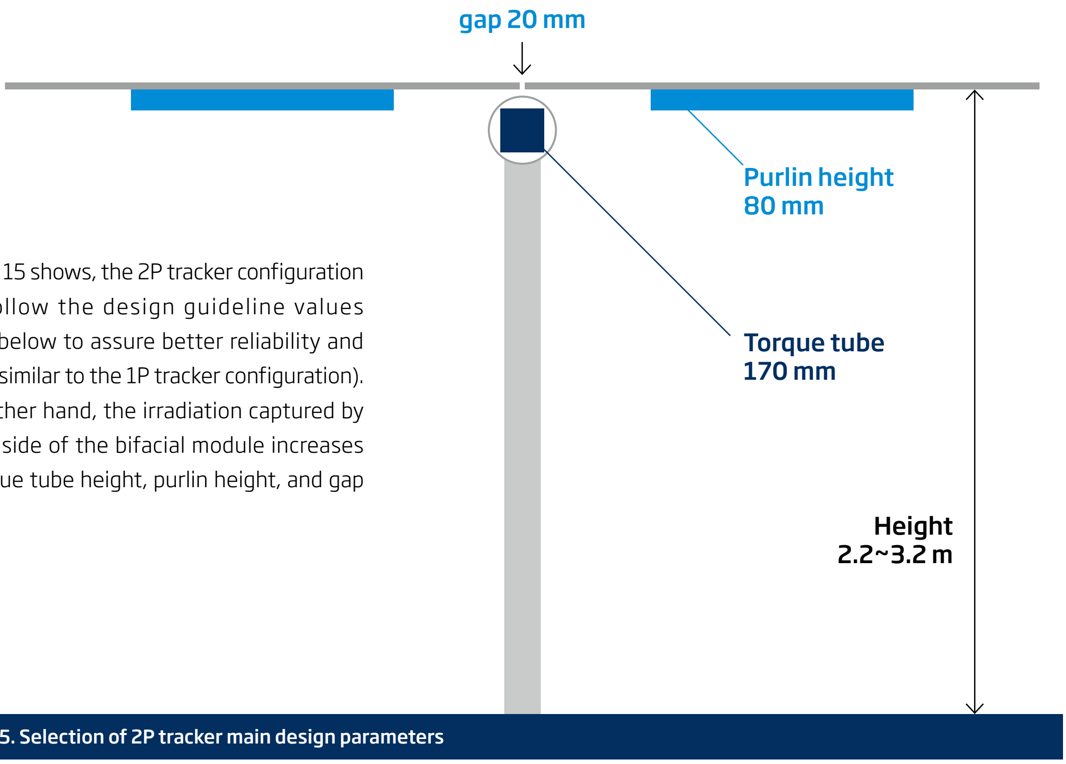


Figure 14. Influence of 2P tracker design / structure on power generation



As Figure 15 shows, the 2P tracker configuration might follow the design guideline values detailed below to assure better reliability and stability (similar to the 1P tracker configuration). On the other hand, the irradiation captured by the back side of the bifacial module increases with torque tube height, purlin height, and gap width.

Figure 15. Selection of 2P tracker main design parameters

3.2.3. SuperTrack smart tracking technology

SuperTrack consists of two core algorithms: STA (Smart Tracking Algorithm) and SBA (Smart Backtracking Algorithm). Depending upon proprietary technology for the Bifacial Irradiance Model (BIM), STA can improve power generation on a cloudy day or in other conditions with highly diffused irradiance. The module can absorb more direct irradiance on a sunny day when facing the sun. STA dynamically optimizes the angle of the tracker inclination, capturing more diffuse irradiance.

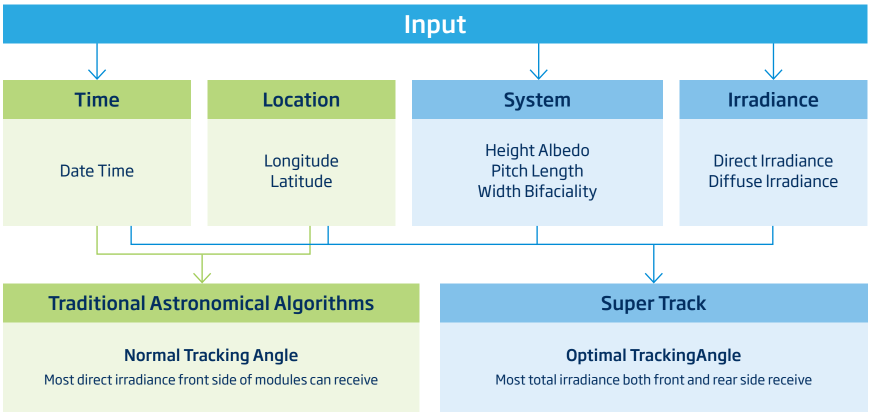


Figure 16. Main factors affecting power generation within a bifacial module

Under the recent trend of increased market penetration, bifacial modules are quickly replacing monofacial modules that feature horizontal single-axis tracker systems. The conventional astronomical tracking algorithm only considers maximum front irradiance, while the bifacial module needs to account for maximum front and rear irradiance. Therefore, the tracking angles of bifacial and monofacial modules differ under various conditions. As shown in Figure 16, the BIM that we originally developed fully considers 12 key factors, calculates front direct irradiance, diffuse irradiance, reflected irradiance, and rear reflected irradiance, and finally gets the total irradiance of the bifacial module.

Moreover, as illustrated in Figure 17, our SuperTrack Smart Backtracking Algorithm (SBA) adopts system operation data to perform disturbance training and (or) adopts UAV sensing technology to identify shading and construct three-dimensional terrain. Based on machine learning algorithms and the Mini-Shading Model, SBA puts out the optimal backtracking angle group for overall power generation through iterative decision-making. It effectively enhances power generation at the backtracking stage and consequently achieves the identification and optimization of complex terrain. This gives full play to the tracker's power generation advantage.

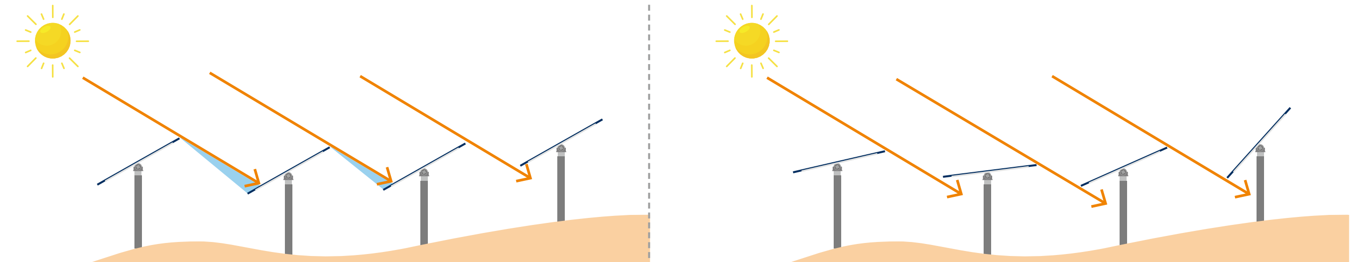


Figure 17. Smart Backtracking Algorithm (SBA) Diagram

3.3. Inverter

Bifacial PV panels are a new technology that takes advantage of the rear module side by collecting light from both sides, increasing the energy yield compared to traditional monofacial modules. These modules work with the same voltage range as monofacial ones, so the number of panels per string is the same. However, bifacial modules can operate at higher currents and therefore theoretically require fewer strings of solar modules.

Generally, these modules yield up to 11% more energy in fixed-tilt installations than conventional panels, but this value reaches up to 30% with solar trackers. Those modules also function in a vertical position. This performance gain occurs with only a modest price increase, so nowadays, it is one of the key factors favoring PV array oversizing (clipping) in solar plants.

How does the use of bifacial modules affect PV inverters?

From a purely electrical point of view, the main differences between the use of either monofacial or bifacial panels are as follows:

- **Differences in DC voltage**

The difference in DC voltage between monofacial and bifacial technologies is minimal because the rated voltage is almost the same. Therefore, the composition of strings would have the same number of solar panels in the series.

- **Differences in DC current**

Bifacial panels can provide higher currents than traditional ones with the same module size. Therefore, they would theoretically need fewer string lines connected in parallel to match the equivalent power of a monofacial configuration.

However, solar industry experts are aware that the module's maximum power is not yet fully definable. We, therefore, cannot yet define the peak power of the plant itself.

Normally, module manufacturers define the panel maximum power (Pmax) in our datasheets, considering only the energy harvest from one side. At the same time, manufacturers include the rear-side power gain separately, considering different values of the bifacial gain (typically between 5% and 30%).

Accordingly, PV plant designers can face two possible scenarios/ situations:

a. They can estimate the power from the module's rear side (the latest simulation software versions allow this), but the estimation might differ from the actual outcome due to several uncertainties (such as different albedos, ground unevenness, and so on).

b. They can only take into account the power from the module's front side and consider any power from the rear side to be an extra clipping.

As a result, bifacial technology implies an increasing DC-AC ratio for PV plants. In most situations, plants cannot accurately bound this ratio. Central or string inverters are necessary to handle this extra current in the worst-case scenario, i.e. values higher than the short-circuit current of the entire bifacial PV array flowing through the inverter's DC stage and corresponding to some bifacial gain on the module's back side.

For central inverter architecture, upgrades in their DC stages (mainly DC breakers, busbars, and cables) fulfill the previous requirement and allow them to accommodate very high current loads. On the other hand, customers quite often require central inverters to connect Battery Energy Storage Systems (BESS) through both topologies: DC-coupling or AC-coupling. Both applications (pure PV and PV+storage) let the central inverters reach high DC-AC ratios up to 200% (or even higher) and allow them to accommodate both types of applications together.

For string inverters, trade-offs between the number of DC inputs, the maximum short-circuit current (and MPPT current), and the number of available MPPTs are necessary to cope with high DC-AC ratios.

3.3.1. DC-AC ratio and impact on PV inverters

The DC-AC ratio is the relation between PV array power (DC) and inverter rated power (AC). It delimits the ***clipping losses*** *and the inverter power saturation when the available DC power exceeds the maximum AC output power. The establishment of a suitable DC-AC ratio is a key factor during the design stage of any photovoltaic plant.*

To optimize the energy yield and overcome component non-idealities, PV plants should include DC-AC ratios higher than 1, reducing projected LCoE and improving return on investment.

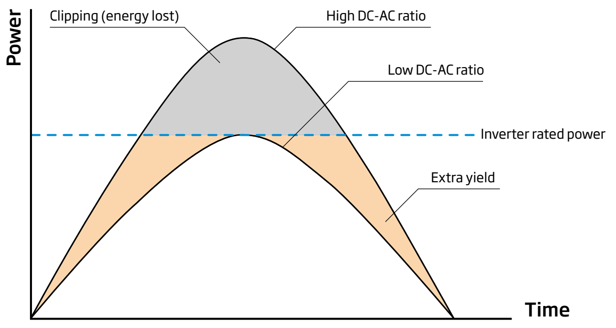


Figure 18. DC/AC ratio vs clipping

A DC-AC ratio between 1.2 and 1.4 (PV array 20% to 40% oversized in relation to inverter power) used to be the most common choice for designers, as it provided a compromise solution to compensate for all non-idealities such as:

- Power plant design calculations made at STC conditions
- The effects of power reduction due to temperature
- The presence of dirt or shadows on the PV array
- System losses
- PV array aging

Other considerations might also increase the DC-AC ratio. For example, PV plants in desert areas could look for a high ratio to compensate for the direct solar radiation reduction due to dust and sand.

Apart from the compensation of non-ideal phenomena and other considerations, the main advantage of using high ratios is increased energy yield. PV inverters not only operate at higher power levels for longer periods across a single day but also across the whole PV plant life expectancy (usually 25-30 years). Furthermore, performance and yield at low irradiance conditions will improve, and, in some cases, extra energy production can compensate for clipping losses.

However, the use of high DC-AC ratios could also have some drawbacks, such as:

a. Higher installation cost (CAPEX)

b. The potential reduction of inverter component lifespans due to the increasing operation hours

c. The failure of the PV inverter to track the Maximum Power Point (MPP) when clipping

However, higher DC-AC ratios are used more often in the solar industry due to decreased module prices over the last few decades and the appearance of new technologies such as bifacial modules that can provide higher power in the same dimensions (via energy captured from both module sides). Moreover, energy storage penetration (required by many grid codes to guarantee grid stability) also helps make a case for higher ratios, as extra energy generated can charge BESS systems.

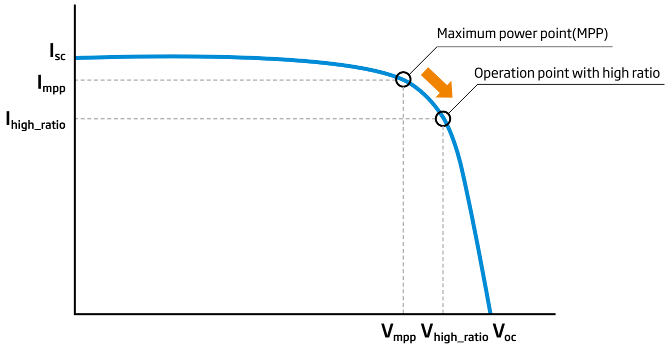


Figure 19. DC/AC ratio affection on MPP tracking

How does the design of a PV inverter affect the DC-AC ratio?

The DC-AC ratio depends upon the inverter rated AC power ($P_{inverter}$) and PV array configuration (P_{PV}):

$$Ratio_{DC\text{-}AC} = \frac{P_{PV}}{P_{inverter}}$$

To define the maximum DC-AC ratio allowable in any power plant, we must calculate the PV array power (P_{PV}) in the following way:

$$P_{PV} = N_{strings} \cdot N_{module} \cdot P_{module}$$

Electrical data within module datasheets are STC (STC: Irradiance 1000W/m^2, cell temperature 25°C, air mass AM1.5) conditions. Hence, we must calculate them for the site design conditions by applying the temperature coefficients (α and β) available on module datasheets. The following variables show the relationship between inverter parameters and the DC-AC ratio:

$N_{strings}$ ▸ Maximum number of strings possible to connect to inverter (current limitation).

$$N_{strings} < \frac{I_{SC_{inverter}}}{I_{SC_{module}} \cdot (1 + \beta \cdot (T_{max} - 25))}$$

$I_{SC\_inverter}$ ▸ Inverter short-circuit current
I_{SC_module} ▸ PV module short-circuit current
β ▸ I_{SC_module} temperature coefficient
T_{max} ▸ Maximum cell temperature at location

$N_{modules}$ ▸ Maximum number of possible modules per string which to connect to inverter (voltage limitation).

$$N_{modules} < \frac{V_{OC\_inverter}}{V_{OC\_module} \cdot (1 + \alpha \cdot (T_{min} - 25))}$$

$V_{OC\_inverter}$ ▸ Inverter open-circuit voltage
V_{OC_module} ▸ PV module open-circuit voltage
α ▸ V_{OC_module} temperature coefficient
T_{min} ▸ Minimum cell temperature at location

$P_{modules}$ ▸ Module maximum power under STC is provided by the technical datasheet.

$P_{inverter}$ ▸ Inverter rated power at site temperature is provided by the technical datasheet.

The above equations show how inverter characteristics can limit the DC-AC ratio, i.e., how the inverter affects the PV array configuration.

4. BIFACIAL PV PLANT.
Key Parameters

Since the rear side of a bifacial module relies on diffused and reflected light for generating electricity, its performance depends heavily on the type of installation and the environment. Depending on factors such as device design, site albedo, mounting conditions, and the cell type itself, the additional power gain of an average PERC system varies from 5% to 30%. With a regular flat rooftop and ground installation, the rear side of a bifacial module can generate an additional 5-10% energy output.

The rear side can generate more output than a standard installation in a fixed-tilt system on a sandy area. Meanwhile, installations on a white-painted surface can provide an additional energy output of approximately 20%. ***Combined with a tracker system, the rear side can generate an additional output of up to 30%.***

With such a wide range of results, solar projects with bifacial modules require more complex performance modeling than projects with standard monofacial modules. The most important factors to the overall bifacial energy production are:

Type of solar cells used for the module and its **bifaciality factor**.

The **albedo** factor, a measure of reflected irradiance from the ground.

The site location, where the **diffused radiation** and **direct radiation** affect the energy yield.

The **tilt angle** of the PV system. Depending on latitude, it requires optimization for diffused irradiation and reflected light.

Ground coverage ratio (GCR), based on the distance between the rows.

The normalized **height of the mounting system**, which minimizes self-shading issues specific to the structure, to have sufficient, more uniform diffused and reflected light on the rear side.

4.1. Albedo

We can define the albedo as the ratio of the reflected irradiance (RI) to the global horizontal irradiance (GHI) received by the ground surface. It is a dimensionless value that can range from 1 (a perfect reflector) to 0 (a perfect absorber). The albedo varies with the color and characteristics of the surfaces that reflect light onto the rear of a module. Lightly-colored and smooth surfaces have high albedos that can lead to high energy output from the rear of a module.

Despite its apparent simplicity, accurate estimations of the levels of albedo radiation involve complex boundary conditions. This is because they depend on multiple factors, such as the ground surface properties and the spectral and angular distribution of solar radiation reaching the ground. These factors vary depending upon the composition of the atmosphere, the geographic location, and the time. As a result, the albedo varies throughout the year (intra-annually) and over the years (inter-annually).

Intra-annual variability is mainly affected by seasonal variation of ground cover related to vegetation growth, the sun's position, and atmospheric factors, which may lead to significant variations in albedo levels throughout the year.

Inter-annual variability is conditioned by year-by-year changes to vegetation growth and atmospheric conditions, such as climate and aerosol optical depth. Since inter-annual variability is strongly related to vegetation growth, its impact will be lower on desert lands than on meadows or grazing and cropping lands.

Albedo is the main factor affecting how much solar radiation the ground surface reflects. As such, it is a key factor when assessing bifacial gain. We must be able to accurately estimate the evolution of albedo irradiation throughout an entire year to calculate the energy output of a bifacial PV project.

Trina Solar has repeatedly tested the generating capacity gain of our bifacial modules under different surface circumstances. One project, for example, involved a conventional monocrystalline PERC dual glass module with the following configuration data:

- **Unsheltered installation in fixed-tilt configuration with a tilt angle of 27°**
- **Module height at least 0.4m above the ground.**

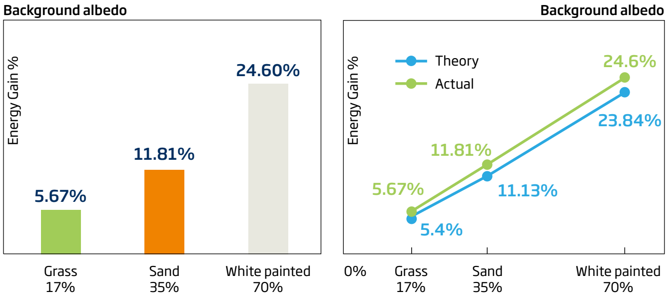


Figure 22. Bifacial gain affection by different albedos (different surfaces)

Figure 22 on the left and Table 1 mainly compare the data on sunny days. With the fixed-tilt installation method, the generating capacity gain increases gradually with the increase of ground surface reflectance. The generating capacity gain is around 20% in the case of white paint.

Types of ground	Albedo (%)	Estimated Bifacial Gain (%)
Grass	17	5.67
Sand	35	11.81
White Painted	75	24.6

Table 1. Measured Bifacial Gain for different albedos (surfaces) **on real PV plant**

Figure 22 on the right shows the contrast between simulated and practical generating capacity gain with installations on different ground surfaces. The theoretically simulated value is approximately equal to the practical value. The generating capacity gain corresponding to other surface reflectance is also roughly determinable from the curve.

Moreover, we must analyze the impact of the latitude on the bifacial gain related to different albedos. For this purpose, our team at Trina Solar has performed a bifacial gain (energy yield) test campaign on three different cities/locations within China with different latitudes, as detailed in Table 2.

City	Latitude
Tianjin	39°N
Golmud	36.4°N
Sanya	18.24°N

Table 2. Latitude of albedo test locations

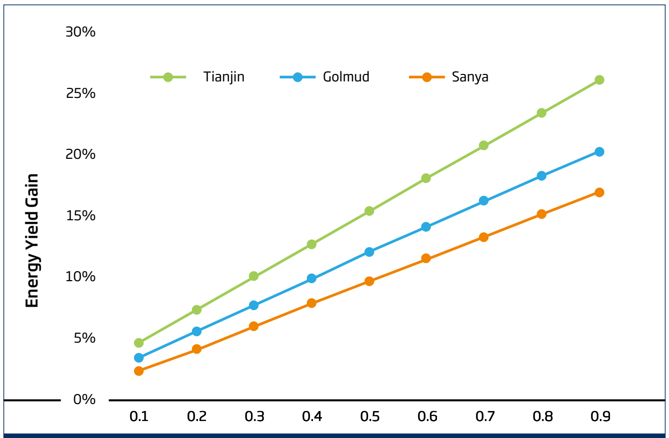
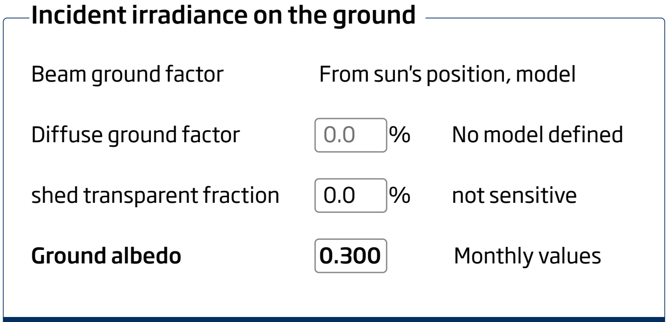


Figure 23. Bifacial gain is affected by different location latitude

As Figure 23 shows, high latitude sites typically imply a bigger pitch and greater tilt inclination. Bifacial gain (and therefore yield) is more sensitive to albedo changes in this situation. This becomes clear when comparing the Tianjin and Sanya locations, for example.

Please note that the previous conclusion is subject to land constraints (or other factors) that prevent bigger pitches at higher latitude sites.



Incident irradiance on the ground

Beam ground factor From sun's position, model

Diffuse ground factor 0.0 % No model defined

shed transparent fraction 0.0 % not sensitive

Ground albedo 0.300 Monthly values

Figure 24. Albedo parameter configuration in PVsyst®

Albedo is one of the most critical variables for configuration when simulating yearly energy production for a bifacial PV plant with the PVsyst® simulation package. Albedo data availability for a specific project location can be either the average annual or a more accurate monthly basis (if data is available).

4.2. Pitch / Ground Coverage Ratio (GCR)

The pitch of a module array is the distance between one module row and the next one. It is directly correlated with the Ground Coverage Ratio (GCR) as depicted in Figure 25.

$$GCR = \frac{module\ area}{ground\ area} = \frac{L}{P}$$

As the distance between adjacent tracker rows increases, the surface area reflecting light onto the module's rear side also increases. So does the bifacial gain.

Figure 26 demonstrates this concept for the same albedo. It describes how the area that reflects light onto the module's rear side increases as GCR decreases (pitch increases). For example, for the same albedo, a GCR of 0.2 is achieving a bifacial gain around 14.5% meanwhile a GCR of 0.5 is decreasing this bifacial gain down to roughly 11.5%.

In conclusion, as GCR increases, bifacial gain decreases. On the other side, as GCR decreases, land, cables and other component costs can be increased (the layout is less optimized). Therefore, a trade-off must be reached to increase bifacial gain (as well as the yield) without compromising the CAPEX. An LCoE perspective is critical to tune the best values for pitch /GCR at every single PV plant.

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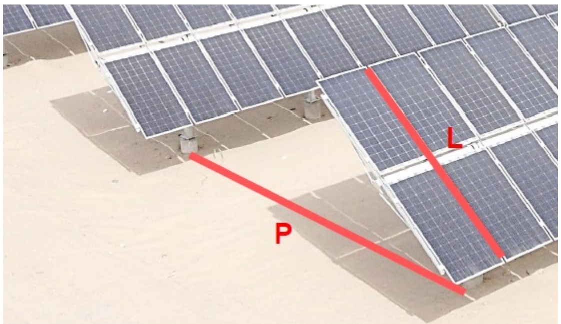


Figure 25. Pitch (P) and Length (L) are part of the basic definition of the GCR

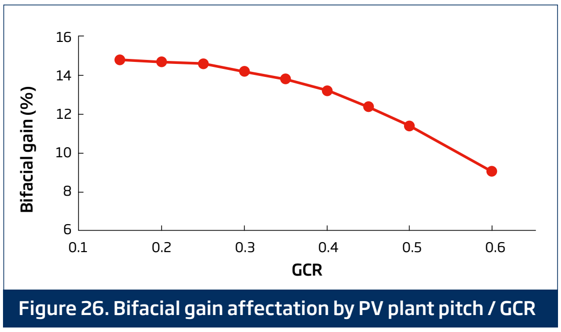


Figure 26. Bifacial gain affectation by PV plant pitch / GCR

4.3. Structure/module mounting height

Module elevation can influence the irradiance on the rear side of a module in different ways.

First, modules located at higher positions on the mounting system (or the upper side of the modules) can capture more diffuse irradiance than the ones closer to the ground. The concept is similar to how the shadow of an object becomes lighter as it moves higher above the ground.

Secondly, modules higher off the ground receive more reflected irradiance than those closer to the ground, as Figure 27 illustrates.

Finally, modules installed higher normally work at lower temperatures.

Previous conclusions and effects, in terms of bifacial gain improvement, are also in line with real field measurements reported by TrinaTracker, and illustrated in Figures 12 and 14.

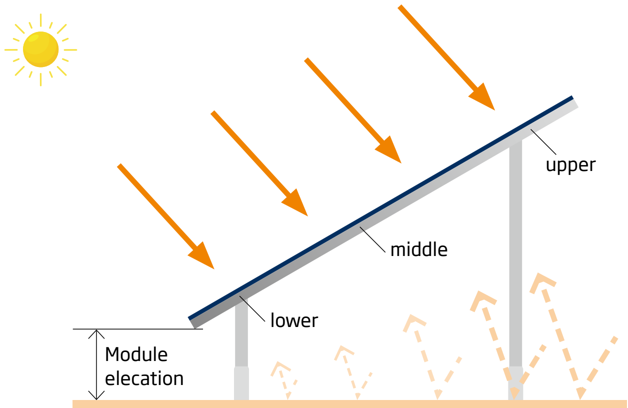


Figure 27. Reflected radiation affectation by structure/ module mounting height

4.4. Shading

Shading always negatively impacts the performance of a module, regardless of whether it is a monofacial or a bifacial module. This is mainly because the appearance of a shadow on a module implies a reduction in the energy production (and therefore in the revenue stream of the PV project). Thus, mounting system suppliers need to design their structures to minimize the presence of objects (such as actuators, cables, etc.) that can cast shadows on the modules' rear side.

Figure 28. Shading coming from a 1P tracker

Generally, the torque tube is a major source of module shading for solar trackers, as Figure 28 shows. However, PV power plant performance simulation software, such as PVsyst®, does not model the specific features of a particular tracker. For example, PVsyst® assumes that the PV modules are a continuous plane suspended in the air with no other shading elements and estimates the irradiance on the rear of the modules by using a Structure Shading Factor (SSF). Structure Shading Factor is the ratio of irradiance loss caused by shading versus the total received irradiance on the rear side.

4.4.1. Shading modeling

Our team at Trina Solar has developed a shading model for tracking systems based on our "View Factor Model" and analyzed a summary of recommended values for "**Structure Shading Factor**" to configure this parameter properly in PVsyst® simulations.

Many installation parameters influence the **Structure Shading Factor (SSF)** and **Mismatch Loss Factor (MLF)**, as Figure 29 shows, including array configuration, array width, module clearance, ground albedo, torque tube/beam support size, the distance between modules and torque tube support, and the module tilt. In addition, the diffuse irradiance ratio also affects the Structure Shading Factor.

w: array width
h: clearance of module
t: module tilt
a: albedo of ground
d: torque tube size
g: module gap
s: distance between module and torque tube

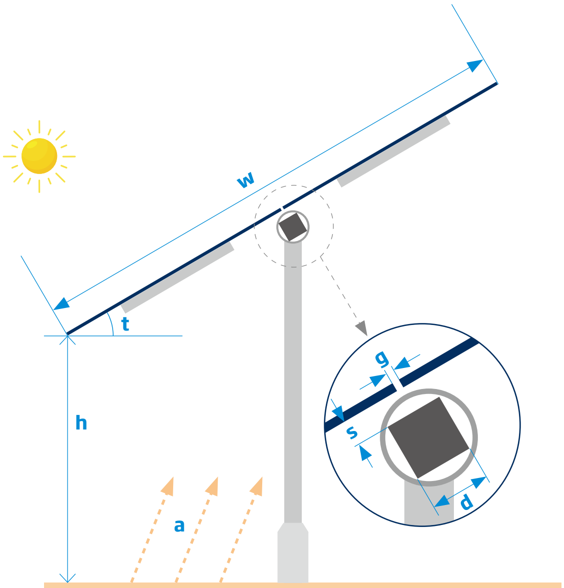


Figure 29. Main parameters affecting the Structure Shading Factor (SSF)

Our proprietary Trina Solar bifacial modules provide the basis for the shading model proposal, based on our "View Factor Model" recognized by the PV industry. Generally speaking, the Structure Shading Factor is the ratio of irradiance loss caused by shading versus the total received irradiance on the rear side. We determine irradiance loss through the integral of irradiance, from ground reflection and diffuse natural light, blocked by the torque tube/beam support. We then calculate the total received irradiance based on bifacial models.

Below, Figure 30 illustrates the shading effects at different points along the module. The rear side of bifacial modules receives the reflected irradiance from the ground and the diffuse sky irradiance. For lower position A, the torque tube/beam support mainly blocks the sky diffuse irradiance, reducing the effective angle from α to γ for diffuse irradiance. For upper position B, the reflected irradiance from the ground is partially blocked, which means that the reflected irradiance from area L cannot be received at the B position.

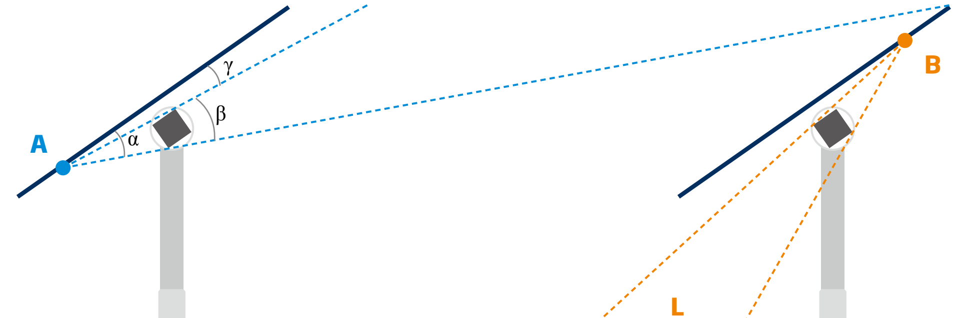


Figure 30. Shading effects at different module points

The shading model we have proposed has allowed the simulation and computation of numerous application scenarios. The model also allows the evaluation of the influence of every single factor. Among all the factors, the following play a crucial role in shading modeling:

- **Array configuration**
- **Array width**
- **Torque tube/beam support size**
- **Distance between module and torque tube/beam support**

Table 3 shows the recommended SSF and MLF values for TrinaTracker products and the recommended values for Shed Transparent Fraction (STF).

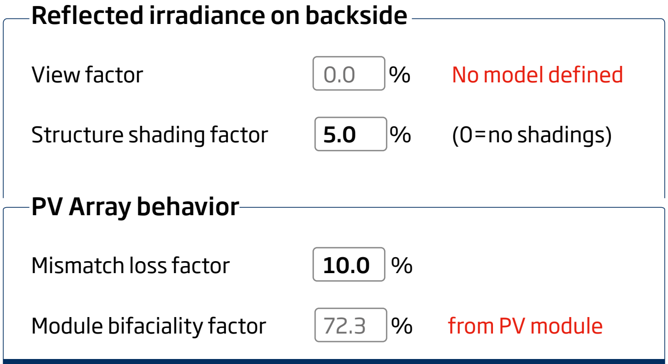
Albedo	2P Tracker			1P Tracker		
	SSF	MLF	STF	SSF	MLF	STF
0.2	3.4%	2.2%	MT+0.9%	4.9%	5.1%	MT+2.1%
0.4	3.7%	2.6%		5.0%	6.2%	
0.6	3.8%	2.7%		5.1%	7.3%	

Table 3. Recommended values for SSF, MLF and STF for a Vertex module under different application scenarios

Figure 31 describes how to configure recommended values using PVsyst® simulation software.

PVsyst® simulates the bifacial gain using several factors: the Structure Shading Factor, the Rear side Mismatch factor, and the Shed Transparent Factor (STF). We usually determine these factors based on empirical experiments rather than demonstration plants. The only one of these factors that we can calculate with a non-complex geometrical methodology is the STF.

The STF represents how much irradiation could go through the module shed and reach the ground. We find it reasonable to assume that sheds may not be entirely opaque to the sunlight since there may be spaces between the modules that are not obstructed by components or mounting structures. This would lead to additional light reaching the ground. Figure 32 shows how to configure STF in the PVsyst® software.



Reflected irradiance on backside

View factor 0.0 % No model defined

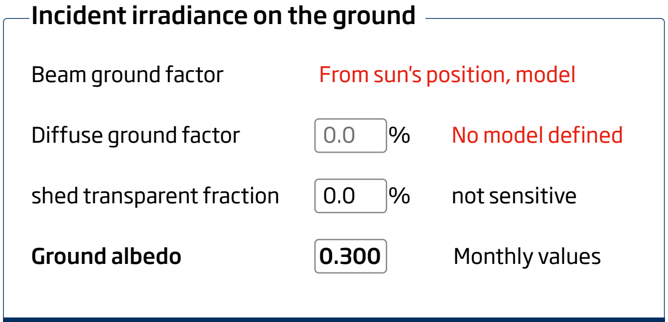
Structure shading factor 5.0 % (0=no shadings)

PV Array behavior

Mismatch loss factor 10.0 %

Module bifaciality factor 72.3 % from PV module

Figure 31. SSF and MLF parameters configuration in PVsyst®



Incident irradiance on the ground

Beam ground factor From sun's position, model

Diffuse ground factor 0.0 % No model defined

shed transparent fraction 0.0 % not sensitive

Ground albedo 0.300 Monthly values

Figure 32. STF parameter configuration in PVsyst®

How does the Structure Shading Factor affect the Energy Production Assessment?

We have used a series of values for the Structure Shading Factor and Mismatch Loss Factor (for the same previously analyzed Vertex module) within the PVSyst® simulation to compare and demonstrate the impact on energy generation. As table 4 shows, energy generation output depends largely on the Structure Shading Factor, the Mismatch Loss Factor, and the ground albedo. As the Structure Shading Factor, Mismatch Loss Factor, or the ground albedo increase, the resulting energy loss increases accordingly. Therefore, when performing PVSyst® simulation, we must set up appropriate values for the Structure Shading Factor and Mismatch Loss Factor to achieve an accurate result.

Albedo	SSF	MLF				
		2%	4%	6%	8%	10%
0.2	2%	BL	-0.13%	-0.30%	-0.44%	-0.57%
	4%	-0.10%	-0.24%	-0.40%	-0.54%	-0.67%
	6%	-0.24%	-0.37%	-0.50%	-0.64%	-0.77%
	8%	-0.34%	-0.47%	-0.60%	-0.74%	-0.87%
0.4	2%	BL	-0.26%	-0.51%	-0.74%	-0.99%
	4%	-0.19%	-0.45%	-0.67%	-0.93%	-1.19%
	6%	-0.38%	-0.64%	-0.87%	-1.09%	-1.35%
	8%	-0.58%	-0.80%	-1.06%	-1.28%	-1.51%
0.6	2%	BL	-0.34%	-0.68%	-1.01%	-1.35%
	4%	-0.28%	-0.58%	-0.92%	-1.23%	-1.57%
	6%	-0.52%	-0.83%	-1.17%	-1.48%	-1.81%
	8%	-0.77%	-1.08%	-1.41%	-1.72%	-2.03%

Table 4. Simulation results for energy loss with different SSF, MLF, and albedo values under different simulation scenarios with PVsyst 7.0

5. FIELD TEST RESULTS.

Third Party Field Test Results

5.1. PVEL case study in California, USA

This case involved one of PVEL's test farms in Davis, California. Known for a typical Mediterranean climate, California has offered tremendous promise for bifacial module applications due to warm and humid winters, hot and dry summers, abundant solar resources, and flat terrain.

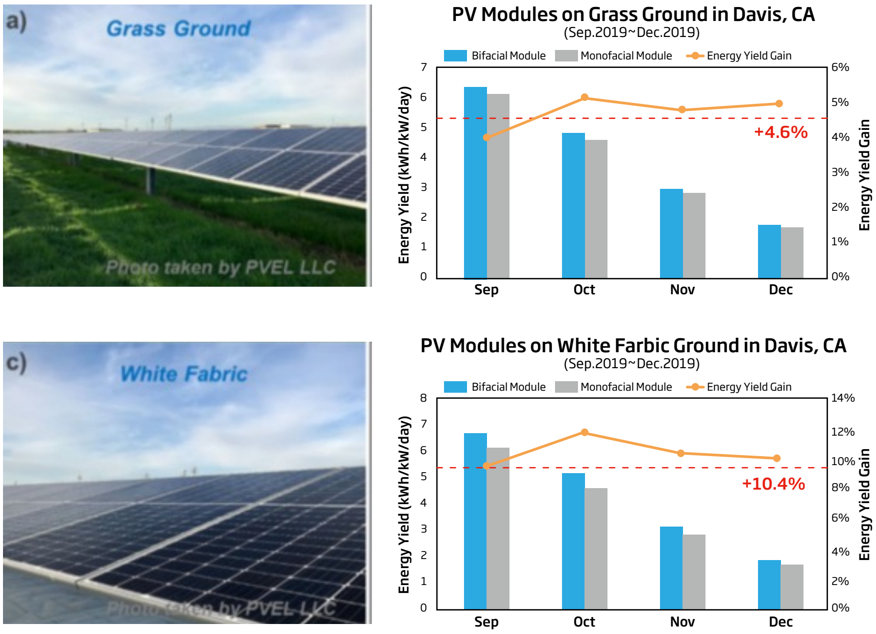


Figure 33. PVEL test farm in the US. Energy yield assessment with bifacial technology

As Figure 33 shows, modules were mounted on a horizontal single-axis tracker with a ground clearance of 0.5 meters. The measured reflectance of grass ground and white fabric was 20% and around 44%, respectively. (Note: the local solar farms extensively adopted white fabric with a reflectance of 40%, approximating the reflectance of sand, while the reflectance of simulated traditional ground snow was around 80-90%). Based on the measured energy yield data from Sept. through Dec. 2019, our bifacial module proved to have a 4.6% yield gain on grass ground and a 10.4% yield gain on white fabric. PVEL, an authoritative third-party global certifying agent, released figures that demonstrated the strengths of our Trina Solar bifacial model.

5.2. Case study in Changzhou, Jiangsu, China

Our Changzhou testing farm, located next to our State Key Lab for PV Science and Technology (SKL), is the site of four of our ground testing projects, utilizing grassy ground, sand, white backsheet, and cement. All testing projects have identical fixed mounts. As Figure 34 shows, we began testing the grassy ground, sand, and white backsheet from 2017 onward, with the modules mounted at 0.5 meters height.

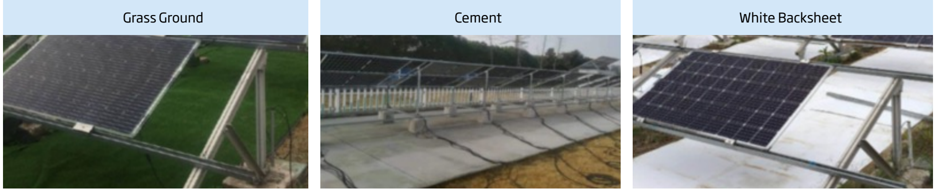

Grass Ground
Cement
White Backsheet

Figure 34. SKL test farm in Changzhou, China.

1. Location:
Changzhou, Jiangsu (N31°, E119°)

2. Ground Type:
grass ground, sand,white backsheet, cement

3. Ground clearance:
0.5m, 1.2m

Related to our energy yield assessment (as Figure 35 shows), the grassy ground mount had a measured reflectance of merely 18%, but the resulting yield gain still averaged 5.9% and could achieve as high a gain as 6.9% in summer. Our bifacial module on the sandy mount, with a reflectance of 35%, achieved as high a yield gain as 11.5%. In the case of the highly reflective white backsheet, the bifacial module could achieve as high a yield gain as 22.5%.

In the cement mount, the mounting height was 1.2 meters to explore the effect of different heights. We began testing at the end of 2019 and found that the bifacial module contributed to an average yield gain of 11.5% in three months, from Dec. 16, 2019, to Feb. 25, 2020.

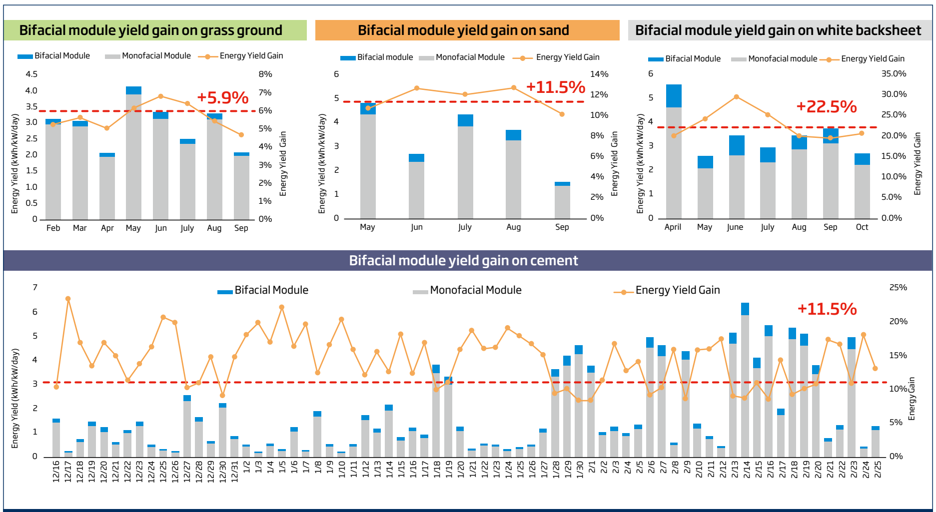

Bifacial module yield gain on grass ground
Bifacial module yield gain on sand
Bifacial module yield gain on white backsheet
Bifacial module yield gain on cement

Figure 35. SKL test farm in Changzhou. Energy yield assessment with bifacial technology

5.3. Case study in Yinchuan, Qinghai, China

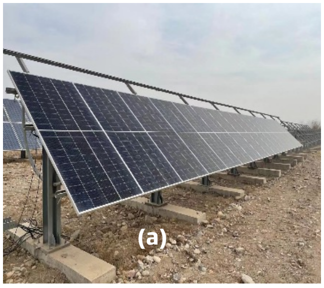


Figure 36.a. Yinchuan PV plant with Trina Solar Vertex (210 mm) monofacial configuration

Figure 36.b. Yinchuan PV plant with Trina Solar Vertex (210 mm) bifacial configuration

Yinchuan, located in northwest China (Qinghai province), is one of the world's most abundant sunlight resource areas. Here, the solar spectrum is close to the standard AM 1.5. The annual radiation intensity is 500W/m^2 and above for more than 2,000 hours. The average daily direct irradiation is 5.75 kWh/m^2. Yinchuan has a temperate continental climate, with dry and hot summers and wide variances between morning and evening temperatures. We began the project in April 2021 and completed it in April 2022. We deployed this study with the newest 210-millimeter wafer Vertex series modules, as we describe in figures 36a and 36b.

Some other considerations about the Yinchuan project:

1. **Location:** Yinchuan (38.47°N)
2. **Tilt angle:** 40°
3. **Installation height:** 1m
4. **Surface:** sand
5. **Data collection method:** High precision DC meter + inverter SG20RT-20

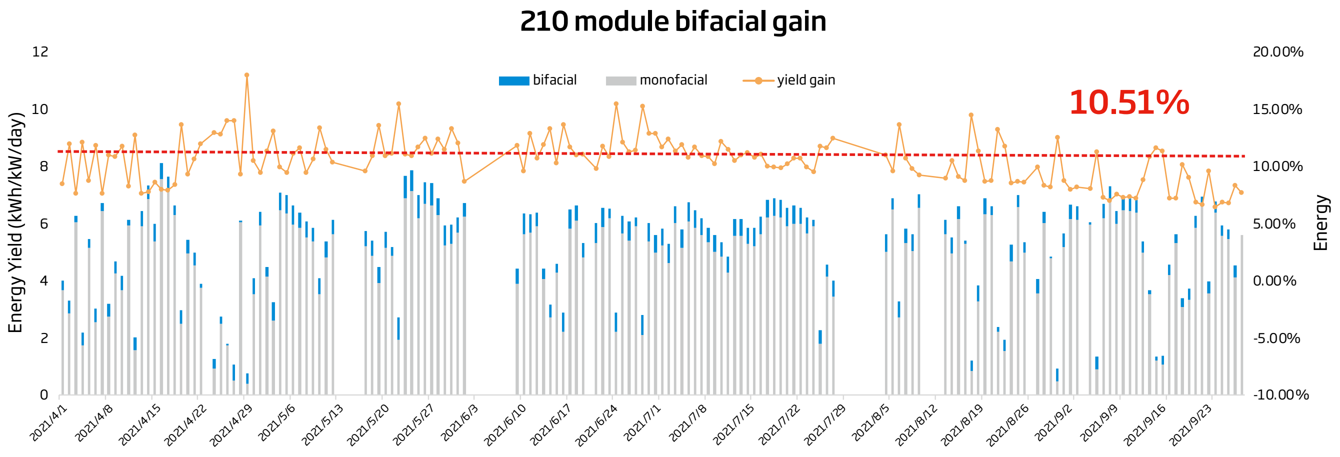


Figure 37. Yinchuan PV plant. Energy yield assessment with bifacial technology conducted by CPVT

Modules were installed on fixed-tilt structure one meter above the sandy surface. A reputable Chinese independent third party (CPVT) conducted the project measurement campaign and energy yield assessment with high accuracy DC meter data collection. As shown in Figure 37, the data for April 2021 to September 2021 indicate an average 10.51% energy yield gain achieved by the bifacial module.

6. CASE STUDIES.
Bifacial Technology Assessment

Trina Solar has contracted ATA (Astrom Technical Advisors), an independent third-party, to conduct a comparative LCoE analysis for diferent modules (monofacial and bifacial) and mounting systems (fixed-tilt structure and 1P tracker) within the Trina Solar portfolio to assess their performance in two PV projects located in Spain and Germany. An abstract with summary, key figures, takeaways and main conclusions is described next.

The study's goal is to assess how these solar modules behave under different solar resource conditions, one representing Southern European conditions (Spain) and the other representing Central European conditions (Germany). The Spanish case study occurred on a 50 MW reference PV project in Alcalá de Guadaíra (Spain), with a central inverter configuration. The German case study occurred on a 10 MW reference PV project in Hofdorf (Germany), with a string inverter configuration. ATA evaluated several configuration cases on each PV project for these assessments, analyzing their CAPEX, OPEX, and energy yield. In total, we have assessed four cases for each PV project:

PV Project	**Spain**				**Germany**			
Module	TSM-670DE21		TSM-670DEG21C.20		TSM670-DE21		TSM-670DEG21C.20	
Structure	Fixed-Tilt Structure	Single-axis Tracker	Fixed-Tilt Structure	Single-axis Tracker	Fixed-Tilt Structure	Single-axis Tracker	Fixed-Tilt Structure	Single-axis Tracker
Inverter	Power Electronics HEMK FS3430K				Huawei SUN2000-215KTL-H3			
Case #	1	2	3	4	1	2	3	4

Table 5. Main Equipment configuration of Study Cases

The following steps have been followed to perform the study:

1. **Project Site Location:** ATA has proposed two reference projects in Alcalá de Guadaíra (Spain) and Hofdorf (Germany) since they are good reference points for the current Southern and Central European markets.
2. **Cases Definition:** ATA has proposed an optimized configuration for each case in terms of Ground Coverage Ratio (GCR%) and DC/AC ratio. They have drawn a reference layout for each case to define the minimum achievable GCR.
3. **CAPEX Estimation:** Taking previous layouts as references, ATA obtained electrical, mechanical, and civil measurements using PVcase software to get the Bill of Quantities (BoQ) for each case. From the BoQ, ATA calculated the CAPEX required for investments in each case. We and ATA reached an agreement on the main equipment unit prices, while we used ATA assumptions on unit prices to quote the rest of the BoQ items. In addition, we have adapted supply prices and workforce tariffs according to the Spanish and German markets.
4. **OPEX Estimation:** ATA has estimated the OPEX for each case based on its own experience and references in Spanish and German markets.
5. **Energy Yield Assessment:** We used PVsyst® to get the year-0 energy yield for each case.
6. **LCoE Calculation:** Once they estimated the CAPEX, OPEX, and energy yield, ATA ran a simplified financial model to calculate the LCoE of each case.

As a result of the study, ATA has determined the optimal case for each PV project, always assuming that the optimal case is the one that achieves the lowest Levelized Cost of Energy (LCoE). In other words, the optimal case will maximize the project's Internal Rate of Return (IRR).

6.1. Energy Yield & Generation (Year 0)

6.1.1. Spain case study

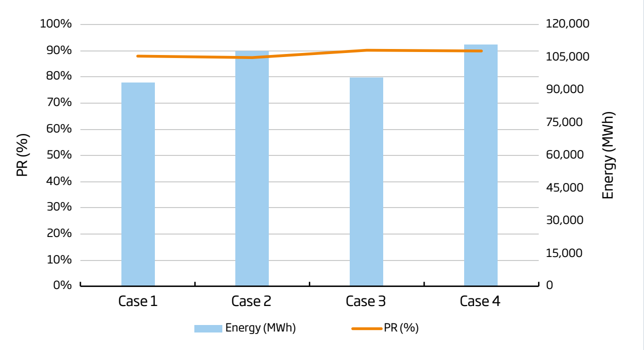


Figure 38. Spain case studies year-0 energy generation and PR

We can conclude from the above results that Case 4 has the highest yield and the highest injection of energy into the grid. However, we were able to get a better Performance Ratio (PR) in Case 3. This only means that in Case 3, we harnessed slightly more global incident irradiation in collector planes than the global average. In Spain, and therefore in Southern European countries with similar ground and solar resource conditions, using tracker systems along with bifacial PV modules is the best way to maximize the energy injected into the grid.

It is also interesting to note that the gain when using a tracker instead of a fixed-tilt structure is higher than the gain when using the bifacial instead of the monofacial modules.

6.1.2. Germany case study

From the above results, it can be concluded that Case 4 is the one with the highest yield and energy injected into de grid. However, Case 3 gets a better PR. This fact, indeed, actually only means that Case 3 is harnessing slightly better the global incident irradiation in the collector plane. In short, it also seems clear that in Germany, and therefore in central European countries with similar ground and solar resource conditions, using tracker systems along with bifacial PV modules is the best way to maximize the energy production injected into the grid.

It is also interesting to note that the gain for using a tracker instead of a fixed-tilt structure is higher than the gain for using bifacial instead of monofacial modules. However, this difference is less significant than in Spain.

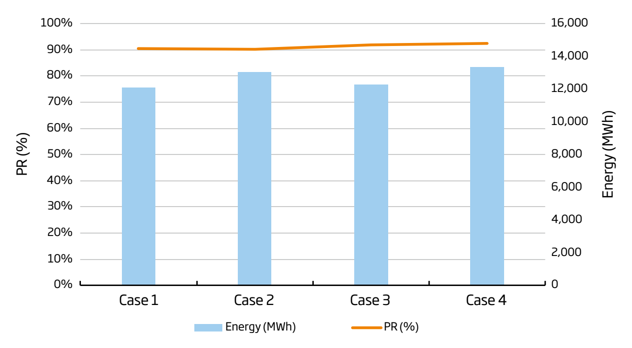


Figure 39. Germany case studies year-0 energy generation and PR

6.2. CAPEX estimation

Electrical, mechanical and civil measurements were obtained using PVcase software, in order to get the Bill of Quantities (BoQ) of each study case. From the BoQ, the required CAPEX for investing has been calculated depending on the case. The following table shows the unit price assumptions for main equipment:

Project	Spain	Germany
Main equipment	**Unit price (EUR/Wp)**	
Monofacial PV module Trina Solar TSM-670DE21 [1]	0.2622	0.2622
Bifacial PV module Trina Solar TSM-670DEG21C.20 [2]	0.2666	0.2666
Central inverter Power Electronics HEMK FS3430K	0.036 EUR/Wac	-
String inverter Huawei SUN2000-215KTL-H3	-	0.038 EUR/Wac
Fixed-tilt structure	0.055	0.0633
Single-axis tracker 1P configuration	0.071	0.081

Table 6. Main equipment unit prices.

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[1] Price assuming CIF Rotterdam Incoterm.
[2] Price assuming CIF Rotterdam Incoterm.

6.2.1. Spain case study

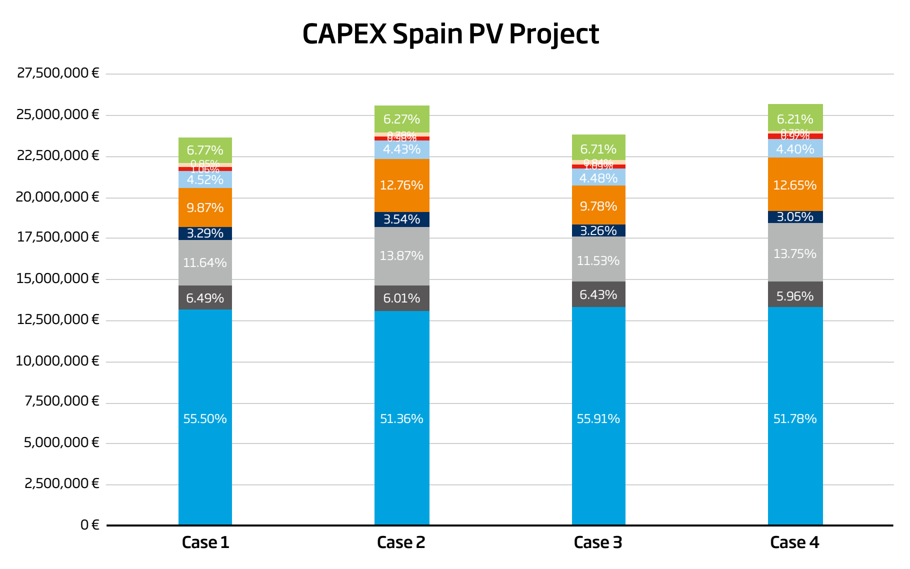

Figure 40. CAPEX breakdown for Spain case study

6.2.2. Germany case study

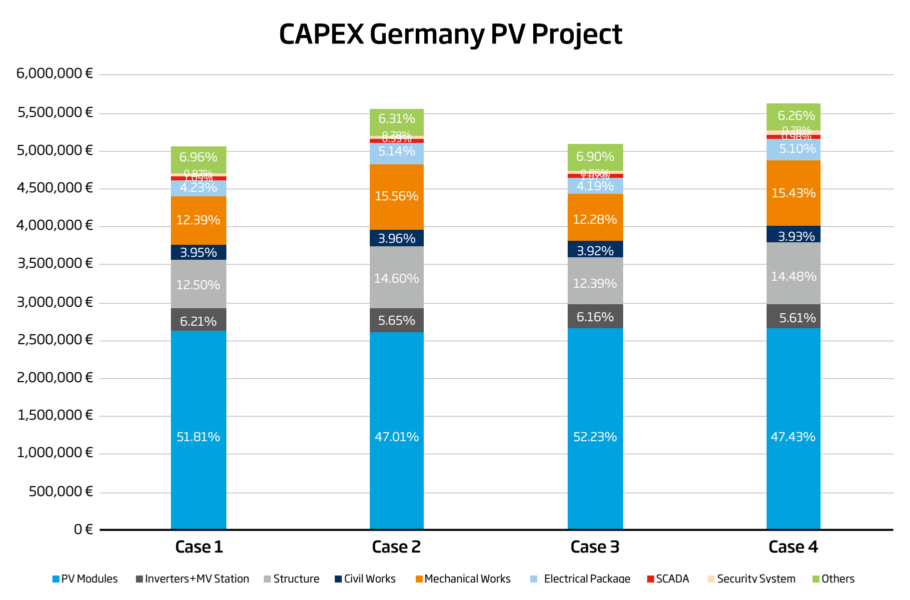

Figure 41. CAPEX breakdown for Germany case study

6.3. OPEX estimation

Following a similar approach as the CAPEX, we can divide OPEX into three categories: General OPEX costs, O&M costs, and Maintenance Reserve Account Costs.

The general OPEX costs considered in this study are land rental, asset management, security, O&M substation, or any other interconnection infrastructure, grid access fees, real estate asset taxes, and other factors such as night consumption or environmental activities. In short, these are incurred costs related to the operation of a PV plant but are not directly linked to PV plant O&M. Apart from the expenses we describe in the tables above, a 1% additional OPEX cost has been added as insurance when running the financial model.

In addition, there are also costs directly incurred from operating and maintaining a PV plant and properly injecting energy into the grid. These costs are divided into general O&M costs, including all O&M services provided by the operator (except spare parts included in the O&M contract). As per the O&M contract, we also specify the Maintenance Reserve Account as a budget continually kept in the warehouse for the general and main equipment spares, as per the O&M contract.

6.3.1. Spain case study

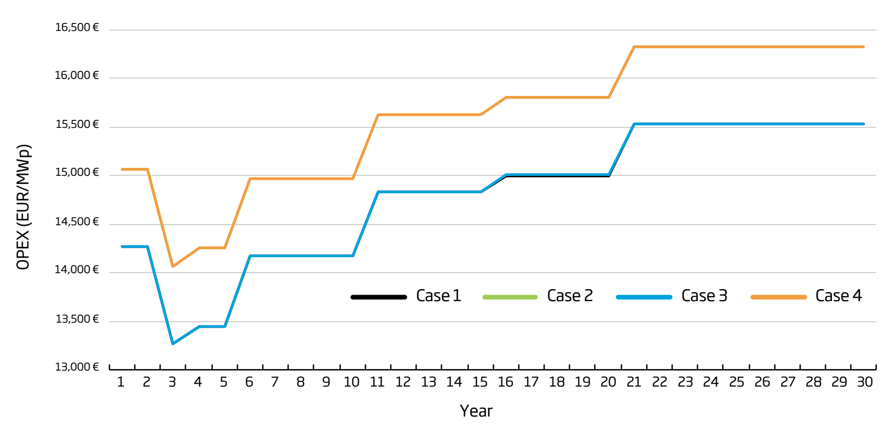

Figure 42. OPEX for Spain cases

6.3.2. Germany case study

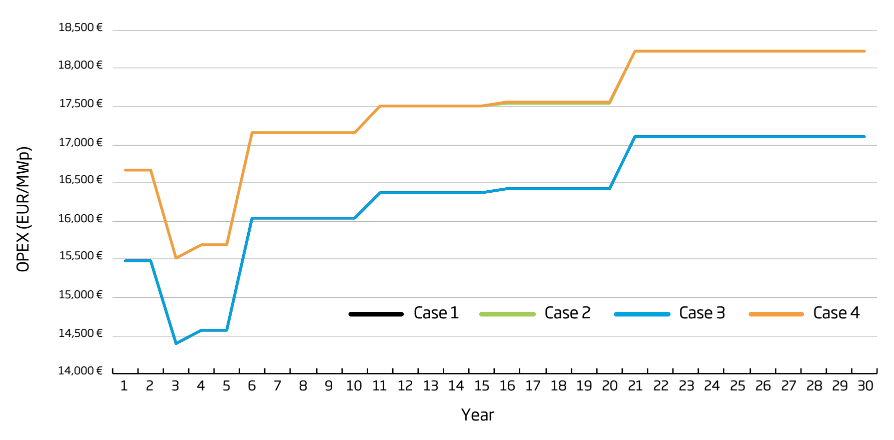

Figure 43. OPEX for Germany cases

The graphs above clearly show how OPEX evolves during the entire lifetime of the PV plant. The first two years of operation are usually covered by the EPC warranty period. This is also when most construction malfunctions are detected, which explains why the O&M price decreases after the second operational year.

6.4. LCoE results

6.4.1. Spain case study

Case	1	2	3	4
MWp	49.998	49.977	49.998	49.977
MWac	42.60	42.60	42.60	42.60
Clipped at (MWac)	50.00	50.00	50.00	50.00
Year-0 energy production (MWh)	93,296	107,779	95,747	110,981
CAPEX (MEUR)	23.62	25.51	23.84	25.71
Unitary CAPEX (EUR/Wp)	0.472	0.510	0.477	0.515
OPEX (EUR/MWp/y)	15,798	15,598	14,801	15,601
Equity investment (MEUR)	6.36	6.85	6.41	6.93
Initial debt (MEUR)	19.02	20.53	19.18	20.68
Internal rate of return (IRR) [3]	8.5%	8.5%	8.5%	8.5%
LCoE (EUR/MWh)	**23.89**	**22.15**	**23.43**	**21.65**

Table 7. LCoE Spain case study

6.4.2. Germany case study

Case	1	2	3	4
MWp	9.991	9.970	9.991	9.970
MWac	7.800	7.800	7.800	7.800
Clipped at (MWac)	10.00	10.00	10.00	10.00
Year-0 energy production (MWh)	12,025	13,028	12,260	13,345
CAPEX (MEUR)	5.164	5.667	5.208	5.711
Unitary CAPEX (EUR/Wp)	0.506	0.558	0.510	0.562
OPEX (EUR/MWp/y)	16,141	17,455	16,145	17,458
Equity investment (MEUR)	1.36	1.49	1.37	1.50
Debt (MEUR)	4.05	4.45	4.08	4.48
Internal rate of return (IRR) [4]	7.5%	7.5%	7.5%	7.5%
LCoE (EUR/MWh)	**34.35**	**34.73**	**34.00**	**34.07**

Table 8. LCoE Germany case study

We can conclude from the above results that Case 4 is the optimal configuration for the Spanish project currently under study. In other words, for a 50 MW PV plant in Spain, investing in a PV configuration with tracking systems and bifacial PV modules will return the highest IRR.

On the other hand, we can conclude that Case 3 is the optimal configuration for the German project under study. In other words, for a 10 MW PV plant in Germany, an investment in a PV configuration with a fixed-tilt structure and bifacial PV modules will return the highest IRR. However, in this location, Case 3 and Case 4 LCoE values are similar enough to determine that both configurations could be optimal, depending upon the specific characteristics of a particular project.

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[3] IRR has been assumed as discount rate calculated from CAPM in the base cases.
[4] IRR has been assumed as discount rate calculated from CAPM in the base cases.

6.4. Conclusions

Our main findings from this comparative analysis are as follows:

- A bifacial PV module mounted on a tracker system is the optimal configuration for a 50 MW PV plant in Spain since this configuration will return the highest IRR.
- A bifacial PV module mounted on a fixed-tilt structure is the optimal configuration for a 10 MW PV plant in Germany since this configuration will return the highest IRR. However, in this case, we can also consider a bifacial PV module mounted on a tracker system to be an optimal solution since LCoE differences are marginal. Thus, depending on the specific characteristics of a particular project, both alternatives should be up for assessment.
- The optimal case in Spain would need an LCoE of 21.65 €/MWh to get an 8.5% IRR, while the optimal case in Germany would need an LCoE of 34.00 €/MWh to get a 7.5% IRR.

Looking at the sensitivity analysis, we conclude that:

- In general, the greater the albedo value, the height of the structure above ground, and the module spacing, the greater the energy production.
- As expected, the LCoE linearly increases with module prices and mounting structure prices.
- Regarding the Internal Rate of Return (IRR), the previous analysis of module prices still holds. LCoE increases as IRR does, although the LCoE curve slope slightly decreases as IRR increases.

The Ultimate Guidebook for
Bifacial System Design

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