energies

MDPI

Review

Bifacial Photovoltaics 2021: Status, Opportunities and Challenges

Radovan Kopecek * and Joris Libal

ISC Konstanz, Rudolf-Diesel Straße 15, 78462 Konstanz, Germany; joris.libal@isc-konstanz.de
* Correspondence: radovan.kopecek@isc-konstanz.de; Tel.: +49-7531-36183-22

Abstract: In this paper we summarize the status of bifacial photovoltaics (PV) and explain why the move to bifaciality is unavoidable when it comes to e.g., lowest electricity generation costs or agricultural PV (AgriPV). Bifacial modules—those that are sensitive to light incident from both sides—are finally available at the same price per watt peak as their standard monofacial equivalents. The reason for this is that bifacial solar cells are the result of an evolution of crystalline Si PV cell technology and, at the same time, module producers are increasingly switching to double glass modules anyway due to the improved module lifetimes, which allows them to offer longer product warrantees. We describe the general properties of the state-of-the-art bifacial module, review the different bifacial solar cells and module technologies available on the market, and summarize their average costs. Adding complexity to a module comes with the increase of possible degradation mechanisms, requiring more thorough testing, e.g., for rear side PID (Potential Induced Degradation). We show that with the use of bifacial modules in fixed tilt systems, gains in annual energy yield of up to 30% can be expected compared to the monofacial equivalent. With the combination of bifacial modules in simple single axis tracking systems, energy yield increases of more than 40% can be expected compared to fixed tilt monofacial installations. Rudimentary simulations of bifacial systems can be performed with commercially available programs. However, when more detailed and precise simulations are required, it is necessary to use more advanced programs such as those developed at several institutes. All in all, as bifacial PV—being the most cost-effective PV solution—is now becoming also bankable, it is becoming the overall best technology for electricity generation.

Keywords: photovoltaics; bifacial; energy yield

Citation: Kopecek, R.; Libal, J. Bifacial Photovoltaics 2021: Status, Opportunities and Challenges. *Energies* **2021**, *14*, 2076. https://doi.org/10.3390/en14082076

Academic Editors: Antonino Laudani and Jürgen Heinz Werner

Received: 11 December 2020
Accepted: 1 April 2021
Published: 8 April 2021

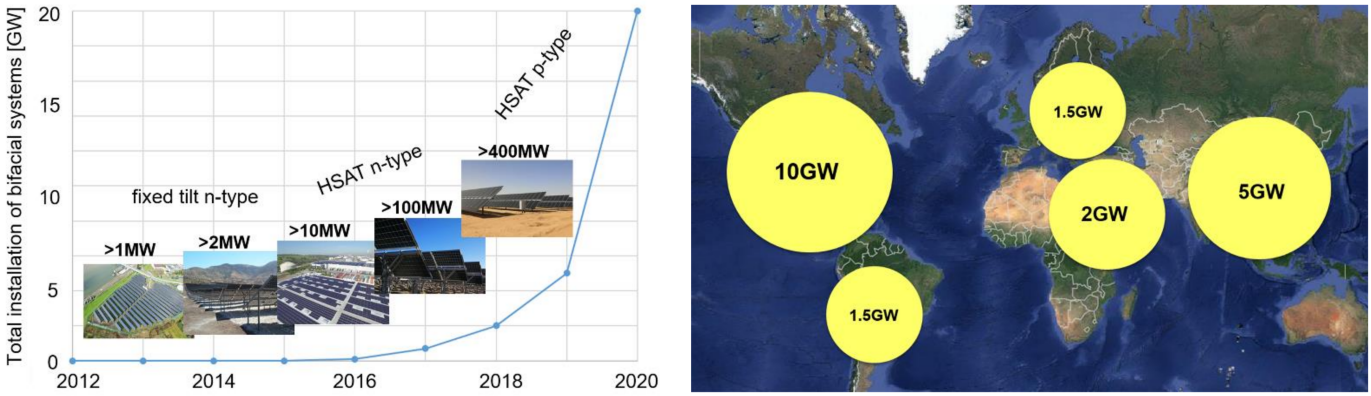
1. Introduction

"Solar is the new king of energy markets" is what the International Energy Agency's executive director Fatih Birol stated earlier this year [1], despite never being a friend of renewables in previous years. However, he has no choice, because in some countries, e.g., in the MENA (Middle East North African) states, PV is achieving electricity generation costs well below 2 USDct/kWh, as seen in many offers for energy tenders including the 800 MWp plant planned in Qatar by TOTAL, with 1.567 USDct/kWh [2]. The installation will use bifacial HSAT (Horizontal Single Axis Tracking), which is a system that has been attracting much attention over the last two years, since the combination of both technologies leads to the lowest possible LCOE (Levelized Cost of Electricity).

The fact that the bifacial gain in HSAT systems is still high, even though the rear side is turned away from the reflective ground surface (apart from the time period around noon), was presented for the first time by Enel in 2017 at e.g., the bifiPV2017 workshop [3]. Enel reported an annual bifacial gain of 12.8% in a HSAT bifacial system using nPERT BiSoN modules (bifaciality factor of 0.87), compared to a monofacial HSAT system, and this marked the starting point of a new "bifacial HSAT era".

Figure 1a shows that large bifacial PV systems started with nPERT and SHJ modules in fixed tilt configuration systems. The first >1 MWp system was built in Japan by a private investor with bifacial nPERT modules (manufactured by the Japanese company PVGS). At that time, bifacial PV was not bankable i.e., the overall risks of the bifacial PV projects were

not low enough for financing costs to be affordable, and therefore private investors had to take the risk to prove the technology on a large systems level. Not bankable does not mean only that the technology was not proven in the field, but also that standards were not yet developed to measure and test bifacial modules, as well as that no commercially available energy yield simulation program was yet able to quantify the energy yield for bifacial PV systems. For these reasons, in 2012 we began to organize bifacial workshops to bring R&D, industry, and investors together to work on the challenge of making bifacial PV bankable (www.bifiPV-workshop.com). Then, in 2016 the first >2 MWp fixed tilt bifacial PV system ("La Hormiga") was built by MegaCell (also with private money) in San Felipe, located in the region of Valparaiso in Chile, using nPERT BiSoN modules. The innovations in this system were the adapted mounting structures (which were not covering the rear side of the modules), as well as the enhancement of albedo using white quartz stones below them [4]. The bifacial gain was about 15% with the natural albedo of ca. 28%, whereas the albedo enhancement to 75% provided by the white stones led to a bifacial gain of about 25% [4]. After that, Sunpreme installed their SHJ (Silicon HeteroJunction) modules in a 10 MWp bifacial system on a US industrial rooftop, and large bifacial systems were installed in China in the TopRunner program, where the Chinese Government was supporting innovations to be introduced into the market. Yingli installed a fixed tilt 50 MWp system with bifacial nPERT Panda modules, followed by a 100 MWp "Panda PV system". As already explained, the era of bifacial HSAT nPERT systems started around 2018. However, a game changer in bifacial PV was when bifacial PERC (PERC+ as introduced by ISFH [5]) entered the market. Since then, bifacial modules have become available in any quantity and at a low price, as it is quite simple to adapt monofacial cell production towards bifacial PERC production simply by changing the rear side metallization pattern. In addition, as will be explained in further detail in the module section, the implementation of white reflectors between the cell spaces has made it possible to produce bifacial modules at the same cost as monofacial ones, since the front side power was no longer cannibalized.



(**a**) (**b**)

Figure 1. (**a**) Accumulated power of bifacial PV systems as a function of years and (**b**) geographical spread in power of bifacial PV systems in 2020.

Since these developments, the potential of bifacial HSAT PV with bifacial PERC modules has been unchained (although the bifacial factor is lower for PERC modules compared to nPERT). This trend was amplified even more so when President Trump, another leader renowned for not being a great friend of PV, dropped US import taxes for bifacial believing that bifacial PV is a niche market only and that local US PV manufacturers would not be harmed. He realized quite early after that this was a mistaken perception, as he had underestimated the bifacial market, and since then has tried 3 times to correct his mistakes by reimposing import barriers, fortunately without success [6]. By the end of 2020, the worldwide installations of bifacial systems will add up to about 20 GW, with a geographical distribution as depicted in Figure 1. Bifacial PV has become bankable and

large MW systems are being built—even in the EU, which has been historically conservative in regards to PV innovation, but where the largest bifacial HSAT systems will be now built by Juwi Group in Greece with 204 MW of Jinko's bifacial PERC Swan modules [7]. Kalyon Group is installing a 1 GW HSAT bifacial PV system in the Konya region in Karapinar with their own bifacial PERC modules produced in Ankara [8]; this will be the world's largest bifacial system.

We are quite sure that nPERT/TOPCon will soon re-enter the bifacial market again, as PERC is coming to its efficiency limits and more and more PERC Tier1 producers are also activating their n-type road maps, including Jinko, Canadian, and JA Solar [9]. With this, the LCOEs can decrease even faster due to increased bifaciality (up to 95%) and reduced degradation (no LID, lower LeTID), as well as superior properties such as lower temperature coefficients (due to higher voltage) and better low light performance. With bifacial nPERT/TOPCon, HSAT electricity generation at a cost below 1 USDct/kWh will become possible.

2. Status of Bifacial PV

Bifacial PV is entering the market quickly as the modules are available at the same cost as their monofacial equivalents. This is because bifacial cells are an evolutionary process of c-Si device development and because module manufacturers are, regardless, increasingly switching to double-glass modules to increase the duration of product warrantees.

2.1. Status of Bifacial Solar Cells

As can be seen in Figure 2a, solar cell technology was for many decades dominated by a very simple Al-BSF (aluminum back surface field) technology using mostly cheap mc-Si (blue bars in the chart) with some more expensive mono Cz-Si wafers (orange bars). In 2015 this was still the case.

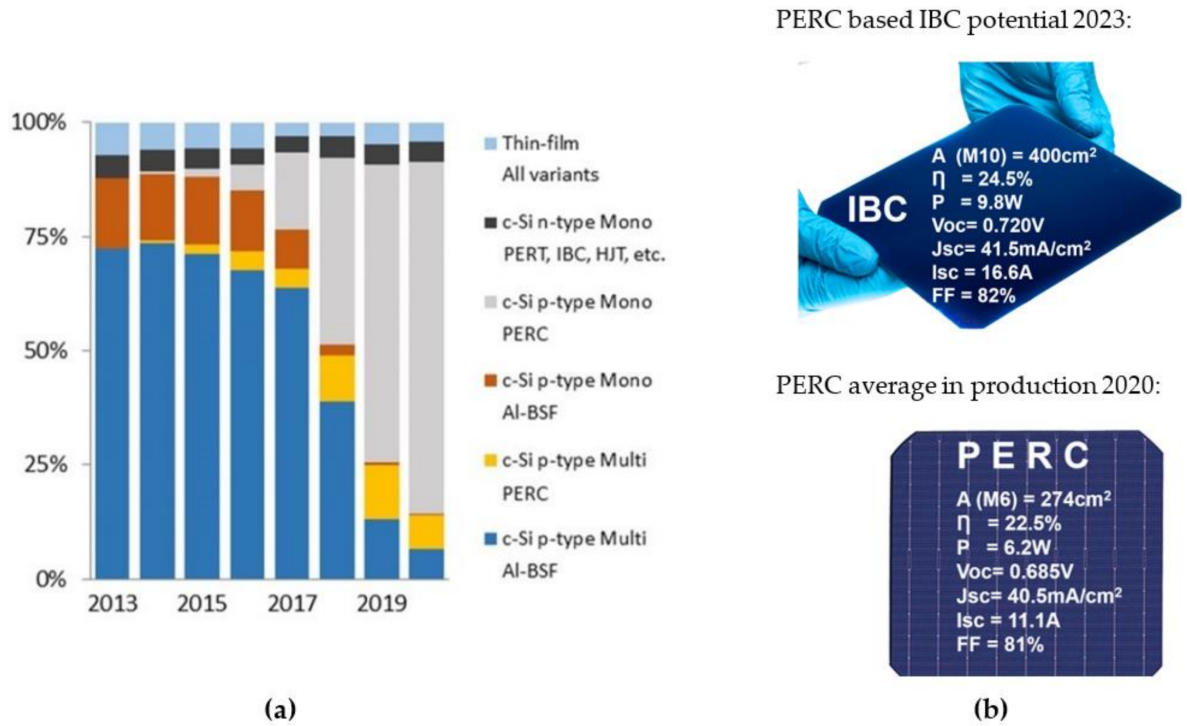


Figure 2. (**a**) PV solar cell technology share [10] and (**b**) PERC average efficiency in 2020 as well as IBC potential in 2023.

In 2016 the situation changed completely as LONGi put low cost c-Si wafers on the market and the PV industry started to become more innovative in terms of implementing new cell concepts such as PERC and nPERT, which were actually already developed in the laboratories years before that. These low-cost c-Si wafers were also the start of a new bifacial era as good material quality allows a better implementation of open rear side. So, it was no wonder that LONGi was the first Tier1 company to announce a bright future for bifacial PV in 2017 [11], pushing bifacial PERC into the PV market. The other large bifacial company is Jolywood, who are however betting on nPERT and TOPCon, and claiming that n-type bifacial is the future. The current situation is that Al-BSF has completely disappeared from the map (only India is still building on Al-BSF mc-Si technology), and PERC still dominates the PV market (gray bar); however, n-type technologies are gaining momentum. This is because PERC, with 22.5% in average in production, is coming to its efficiency limits and it is much easier to implement new technologies such as poly-Si on n-type, as it shows better quality compared to p-type. In order to prolong the p-type dominance in the PV market, LONGi is playing two more aces: improving the p-type material quality by Ga-doping instead of B-doping, and increasing the wafer size. Ga-doping has the advantage that there is no LID (Light Induced Degradation) in the p-type material, since LID occurs due to the formation of B-O complexes. This brings the quality of p-type material closer to n-type; however, n-type still has advantages as it is less sensitive to prominent metallic impurities such as e.g., Fe, and also less sensitive to high temperature processing. Increasing the wafer size from the long time standard, M0 (156 × 156 mm^2) to M6 (160 × 160 mm^2) and even up to M10 (180 × 180 mm^2), and M12 (210 × 210 mm^2) has two major drivers: (1) as PERC is coming to its efficiency limits, further cost down of cell production per Wp is not possible with efficiency increases and can thus only be achieved with wafer size increases enhancing the throughput per Wp of the production and, (2) on the other hand, when you are dictating the wafer size you can wash out the small producers which cannot afford to upgrade their machines to larger wafer formats. At the moment the "wafer-size war" is being fought by two companies: LONGi is promoting M10 as standard, and Zhonghuan Semiconductor is promoting M12 [12].

Figure 3 shows the history and possible future of c-Si wafer formats. In 2015 the market was still dominated by M0 formats with cell having 3 busbars. Today the average wafer size of newly installed manufacturing lines is M6 with increasing numbers of busbar. As the cell size increases, the use of half cut cells is becoming standard so as to avoid increases in resistive power losses due to higher currents from larger cells. A perfect shape for a solar cell is not a square but rather a long rectangle. In 2022, M10 will become standard and beginning in 2025 we believe that back contact technology will start to dominate the market because it is much easier to improve the contacting with e.g., poly-Si on the rear side of the cell meaning that, in the end, IBC will be the winner of the c-Si solar cell development. Later, to increase efficiencies above 30%, c-Si based tandem technologies such as Perovskite/IBC tandems [13] will enter the PV arena. For utility scale applications, these cell architectures will also have to be bifacial.

2.2. Status of Bifacial Solar Modules

c-Si based modules are now the focus of developments in order to increase the efficiency of PERC technology, as on cell level the technology is coming to its efficiency limits. What has been developed in recent years is the use of full square wafers and technologies to pack the solar cells closer together and maximize the front side area efficiencies, yielding PERC modules with front side efficiencies close to 21% at STC (Standard Testing Conditions). Another trend is to make the modules bifacial so that the system can benefit from the additional bifacial gain. Figure 4 depicts such a module from the front and rear.

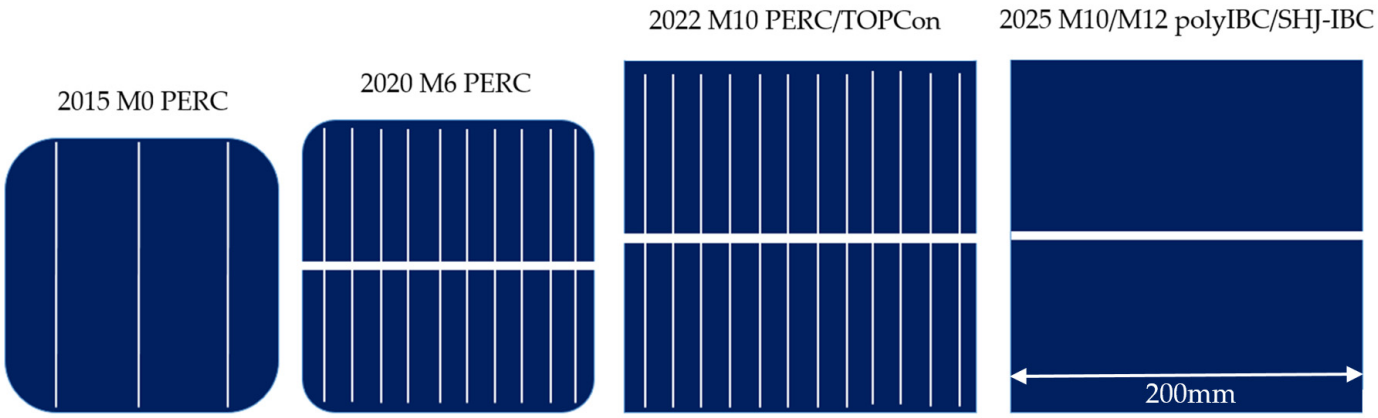


Figure 3. Increasing wafer sizes, number of busbars and solar cells moving away from being a square.

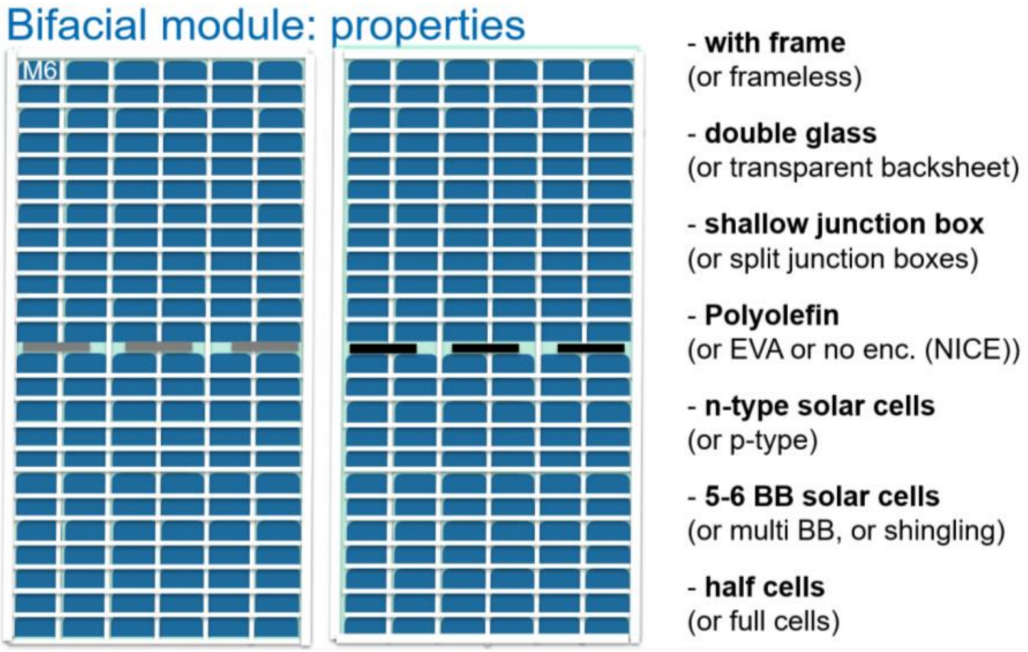


Figure 4. Front (**left**) and rear side (**right**) of a bifacial module and its properties.

The modules can be built either with frame or without, as most of the bifacial modules are produced with double glass. The trend these days rather goes back to bifacial modules with frames as they are more stable and can be installed easier. The junction boxed are designed to be shallow in order not to cause any shadowing on the rear side. For p-type cells, the encapsulant used is ethylvinylacetate (EVA), while for n-type cells polyolefin elastomers (POE) are used to reduce PID (Potential Induced Degradation), which is not as easy for n-type as for p-type to be reduced on a cellular level. Since the current increases with increased efficiency and bifaciality, the number of busbars must be increased and the cells must be cut in half or even smaller pieces so as to avoid increased resistive power losses in the connecting ribbons. The major difference for a bifacial module is that white reflectors are being included in-between the cells so that the front side power is not reduced due to the light escaping through the openings between the solar cells instead of being reflected back into the module as it would in monofacial modules with white backsheet.

Table 1 summarizes the status of modules currently on the PV market, showing the efficiency, power, bifaciality, and costs. Depending on the application and the additional costs for BOS (Balance of System), some modules are useful for utility scale while others are more suited for rooftop applications or building integration.

Table 1. Average solar cell and module parameters of different c-Si technologies from [14,15].

Solar Cell Technology	Solar Cell Efficiency [%]	Module Efficiency [%]	M6 72 Half Cells Modue Power [Wp]	Bifaciaity Factor	COO for Cell [€ct/Wp]
Al-BSF	21.0	19.5–20.0	up to 410	0	9–10
PERC	22.5	20.0–20.8	up to 440	0.60–0.75	9–11
nPERT	22.5	20.0–20.8	up to 440	0.85–0.90	12–13
TOPCon	23.0	20.8–21.5	up to 450	0.85–0.90	13–16
SHJ	23.5	21.5–22.0	up to 460	0.90–0.95	18–22
Low cost IBC	23.5	21.3–21.4	up to 460	0.60–0.75	16–20
Complex IBC	24.5	21.5–22.5	up to 480	0.40–0.60	40–60

2.3. Status of Bifacial PV Systems

By the end of 2020, worldwide PV installations will comprise up to about 700 GWp. Even with this, we are still only at the beginning of the global PV rollout, and it is expected that annual installations of at least 1 TW will become the norm from 2030 at the latest. However, the daily energy generation profile of a bifacial PV installation can be quite different to that of monofacial equivalents. Figure 5a–d shows the possible installations for bifacial modules and Figure 5e their power generation profiles.

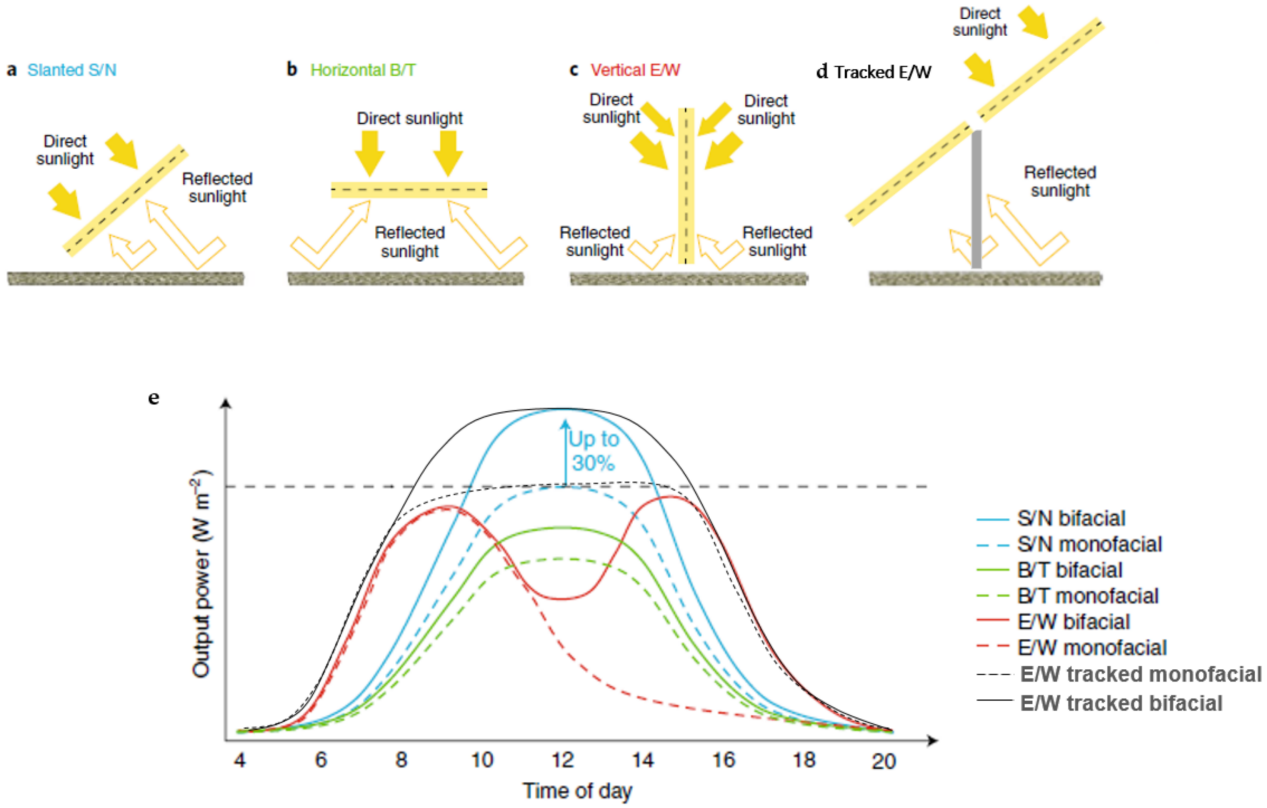


Figure 5. (**a**–**d**) possibilities for installations of bifacial modules and (**e**) comparison of power generation curves for monofacial and bifacial modules [16]. S/N means South/North, B/T is Bottom/Top and E/W is East/West.

Classical fixed tilt installations as depicted in Figure 5a can lead to maximum bifacial yield gains of up to 30% in large PV systems, if the installation geometry is optimal (i.e., bottom module edge installed >0.5 m from the ground, low shading from the rear, high row distance, as well as very high albedo e.g., fresh snow). Horizontal installations (Figure 5b) are interesting e.g., for carports, and vertical installations for making use of low GCR (Ground Coverage Ratio) as in AgriPV where the land is also used for farming (Figure 5c). The installation with the highest energy production is the combination of HSAT (Horizontal Single Axis Tracker) with bifacial modules, and in most cases this also results in the lowest LCOE as described in the introduction. In our opinion, as tracking systems require a rather high row-to-row distance anyway and the modules have to be mounted high from the ground (due to the geometrical constraints of the trackers), it does not make sense to use monofacial modules in HSAT systems anymore, and this fact clearly indicates how fast bifacial modules will penetrate the PV market.

Figure 6 shows examples of real installations of bifacial systems for utility scale (left), flat rooftops (centre) and integrated (right). Fixed tilt, vertical, and tracking systems can be seen in all installations types. For ground mounted utility scale systems, it is necessary to evaluate for each specific project (location) whether the maintenance of the moving parts of a tracking system can be assured at a reasonable cost or not. Minimizing the LCOE for desert systems works best with HSAT, as can be seen in the lowest numbers in the MENA region. An important topic these days is AgriPV (agricultural PV) and the double use of space in the EU. In this context, Next2sun has developed a very interesting technology using vertical mounting systems [17] on dual use land. The company is cooperating on this technology with TOTAL in France [18], as well as other large electricity suppliers throughout countries such as Poland and Sweden. We are sure that this emerging technology will play an important role in AgriPV. Similarly, Solarspar and Solyco are working on vertical installations for flat roof systems to be combined with vegetation on roofs. For electro mobility, vertical installations in sound blocking systems and horizontal installations in car ports will also be useful for generating additional electricity for charging stations.

Figure 6. Possible bifacial installations for utility scale (**left**), flat roof-top (**middle**) and integrated (**right**).

2.4. Energy Yield Measurements and Simulations

2.4.1. Energy Yield Measurements

Finally, there are now enough published measurements from bifacial PV systems [19] to allow reliable, evidence-based conclusions to be drawn regarding the real world performance of this technology. Table 2 shows a summary of annual energy generation gains for different constellations in comparison to their monofacial equivalents.

Table 2. Energy gains in systems using tracking and bifacial modules [20].

Installation Geometry	Monofacial [%]	Bifacial [%]
Fixed tilt (flat roof)	100	105–115
Fixed tilt (utility scale)	100	107–130
Vertical (utility scale)	40–50	95–140 *
HSAT	110–122	117–145

* comparison with monofacial fixed tilt.

Depending on the type of module, the installation geometry, and local albedo, the bifacial energy yield gain can be up to 5–15% on a flat roof. For utility scale this can be increased up to 30% because the installation height can be increased. Vertical installations are comparable to monofacial fixed tilt and, in sun-belt regions, can be lower than for the monofacial reference system. In EU countries such as Germany, Next2sun has measured a 12% bifacial gain. However, the holy grail of highest electricity generation is still HSAT combined with bifacial modules.

2.4.2. Energy Yield Simulations for Bifacial PV Systems

The financial return of a PV project is directly linked to the LCOE (levelized cost of electricity, see e.g., chpater 6 of [19] for an overview) that can be achieved when implementing it, which in turn strongly depends on the accumulated energy generation during the lifetime of this PV system. Therefore, as mentioned earlier, one of the key prerequisites for making PV system projects bankable is the existence of accurate energy yield prediction models. Accordingly, in recent years many academic institutions as well as providers of commercial software tools have been putting a lot of effort into the development of physical and mathematical models suitable for accurately modelling the energy yield of bifacial PV systems (see [21] for an overview). Compared to the modelling of PV systems consisting of monofacial modules, the need to quantify the rear irradiance received by bifacial modules dramatically increases the degree of complexity. The irradiance incident in the plane of the array on the rear side of a bifacial module is determined by a series of factors that have little or no impact on the energy yield of monofacial modules. These factors are:

- albedo of the ground surface
- mounting height of the modules above the ground
- number of modules in the same row as the module of interest
- ratio between DHI (diffuse horizontal irradiance) and GHI (global horizontal irradiance) —also called diffuse irradiance fraction

The values of these parameters have to be known with a high degree of accuracy in order to feed the simulation models with high quality input data, and to thus reduce their contribution to the uncertainty in the simulated energy yield. The two main concepts for the optical models that are pursued by scientists involved in the development of such energy yield models are based either on ray tracing or on the view factor concept. While ray tracing models allow for complex geometries such as the shading of the module rear sides by mounting structure elements to be considered, optical models based on view factor are more suitable for simple system configurations, such as large scale ground mounted PV systems with mounting structures that are optimized for bifacial modules. After having determined the front and the rear side irradiance at a given point in time, these values

—along with the ambient temperature and the wind speed and direction—serve as inputs to a thermal model (e.g., NOCT model or Faiman model) that calculates the operating temperature of the bifacial module under the given conditions. Finally, the front and rear irradiance, as well as the module operating temperature, are fed into an electrical model of the PV module, providing the electrical power output of the module at the considered point in time, and taking into account the I/V characteristics of the module measured at STC under both the front and rear irradiance. Repeating the above procedure over a given time period—typically a complete year, using typical meteorological year (TMY) data as the input—and subsequently integrating the results over this time period delivers the cumulative energy yield for the year, and it is this annual energy yield that serves as the key figure of merit used to differentiate between the investment value of different installation types, locations, and constellations.

As mentioned above, for all three sub models there are also a variety of choices available, each of them having their advantages and drawbacks. Accordingly, one crucial activity in the development of bifacial energy yield prediction models is the validation of their accuracy using high quality field data. In order to enable such validations, it is helpful to first set up a test PV system with a well-defined geometrical configuration and consisting of bifacial PV modules, as well as monofacial references (having accurate indoor I/V measurement data of the modules available is crucial) and to equip them with the required sensors for global and diffuse irradiance, ambient temperature, and wind speed and direction, as well as for the ground albedo. Then, the electrical output power (of a single module or a string of modules) must be accurately monitored with a given frequency over a time period of ideally at least twelve months so as to cover all seasonal variations. By feeding the energy yield model with the geometrical configuration, as well as the meteorological and I/V data of the modules, modelled values for the instantaneous electrical output at each point of time, and thus the cumulative energy yield can be determined and finally compared with the measured values. The deviation between the measured and modelled values—considering all involved measurement uncertainties—represents an important metric for the accuracy of the model under test.

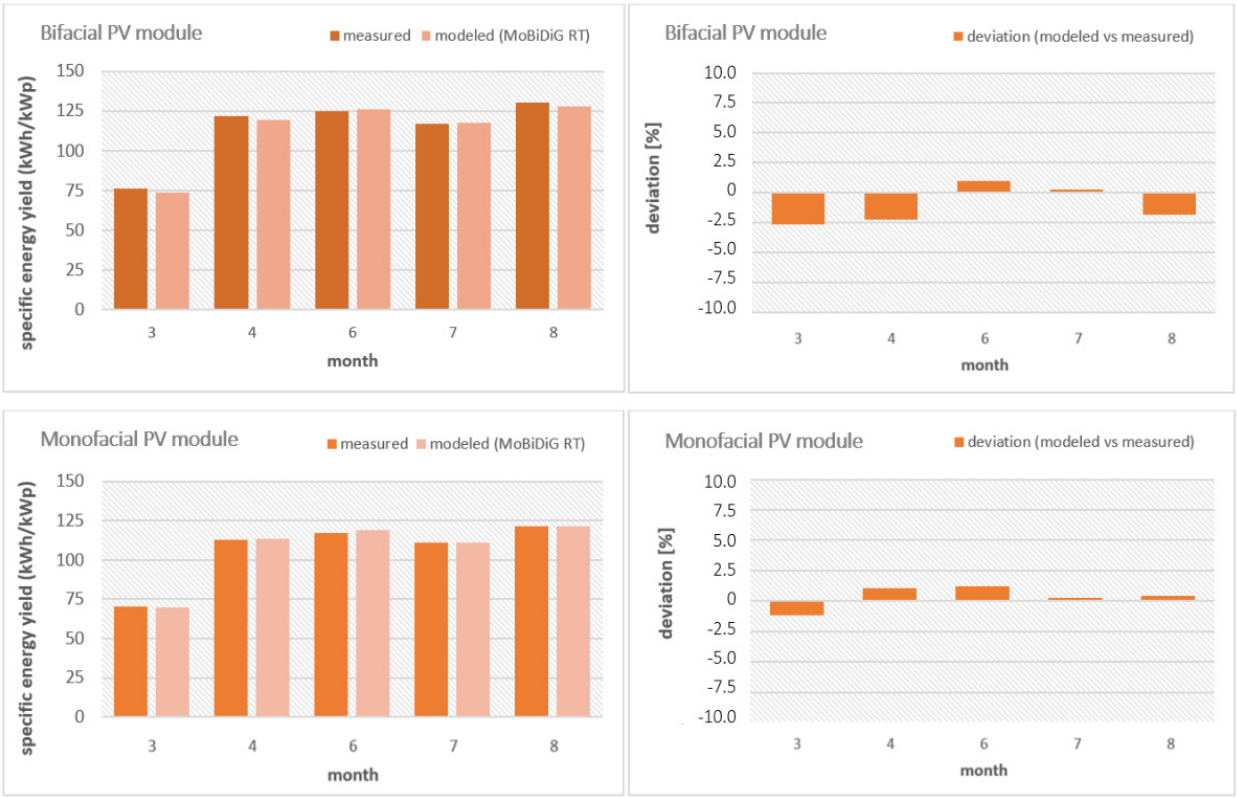
The simulation model that has been under development at ISC Konstanz since 2015 is called MoBiDiG ("modelling of bifacial distributed gain") [22] and this model is capable of simulating the energy yield of bifacial fixed tilt as well as horizontal single axis tracked systems, with either ray tracing or view factor based optical models, according to the choice of the user. Based on the latest improvements to this simulation model with extensive field data, it has been shown that the energy yield of bifacial PV systems can now be predicted with the same accuracy as their monofacial counterparts (Figure 7 and Table 3).

Table 3. Comparison of cumulative energy yield shown in Figure 7 [23].

	Energy Yield [kWh/kWp] 5 Months Cumulated Data	
	Bifacial Module	**Monofacial Module**
measured	569.9	532.3
modeled	564.5	535.0
deviation	−1.0%	0.5%

2.5. Bankability

As already stated, bifacial PV systems are finally bankable. This is partly due to the long development of the technology which has become low cost, and partly to the availability of data generated from large bifacial PV installations, standards, and reliable energy yield simulations as explained in the previous sections. "Bankable" means that banks are now giving loans for large bifacial PV systems and finally the private investors do not have to invest on their own. This cycle is common to most technologies: where the "first movers" such as bSolar and MegaCell had to do the initial risky work, and now the "second movers" can enter the market with a more reliable profit potential.



(a) **(b)**

Figure 7. (**a**) Comparison between measured and modelled specific energy yield of a monofacial and a bifacial PV module (located within a module row) for a time period of 5 months [23] with (**b**) the coresponding deviation. The modelled energy yield has been calculated with the MoBiDiG simulation model using the ray tracing based optical model.

3. Opportunities

Higher complexity offers various installation possibilities. This has been already discussed and shown in previous paragraphs. If you want to reach lowest LCOEs, bifacial HSAT offers the best solution. If you want to benefit from dual use of land area as, e.g., for combined electricity production and agriculture as depicted in Figure 8, then bifacial vertical installations offer the best option.

We call such unconventional installations from the beginning "PV vineyards". Such installations offer many advantages in addition to the double use of the land. The electricity generation of such systems is shifted more to the morning and evenings (see Figure 5e). After snow fall, during winter time, the albedo is increased and the modules are not covered by snow, as can be seen in Figure 9. When combined with already installed PV systems facing to the south, the overall generation curve becomes broader—reducing the need for energy storage. Systems such as those provided by Next2sun are gaining in popularity and, with the ongoing collection of data and experience, this technology is becoming increasingly bankable so that even larger systems will be built with this technology in the future.

Figure 8. Vertical bifacial PV system by Next2Sun showing the advantage of double use of land [17].

Figure 9. Vertical bifacial PV system by Next2Sun in winter, showing one of the advantages not being covered by snow [17].

The opportunities for bifacial PV systems are increasing with time as the bifacial modules these days are now being sold at the same price as their monofacial equivalents. We predict that in a few years it is likely that there will be hardly any monofacial modules left in the PV market for utility scale installations.

4. Challenges

Higher complexity increases the number of degradation mechanisms. Monofacial modules differ from bifacial modules mostly on the rear side, but in some cases also on the edges of the modules.

Figure 10a shows on the left side a monofacial module and Figure 10c solar cell and Figure 10b on the right a bifacial module and Figure 10d solar cell. The differences are the metal grid (in case of PERC an Al-grid, in case of nPERT, TOPCon, HJT, or IBC a Ag-grid) and therefore also an exposed ARC (Anti Reflection Coating) on the rear side. In bifacial modules, the rear side cover consists of either glass or a transparent polymer back sheet. When backsheets are used, the module must be supported by an aluminium frame but the rigidity of the glass-glass modules is enough that in some cases a frame is not needed and the edges are only sealed. The mounting systems are different depending on whether the module has a frame or not.

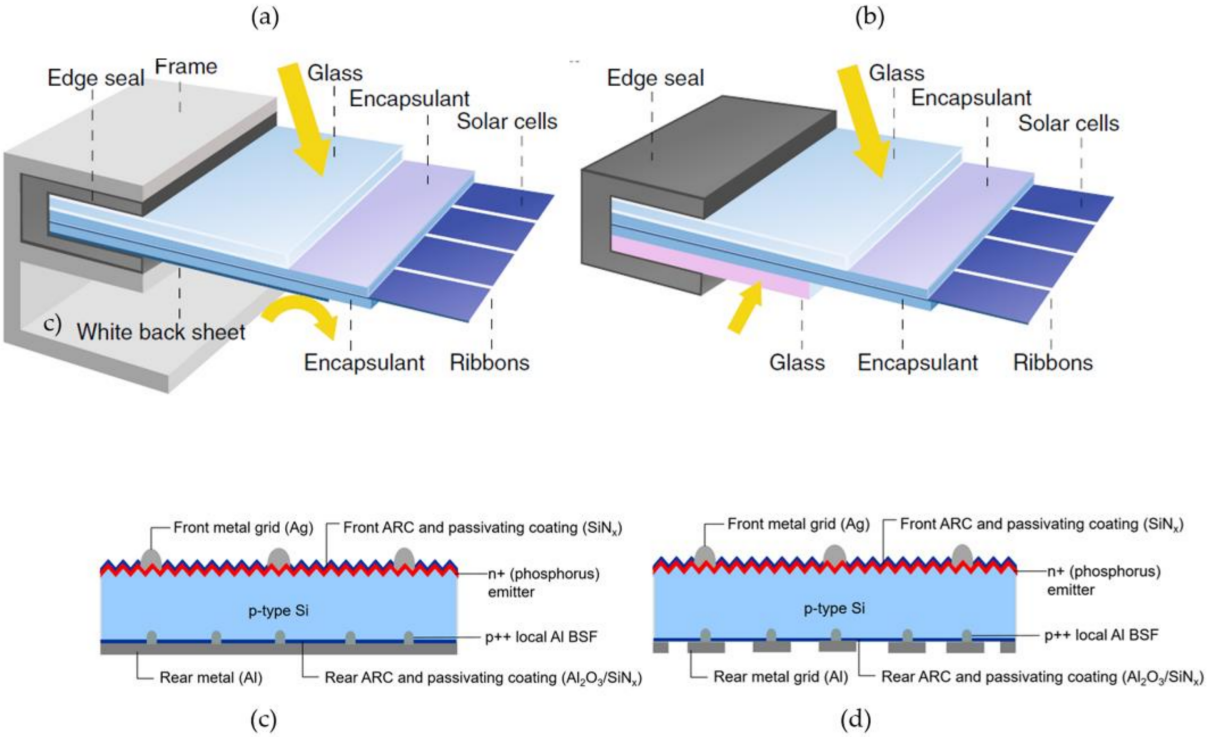


Figure 10. Difference between (**a**) monofacial and (**b**) bifacial module [16] and, (**c**) monofacial and (**d**) bifacial (PERC) solar cell.

Starting from the inside of the module, the first important degradation mechanism on a cellular level is the so called LeTID (Light and elevated Temperature Induced Degradation), which consists of the sum of several degradation mechanisms which will be described in the following paragraph. The printing of Al or Ag fingers on the rear side could cause degradation effects if, for example, acetic acid is formed by decomposition of the EVA encapsulant, or if the fingers become detached by e.g., 'floating' of the cell in the encapsulant. As the ARC is exposed to the rear side in bifacial modules, rear side PID can occur and the effects are different depending on whether the solar cell has a front or rear side emitter. The use of transparent back sheets and frameless double-glass modules could be other sources for potential degradation and, of course, an inhomogeneous illumination of the rear side could cause hot spots additional to those that may occur due to inhomogeneous illumination on the front side. In the following we will describe these various effects in more detail.

4.1. LeTID in Bifacial Cells/Modules

Compared to monofacial solar cells, the processing of bifacial solar cells uses different rear dielectrics and processing temperatures, and the resulting LeTID can differ significantly from the monofacial case, mostly due to the additional contribution of HID (Hydrogen Induced Degradation) [24].

Table 4 summarizes the known and most prominent degradation mechanisms caused by either the formation of BO (boron-oxygen) complexes [25], hydrogenation of metallic impurities [26], or depassivation of PERC´s rear side [27]. Adapting the c-Si material and solar cell process according to the properties as described in Table 4 can minimize the degradation. In addition, many cell producers are using a stabilization process after the cell fabrication in order to transfer the solar cell into a non-degrading state.

Table 4. Summary of PERC degradations and possible solutions during cell process [24].

	Light and Elevated Temperature Induced Degradation (LeTID)		
Degradation Mechanism	**LID**	**HID**	**Passivation Degradation**
Cause	BO complex formation	High hydrogen concentration	Depassivation of dielectrics on undiffused surfaces
Reduction on solar cell level	- Low oxygen Si material - High resistivity Si material - Stabilisation process - Ga-doping - n-type devices	- Use of H-poor dielectrics - Adapted process temperature - Low firing temperatures - Thin wafers	- Use of low doped BSF - Upgrade to PERT

4.2. Potential Induced Degradation (PID)

PID is a degradation phenomenon that arises due to a potential difference between the solar cell and earth (frame and/or glass). It cannot be visually spotted, but power measurements and thermography can help to identify PID onsite. Degradation due to potential differences has been seen in bifacial PV modules based on both n-type [28,29] and p-type [24,30] cells.

Components of the module packaging such as frame, glass, and encapsulant have been shown to play an important role in the extent of PID degradation of PV modules. PID concerns are reduced when the bifacial module is frameless due to the lack of an earth potential near to the cells. The use of POE as encapsulant material can significantly reduce PID affection in comparison to the use of EVA [28]. In some cases, POE can completely avoid PID degradation at module level. In addition, it has been observed that replacing glass with transparent backsheet also completely avoid PID degradation [29].

The structure and the substrate of the bifacial solar cell determines whether the PV module will be affected by positive or negative potential difference. Boron-based substrates experience degradation under negative voltage (applied to the cell) [29,30] while phosphorous-based substrates degrade under positive voltage [13]. As indicated in Figure 11, bifacial modules show two types of PID: the shunting type (PID-s) and the polarization type (PID-p). The former affects the shunt resistance by shunting the p-n junction due to ion migration into stacking faults, while the latter corresponds to a loss of surface passivation due to ion accumulation on the passivation layer [29,30]. While PID-s has been extensively studied and is well-understood, the PID-p mechanism is not yet clear. Sodium ions migrating from glass and affecting n-doped layers can effectively explain PID-p. However, p-doped layers are also affected by PID-p [29] but there is no explanation on the origin of negative ion migration. Finally, it is seen that modules are more affected on the front side than on the rear side [29].

Other challenges, besides a higher potential for degradation as discussed, is the ability to model and forecast the energy generation from a bifacial PV systems and to construct it accordingly, as there are more possibilities for mistakes, as for a monofacial PV system. This has been already discussed in detail in the modeling paragraph.

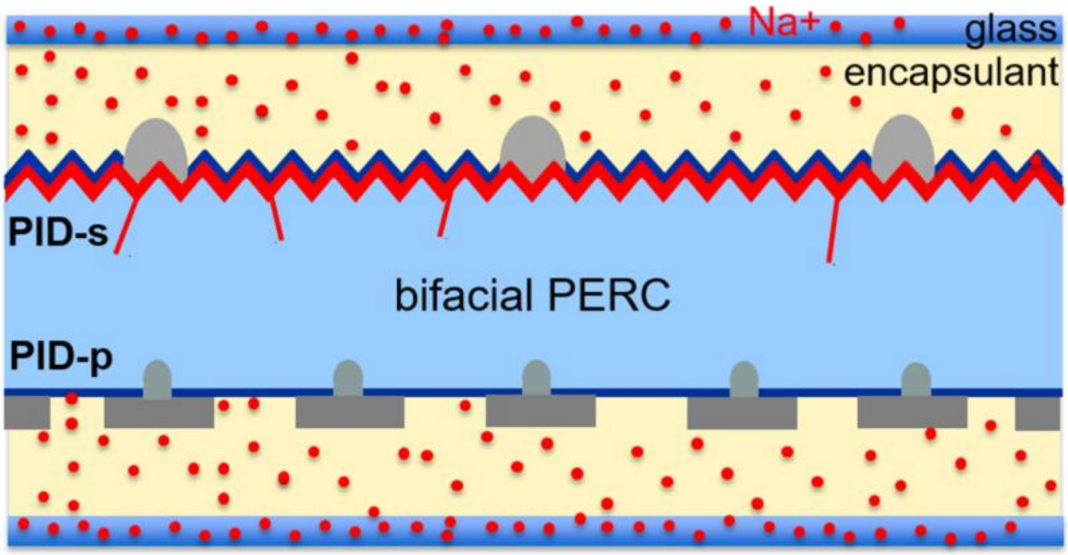


Figure 11. Bifacial PID of bifacial p-PERC solar cells when using glass/glass module: PID-s occurring at the front/emitter side and PID-p occurring at the rear side of the solar cell [30].

5. Summary and Outlook

The future is bifacial is already common thinking among most of the Tier1 manufacturers. However, there are still many areas of development and optimisation in the bifacial PV arena on cellular, modular, and systems levels. The summary of the hottest technical topics from the virtual bifiPV workshop 2020 is provided in a document published by NREL [31]. The ITRPV 2020 roadmap sees bifacial solar cells dominating the market in 5 years from now, as shown in Figure 12.

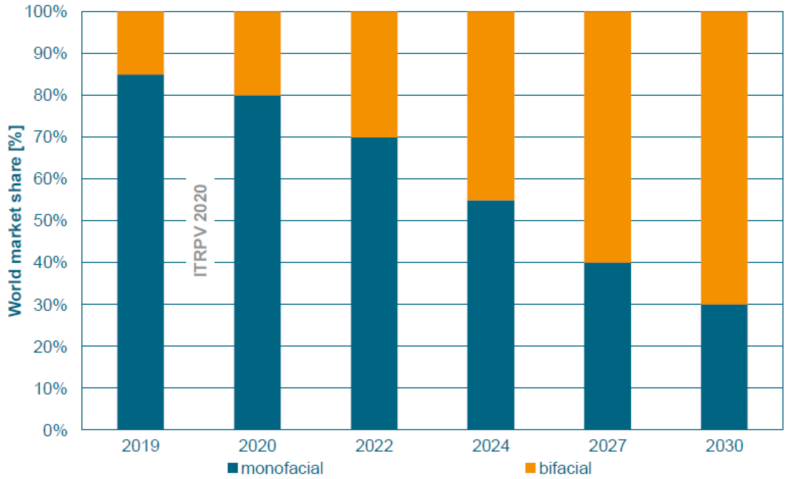


Figure 12. Share of bifacial solar cells in the PV market from ITRPV roadmap 2020 [32].

Experience of the dynamic Chinese PV market tells us that this might happen even faster. It the MENA region large electricity providers also discovered the power of bifacial PV. Dubai Electricity and Water Authority (DEWA) awarded the 900 MW photovoltaic fifth phase of the Mohammed bin Rashid Al Maktoum Solar Park to the consortium led by ACWA Power in partnership with Gulf Investment Corporation (GIC). The winning tariff of 1.7 USc/kWh using bifacial HSAT systems confirms once again the power of bifacial PV [33]. This phase of the solar park is expected to be commissioned in phases starting Q3 2021. In the coming years electricity from bifacial HSAT PV systems will be produced

at lowest costs—even below 1USct/kWh. Finally, we predict that BIPV and AgriPV will flourish with the flexible use of low cost bifacial modules.

Author Contributions: R.K.; investigation, visualization. writing, review and editing, J.L.; investigation, writing, software, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Solar is the New King of Energy Markets. Available online: https://www.pv-magazine.com/2020/10/14/solar-is-the-new-king-of-energy-markets/ (accessed on 9 March 2021).
2. 800 MW Al-Kharsaah PV Plant In Qatar. Available online: http://taiyangnews.info/markets/qatar-0-01567kwh-winning-bid-for-800-mw-pv-tender/ (accessed on 9 March 2021).
3. Enel´s First Bifacial HSAT PV System in Chile. Available online: http://npv-workshop.com/fileadmin/layout/images/Konstanz-2017/9__F._Bizzarri_ENEL_Innovative_tracked_bifacial_PV_plant_at_la_Silla_observatory_in_Chile_.pdf (accessed on 9 March 2021).
4. Kopecek, R.; Libal, J. Complex problems require simple solutions: How to measure bifacial devices correctly? *PV Int.* **2017**, *37*, 105–110.
5. Dullweber, T.; Kranz, C.; Peibst, R.; Baumann, U.; Hannebauer, H.; Fülle, A.; Steckemetz, S.; Weber, T.; Kutzer, M.; Müller, M. The PERC+ cell: A 21% efficiency industrial bifacial PERC solar cell. In Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 14–18 September 2015.
6. Setback For President Donald Trump. Available online: http://taiyangnews.info/markets/bifacial-solar-panels-dodge-trumps-bullet-again/ (accessed on 9 March 2021).
7. JinkoSolar Lands Supply Contract for Europe's Largest Bifacial Solar Farm Yet. Available online: https://www.pv-tech.org/news/jinkosolar-lands-supply-contract-for-europes-largest-bifacial-solar-farm-yet (accessed on 9 March 2021).
8. Turkey's Regulator Licenses 1 GW Karapınar Solar Power Plant. Available online: https://balkangreenenergynews.com/turkeys-regulator-licenses-1-gw-karapinar-solar-power-plant/ (accessed on 9 March 2021).
9. N-Type Expansions to Benefit From 2020 Downturn-Driven PV. Available online: https://www.pv-tech.org/news/n-type-expansions-to-benefit-from-2020-downturn-driven-pv (accessed on 9 March 2021).
10. PV CellTech 2020 to Explain Why n-PERT Emerging as Differentiated Play for Chinese Leaders. Available online: https://www.pv-tech.org/pv-celltech-2020-to-explain-why-n-pert-emerging-as-differentiated-play-for/ (accessed on 9 March 2021).
11. Intersolar Europe 2017: Bifacial will be Mainstream in Two Years Says LONGi. Available online: https://www.pv-tech.org/news/intersolar-europe-2017-bifacial-will-be-mainstream-in-two-years-says-longi (accessed on 9 March 2021).
12. Shifting to a Larger Solar Wafer Format: The Rise of M6. Available online: https://pv-magazine-usa.com/2020/01/28/the-weekend-read-the-rise-of-m6/ (accessed on 9 March 2021).
13. Kopecek, R.; Koduvelikulathu, L.J.; Tune, D.; Kirk, D.; Case, C.; Rienäcker, M.; Schulte-Huxel, H.; Warren, E.; Tamboli, A.; Peibst, R.; et al. tandem PV: A review of c-Si-based tandem technology and what is needed to bring it into production. *PV Int.* **2020**, *45*, 40–52.
14. PV Market Trends. Available online: https://www.infolink-group.com/en/solar/analysis-trends (accessed on 9 March 2021).
15. Taiyang News Advanced Modules 2019 Report Shows Surprising Developments Leading to Significantly Higher Power Ratings of Solar Panels. Available online: http://taiyangnews.info/reports/advanced-module-technologies-2019/ (accessed on 9 March 2021).
16. Kopecek, R.; Libal, J. Towards large-scale deployment of bifacial photovoltaics. *Nat. Energy* **2018**, *3*, 443–446. [CrossRef]
17. Next2sun. Available online: https://www.next2sun.de/en/homepage/ (accessed on 9 March 2021).
18. French-German Alliance for Vertical PV. Available online: https://www.pv-magazine.com/2020/03/30/french-german-alliance-for-vertical-pv/ (accessed on 9 March 2021).
19. Kopecek, R.; Libal, J. (Eds.) *Bifacial Photovoltaics: Technology, Applications and Economics*; Institution of Engineering and Technology: Stevenage, UK, 2018; ISBN 978-1-78561-274-9.
20. White Paper on Bifacial PV. Available online: https://www.pi-berlin.com/wp-content/uploads/2019/10/White-Paper-Bifacial-PV-Technology-PI-Berlin.pdf (accessed on 9 March 2021).
21. Liang, T.S.; Pravettoni, M.; Deline, C.; Stein, J.S.; Kopecek, R.; Singh, J.P.; Luo, W.; Wang, Y.; Aberle, A.G.; Khoo, Y.S. A review of crystalline silicon bifacial photovoltaic performance characterisation and imulation. *Energy Environ. Sci.* **2019**, *12*, 116–148. [CrossRef]
22. Shoukry, I.; Libal, J.; Kopecek, R.; Wefringhaus, E.; Werner, J. Modelling of Bifacial Gain for Stand-alone and in-field Installed Bifacial PV Modules. *Energy Procedia* **2016**, *92*, 600–608. [CrossRef]
23. Berrian, D. Accuracy of Ray Tracing and View Factor Optical Models For Energy Yield Prediction of Fixed Tilt and Tracked Bifacial PV Systems. Ph.D. Thesis, Universität Freiburg, Freiburg, Germany, 2020. Unpublished work.

24. Is LeTID Degradation in PERC Cells Another Degradation Crisis Even Worse Than PID? Available online: https://www.pv-tech.org/guest-blog/is-letid-degradation-in-perc-cells-another-degradation-crisis-even-worse-th (accessed on 9 March 2021).
25. Schmidt, J.; Cuevas, A. Electronic properties of light-induced recombination centers in boron-doped Czochralski silicon. *J. Appl. Phys.* **1999**, *86*, 3175–3180. [CrossRef]
26. Née Wenham, A.C.; Wenham, S.; Chen, R.; Chan, C.; Chen, D.; Hallam, B.; Payne, D.; Fung, T.; Kim, M.; Liu, S.; et al. Hydrogen Induced Degradation. In Proceedings of the IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), (A Joint Conference of 45th IEEE PVSC, 28th PVSEC and 34th EU PVSEC), Waikoloa Village, HI, USA, 10–15 June 2018.
27. Herguth, A.; Derricks, C.; Sperber, D. A Detailed Study on Light-Induced Degradation of Cz-Si PERC-Type Solar Cells: Evidence of Rear Surface-Related Degradation. *IEEE J. Photovolt.* **2018**, *8*, 1190–1201. [CrossRef]
28. Barbato, M.; Meneghini, M.; Cester, A.; Barbato, A.; Tavernaro, G.; Rossetto, M.; Meneghesso, G. Durability of bifacial solar modules under potential induced degradation: Role of the encapsulation materials. In Proceedings of the 32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany, 21–24 June 2014; pp. 1879–1883.
29. Devoto, I.; Halm, A. Comprehensive study of PID mechanisms for n-type bifacial solar cells. In Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille, France, 9–13 September 2019; pp. 1106–1113.
30. Carolus, J.; Tsanakas, J.A.; van der Heide, A.; Voroshazi, E.; De Ceuninck, W.; Daenen, M. Physics of potential-induced degradation in bifacial p-PERC solar cells. *Sol. Energy Mater. Sol. Cells* **2019**, *200*, 109950. [CrossRef]
31. BifiPV2020 Bifacial Workshop: A Technology Overview. NREL Summary of bifiPV2020. Available online: https://www.nrel.gov/docs/fy21osti/77817.pdf (accessed on 9 March 2021).
32. International Terhnology Roadmap for PV. Available online: https://itrpv.vdma.org/ (accessed on 9 March 2021).
33. Dubai Electricity and Water Authority (DEWA) Awarded the 900MW Photovoltaic Fifth Phase. Available online: https://www.acwapower.com/en/projects/dewa-v-pv/ (accessed on 9 March 2021).