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Status of Bifacial PV and simulations of 2 different scenarios for bifacial PV systems in Atacama

- CONFIDENTIAL -

- 07.08.2017 -

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SUMMARY

This report supports the activities of CORFO to model a large 1GWp PV and solar thermal system in the Atacama Desert to power the mining industry. DLR and MW Group are responsible for the entire simulations; ISC Konstanz provides with this report updates on bifacial technology and simulations of 2 scenarios of bifacial installations.

The first part of the report gives an overview on bifaciality and provides a study on actual available bifacial cell & module technologies on the market (PERC+, PERCT, nPERT, HJ, MWT, IBC) including a list of companies offering these products and a short description of each technology. Evaluation of each technology in terms of module-COO and relative LCOE is given and then a selection of most effective technology and estimation of CoO and efficiency (USD/Wp for module, front side Pmpp of given module size, bifaciality ) for 2020 and 2025 is provided.

At the end 2 scenarios for bifacial installations are simulated with the program (MoBiDiG: Modeling of Bifacial Distributed Gain) developed at ISC Konstanz. 72 cells bifacial glass-glass nPERT (BiSoN) modules were selected for the simulations of

1) fixed tilt “BiSoN Farm” (1.247 MW PV bifacial PV system) and
2) tracked “BiSoN Farm” (1.247 MW PV tracked bifacial PV system).

As a result, compared to a monofacial reference system, for the fixed tilt bifacial PV system an energy yield increase of around 12% is predicted. For the bifacial system with single axis tracking the calculated energy yield increase is expected to be 15 % compared to a monofacial system with single-axis-tracking.

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Version: 7.0

Date: 07.08.2017

International Solar Energy Research Center Konstanz e.V., Konstanz 2017
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1. INTRODUCTION

Bifacial photovoltaic devices (cells & modules) are currently gaining more and more attention regarding the evaluation of PV technologies - in particular for commercial or utility scale PV plants - in order to make a choice driven by cost of PV generated electricity (levelized cost of energy, LCOE) in €/kWh instead by installation cost of the system in €/Wp. A minimum bifacial gain of 10% is observed in every system which was increased to almost 30% in systems with perfect conditions regarding module properties, mounting system geometry and reflection of the ground and surroundings (albedo).

![Figure 1: measured bifacial gain (from outdoor monitoring over time periods from several months to several years) in energy yield of bifacial PV systems installed on various ground typologies with different albedo ("bifacial gain") - data collected from literature.](image-url)

As the PV technology is getting bifacial anyhow (more and more module manufacturers switch to glass-glass, cell manufacturers switch to passivated rear side devices (PERC, PERT, HJ) and printing a grid on the rear also to saves material) we have forecasted a bright future for the application of bifacial technology in our article in PV International 32 (February 2016). At that time, the largest bifacial installation, about which we reported in that article as well, was almost finalized in Chile- the 2.5MWp “BiSoN-farm” from MegaCell called Hormiga.

During 2016, the installations of bifacial PV systems “exploded” so fast, so that the MagaCell´s “BiSoN Farm” is rather a small bifacial installation by now. Fig. 2 depicts, to our best knowledge, the 4 largest bifacial systems at the moment.
Figure 2: (Top) largest bifacial installations and (bottom) cumulated power for bifacial systems as a function of years.

Long time being the largest, with 1.25 MWp very often cited, bifacial system from PVGS is now history in terms of size - however being still the one with the best reported data, in respect to bifacial gains and duration of monitoring. The 2.5 MWp system from MegaCell in Chile is now connected and the owners are making experiments regarding the albedo. E.g. they are conditioning the ground putting white pebbles on the ground below the modules in order to increase the albedo of the ground. Pictures of this installation can be seen in the paragraph where we discuss CoO and LCOE. The second largest installation is a 13MWp System from Sunpreme in the US and the largest one with 50MWp from Yingli in China. All these large installations are based on n-type technologies- nPERT (PVGS, MegaCell, Yingli) and heterojunction (sunpreme). However PERC+ (bifacial PERC) will become an important technology for bifacial systems as well, as we will see in next paragraph. On the bottom graph in Fig. 1 the cumulated installed bifacial power is depicted as a function of years. At the moment we estimate the total bifacial power to be at least 120MWp. There are huge plans for large systems for 2017 from many electricity producers - such as the project of EDF in Mexico to install a 90MWp bifacial system. In addition 8minuteenergy is planning to install a 50MWp
bifacial system in the US. To our knowledge both systems will be based on n-type technology in order to benefit from the better bifaciality of the modules. In 2017 we expect bifacial installations to at least triple the total installations in 2016.

Figure 3: Results from simulations by bSolar allowing for a quick estimate of the bifacial gain in single modules and systems.

In order to estimate the bifacial gain, bSolar has created a nice simple graph that is depicted in Fig. 3. In dependence of installation height, distance of rows and the albedo, the bifacial gain can be estimated.

2. HIGH EFFICIENCY PV: OVERVIEW OF WORLDWIDE MARKET PLAYERS AND TECHNOLOGIES

In order to establish a benchmark for the bifacial PV technologies, in the following, an overview of some of the most important current and upcoming high-efficiency PV technologies and the related players will be given (non exhaustive list). As “high-efficiency” we consider in this case, c-Si cell technologies that have advanced process steps and/or sequences compared to p-type Cz-Si Al-BSF solar cells ("standard technology"), leading to an increased efficiency compared to the standard technology. Today, the highest values for the average efficiency that is achieved in industrial cell manufacturing lines using the Al-BSF cell design on p-type Cz-Si wafers, are around 19.5%.

From the point of view of LCOE (€/kWh), bifacial PV is competing with monofacial p-type mc-Si
technology, while from the point of view of efficiencies, cell designs with 20% to 24% efficiency potential are the benchmark: in case of an installation allowing for 30% bifacial gain, a 20% (efficiency measured only under front side illumination) bifacial cell performs like a 26% monofacial cell.

Thereby the selection will be limited to technologies that are already in commercial production or for which the combination between technological maturity and risk is such that - from our point of view - a transfer into commercial mass production within the next 3 years is very likely. As an addition, for lab results, only cell efficiencies that have been demonstrated on wafer sizes of at least 100 cm² have been taken into consideration.

2.1 Overview of considered technologies

In the next paragraph we will summarize the following cell technologies which can be bifacial:

- PERC+ (Passivated Emitter and Rear Cell)
- HJ (Heterojunction)
- IBC (Interdigitated Back Contact)
- MWT (Metallisation Wrapped Through)
- nPERT (Passivated Emitter Rear Totally diffused)
2.1.1 p-type PERC/PERC+

**Cell architecture:**

![Diagram of p-type PERC solar cell](image)

**Figure 4:** Schematic cross section of p-type PERC solar cell (source: Centrotherm)

Industrial PERC (Passivated Emitter and Rear Cell) solar cells are based on p-type silicon wafers and feature a front-side design that is identical to state-of-the art p-type Al-BSF solar cells (i.e. lowly doped or selective emitters). The advanced process steps that are increasing the efficiency potential are regarding the rear side of the cell: instead of an Al-BSF that covers the entire rear surface, the rear side of the cell is covered with a dielectric layer for surface passivation and a local Al-BSF (with point or finger-grid shape) that is contacting the bulk of the cell only on some percentage (around 5%) of the total rear side area.

**Efficiency potential:**

Several industrial players reported an efficiency of 20% or more in industrial mass production. Recently, ISFH reported a record efficiency of 21.2% \[i\] using industrial process steps including some more advanced steps such as metallization by stencil printing and a 5 busbar-design. Another recent record cell efficiency of 21.7% has been reported by Solarworld \[ii\]. The bifacial version or PERC is called PERC+ and is based on the technology that an open rear Al contact is printed. As Al is not very conductive, more metal coverage on the rear side is needed, resulting in a bifaciality of around only 60%.
Special Equipment required:

The PERC process has the advantage that it can be implemented by upgrading existing monocrystalline cell manufacturing lines with equipment for formation of the rear side passivation layer as well as the opening of this layer in order to enable the local rear side contact formation.

![Figure 5: Example of process sequence for PERC process compared to the standard p-type Al-BSF cell process [iii]](image)

There are various technological options for the creation of the rear side surface passivation layer, amongst them are Al₂O₃ (or "AlOx"; deposited by PECVD or ALD), other dielectrics deposited by PECVD and thermal oxidation. The local opening of the passivation layer is usually done by locally ablating the passivating dielectric layer with a laser beam.

Module technology:

According to its device design that includes screen printed busbars on front and rear side, the PERC solar cell is fully compatible with standard module assembly lines.

Particularities/Challenges:

The PERC cell design requires low wafer resistivity in order to achieve high cell efficiencies. Taking into account the fact that the LID effect on p-type (boron doped) Cz-Si wafers is higher for higher doping (low resistivity), in industrial solar cell manufacturing, wafer material with lower doping and with low concentrations of interstitial oxygen should be used in order to achieve the highest stabilized cell efficiency after LID. Accordingly it has been shown in [iv] that 20.5% efficient PERC cells on 0.7 Ωcm p-type Cz-Si wafers can suffer a reduction of the efficiency to values below 19% due to LID.
2.1.2 n-type HIT

Cell architecture:

Figure 6: Schematic cross section of HIT solar cell (source: Sanyo)

The Hetero-junction Intrinsic Thin layer (HIT) concept (or just hetero-junction, HJ) is in commercial production at Panasonic (formerly Sanyo) since many years. As recently some of the important related Sanyo patents expired, more players are currently entering the market. The HJ concept is based on a high lifetime n-type Cz-Si base combined with a thin intrinsic layer of amorphous silicon (a-Si) and a p-doped a-Si layer on the top serving as an emitter. In order to achieve a sufficient lateral conductivity, transparent conductive oxide (TCO) layers are needed on the front side of the cell. As the industrial applicable TCO’s do not resist to the high temperatures used for fast firing of standard metal pastes, the HIT concept uses special low temperature pastes.

Efficiency potential:

In 03/2014, Panasonic reported a record efficiency of 24.7% achieved on 5” wafers using laboratory processes [v]. According to the datasheet of the 245 W module, (72x 5”cells, module area: 1.28 m²), the module efficiency is 19.1%. The average industrial cell efficiency achieved by Panasonic is around 22%.

Equipment required:

CVD equipment for deposition of a-Si-layers, sputtering for TCO
Module technology:

The interconnection of the HIT solar cells requires special low-temperature technologies (e.g. the use of conductive films or conductive adhesives) and related special equipment for tabbing and stringing of the cells. Another particularity is the sensitivity of the amorphous silicon to humidity requiring the use of backsheets with efficient humidity barrier layers (e.g. with aluminum layers embedded to the backsheet material). Consequently, in case of fabrication of bifacial modules, HIT solar cells require a glass-glass module concept, excluding the use of transparent backsheet.

Particularities/Challenges:

The low temperature coefficient of $P_{mpp}$ (0.30 %/K compared to 0.4 to 0.5%/K for standard cell technologies) of the HIT cells is beneficial for the energy yield (kWh/kWp) of a PV system.

The challenging part of the HIT cell technology is the high level of cleanliness (factory floor, equipment and chemicals) that has to be maintained when processing HIT cells. In addition, the potential of the HIT design (in particular in terms of high $V_{oc}$) can only be fully exploited when using very high quality n-type Cz-Si wafers featuring a higher cost than standard n- and p-type Cz-Si wafer material.
2.1.3 n-type IBC

Cell architecture:

**Figure 7:** Schematic cross section of n-type IBC cell with passivated contacts (similar to Sunpower, graph taken from [vi])

Interdigitated back contact solar cells have all metal contacts located on the rear side and require a locally structured doping for emitter and BSF formation on the rear side. The advantages are the complete elimination of shading losses originating from front side metallization and the possibility of very efficient surface passivation on the front side.

**Efficiency potential:**

Using an advanced and complex cell process, Sunpower is reaching up to 24% cell efficiency in industrial mass production. Combined with HJ technology (laboratory process), Kaneka reached a record cell efficiency of 26.3% on large area wafers (180cm²) [vii].

**Availability of technology:**

Various institutes and cell manufacturers are working on less complex IBC cell structures and the related manufacturing processes in order to achieve a more cost effective process. To our knowledge, with a demonstrated cell efficiency of 22%, the ZEBRA process by ISC Konstanz is the most mature process amongst the industrially relevant low-cost processes.

**Module technology:**

Standard module assembly lines are not compatible with IBC-cells. Depending on the contact design of the cells, customized solutions (see e.g. [viii]) are required or equipment that has
been developed for MWT-cells can be used.

**Particularities/Challenges:**

IBC has a very high efficiency potential, however, in order to reach a competitive LCOE, a compromise must be found between the complexity (= cost) of the process and the cell efficiency that can be reached. In this context it has also to be noted that, due to the absence of front-side metallization, the missing internal reflection between finger-grid and inner side of the module glass, special effort has to be put into the containment of the cell-to-module $P_{mpp}$-losses.
2.1.4 Metallization wrapped through (MWT, n-type and p-type) solar cell

Cell architecture:

![Schematic cross section and top view of p-type MWT solar cell.](image)

As shown in Fig. 8, the MWT cell design allows a reduction of the shading losses on the front side of the solar cell. From the equipment point of view, the MWT cell manufacturing process can be obtained by upgrading a p-type standard Al-BSF cell line with a Laser for drilling holes into the Si wafer. In addition, the screen printing process must be optimized in order to achieve a correct metallization of the through holes.

**Efficiency potential:**

On p-type silicon 19-20% cell efficiency has been demonstrated. On n-type silicon, ECN recently demonstrated 21% cell efficiency [ix].

**Availability of technology:**

Various manufacturers and institutes are developing proprietary processes for the manufacturing of p-type MWT solar cells. ECN is licensing p- and n-type MWT cell technology (e.g. n-type MWT to Yingli).

**Module technology:**

As for MWT (and also IBC), the contacts for both polarities are on the rear side, MWT cells are not compatible with standard module assembly lines. One of the possibilities to interconnect...
such cells within the module is the conductive backsheet technology. Several equipment suppliers (Eurotron, Cencorp, Formula E) offer module assembly lines based on conductive backsheet technology.

2.1.5 n-type PERT ("standard" bifacial cell)

Cell architecture:

![Schematic cross section of n-type PERT cell (source Centrotherm).](image)

**Figure 9:** Schematic cross section of n-type PERT cell (source Centrotherm).

Efficiency potential:

As shown in Fig. 9, depending on the process technology used, efficiencies from 20.5% to 21.5% can be reached with standard tube diffusions and optimized screen printing of the metal contacts. Introducing plating technologies for metallization and ion implantation for emitter and/or BSF formation, over 21.5% are feasible (see e.g. results by LG). As on the rear side of the cell a finger-grid is located instead of a full-area metallization, this cell-technology is inherently bifacial.
**Figure 10:** Overview of bifacial n-type PERT cell efficiencies published by various institutes and manufacturers.\[x\]. The original graph - as shown here - must be corrected as follows: SSNED, Suniva and PVGSolutions (Earthon, 19.6%) are industrial stage, while PVGSolutions (R&D, 20.4%) is laboratory stage.

**Availability of technology:**

ECN is licensing an n-type PERT technology under the name "n-Pasha" ("Panda"-cell since 2010 in industrial production at Yingli/China, since 2014 at Mission Solar/USA) while ISC Konstanz licensed its BiSoN ("bifacial solar cell on n-type“) technology to MegaCell/Italy and Adani/India. At the same time, many cell manufacturers are working on own developments, some of them in commercial production, others at R&D stage (see Fehler! Verweisquelle konnte nicht gefunden werden. and Table 1).

**Module technology:**

For monofacial modules, standard module assembly lines can be used. In case of bifacial module production, in order to prevent shading on the rear side, modifications of glass size and of the type of junction box is necessary as well as the use of an adapted frame design. Bifacial modules can be produced with transparent backsheet or glass on the rear side. For glass-glass modules, compatibility of the module assembly line (in particular the laminator) with a glass-glass process has to be verified.
Particularities/Challenges:

N-type PERT cells allow for a high bifacial factor (>90%) combined with the ability to use low cost production processes. Compared to standard p-type Al-BSF solar cells, the following process elements are requiring additional equipment/material and have to be optimized and adapted for industrial production:

- Boron-diffusion for emitter formation
- p'-Si surface passivation,
- procurement of good quality n-type wafers at competitive price

While the first two points have been successfully implemented by industrial players such as Yingli and PVGS, the current wafer prices for monocrystalline n- and p-type wafers reported e.g. on pvinsights.com show that, meanwhile, the price gap between p- and n-type Cz-Si wafers - with a quality suitable for >21% efficient solar cells - has become smaller compared to a few years ago. The current prices (according to pvinsights.com, 22.02.2017, Solar PV Wafer average Weekly Spot Price) are:

- 156 mm p-type Cz Si wafer: 0.76 USD/wafer
- 156 mm n-type Cz-Si wafer : 0.84 USD/wafer

The manufacturing cost (transformation cost from wafer to cell) of nPERT is comparable to or lower than for e.g. PERC cells (that also feature >21% front side efficiency, but without being bifacial or - in case of the bifacial PERC+ concept, with a bifaciality of around 60 - 70%). Consequently the largest contribution to the price (and cost) gap between PERC cells and bifacial n-PERT is due to the fact that - up to now - n-type Cz-Si wafers are more expensive than p-type Cz-Si wafers. The difference between the wafer prices for p- and n-type has no technological reasons but is due to the - up to now - much lower global production volumes of n-type wafers.

When integrated into monofacial modules (with white backsheet) n-PERT cells can result in the same (or higher) module efficiencies as modules with comparable PERC cells. In this case, the cell to module transformation cost is the same as for standard monofacial (mc-Si or Cz-Si) modules.

When building bifacial modules, using transparent backsheet on the rear side is a way to maintain the cell-to-module transformation cost at the same level as for standard modules. However, very often, bifacial modules are so called glass-glass modules that feature a glass also on the rear side. While this increases the manufacturing cost due to an impact to the cycle time during lamination (the cost of the rear side glass is very similar to the cost of a backsheet), a glass-glass module is considered a premium product that features a higher durability - in particular under harsh environmental and climatic conditions.
2.2 Bifacial high-efficiency PV: worldwide players

There are basically three different bifacial solar cell concepts on the market, which are pPERC+, nPERT and nHJ. In addition to that, e.g. the Chinese company Luan is also involved in multicrystalline pPERCT production. So far most of the spread bifacial cells are based on n-type Cz-Si technology however, as the PERC technology has a total installed capacity of ca. 15GWp in Asia, “PERC+” (bifacial PERC) technology will strongly come on the market. The most prominent PERC+ manufacturers currently are Solar World, NSP and Sunrise. The bifacial factor at the moment is much lower (60%-70%) compared to PERT (85%-95%), but Al-paste development and improved alignment of the Al-grid at the rear side is continuously improving this. However the big plus of PERT remains the totally diffused rear side with the advantage that high resistivity and high lifetime wafers can be used. In addition, the surface passivation of the diffused rear side of the PERT cells is more stable in time.

Figure 11: Companies in production or in pilot production of bifacial solar cells.

MegaCell, Mission Solar and First Solar stopped the production of bifacial devices, however there are more new companies like Adani entering the market, companies like LG electronics expanding their bifacial capacities or companies like NSP bringing new products such as PERC+ on the market. The current (02/2017) total capacity for bifacial solar cell production is estimated to around 2GWp/year.

Table 1 represents a (non-exhaustive) selection of relevant players (manufacturers and institutes) in the field of advanced industrial bifacial cell technologies. Pure module manufacturers are not included in this list.
### Table 1: List of players in the field of bifacial high efficiency PV cell technologies.

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Brand/Technology</th>
<th>Efficiency (front side)</th>
<th>Development stage &amp; capacity (where available)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MANUFACTURERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVG Solutions</td>
<td>Japan</td>
<td>EarthOn n-type, PERT spin-on boron dopant</td>
<td>cells: max: 19.9% (6&quot;)</td>
<td>industrial mass production, 35 MW/year (cells)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>median: 19.5%</td>
<td>[xi], [xii]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>avg. bifacial ratio (rear side efficiency divided by front side efficiency): 96%</td>
<td></td>
</tr>
<tr>
<td>Panasonic</td>
<td>Japan</td>
<td>bifacial HIT, &quot;HIT double&quot;, n-type heterojunction cell</td>
<td>cells: max: 24.7% (102 cm²) avg. cell efficiency in industrial prod.: 20.1%</td>
<td>capacity of bifacial modules low (= 10 MW/year (?)) &quot;special order&quot;), but re-newed interest since last years (re-design in 2014) [xiii]</td>
</tr>
<tr>
<td>Shin Etsu Chemical</td>
<td>Japan</td>
<td></td>
<td>cell: &quot;potential&quot; for 21% (own statement from press release [xiv])</td>
<td>Offering technology license</td>
</tr>
<tr>
<td>LG Electronics</td>
<td>Korea</td>
<td>n-type, PERT, ion implantation for P</td>
<td>cells: &gt; 21% module 60 cells: 305 W (6&quot;)</td>
<td>High Efficiency Mono X® NeON Module efficiency 18.6%</td>
</tr>
<tr>
<td>First Solar/Tetrasun</td>
<td>US</td>
<td>n-type, copper-plated heterojunction cell, w/o TCO. compatible with std. module assembly</td>
<td>cells: &gt;21%</td>
<td>in production: since 01/2015 current capacity: 100 MW/year ; cell-factory in Malaysia [xv]</td>
</tr>
<tr>
<td>Shinsung Solar</td>
<td>Korea</td>
<td>p-type, ion implantation for P (?)</td>
<td>Avg. : &gt;19% (?)</td>
<td>Bifacial module introduced at Green Energy Expo 2011</td>
</tr>
<tr>
<td>bSolar Ltd.</td>
<td>Israel</td>
<td>p-type PERT, Proprietary Boron spin-on solution</td>
<td>cells: avg.:18.5% (6&quot;) bifacial ratio : 75%</td>
<td>[xvi] mass production stopped</td>
</tr>
<tr>
<td>Solarwind</td>
<td>Russia</td>
<td>p-type PERT</td>
<td>cells: 18.6 (5&quot;) bifacial ratio: 72%</td>
<td>[xvii] production stopped</td>
</tr>
<tr>
<td>MegaCell</td>
<td>Italy</td>
<td>n-type, PERT, BiSoN (ISC Konstanz technology) POC13 and BBr3 diffusion process,</td>
<td>cell: 20% (6&quot;) (20.3% demonstrated at ISC) bifacial ratio: &gt; 85%</td>
<td>80 MW/year (cells, modules via OEM)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>Technology/Passivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunpreme</td>
<td>USA</td>
<td>n-type heterojunction</td>
</tr>
</tbody>
</table>
|                               |         | cell: 20.5% (?)
|                               |         | modules: 290 W (front, 60 cells) |
|                               |         | 40 MW sales (modules) in 2014 [xviii] |
|                               |         | cells also used by HyperX [xix] |
| Prismsolar                    | USA     | n-type                 |
|                               |         | cell: 19.5%            |
|                               |         | module: 260W (front, 60 cells) |
|                               |         | capacity: <50 MW/year (?) |
| Nexolon America/Mission Solar | USA     | nPasha (n-type PERT technology from ECN) |
|                               |         | 19.7% [xx]            |
|                               |         | bifacial cell production started in 2014, meanwhile the production stopped |
| Motech                        | Taiwan  | n-type, PERT           |
|                               |         | cells: max: 20.63% (certified measurement with conductive chuck) [xxi] |
|                               |         | bifacial ratio < 90% |
| NeoSolar (NSP)                | Taiwan  | n-type PERT            |
|                               |         | cells: avg.:>19.5% (6") in production |
| Topcell Solar                 | Taiwan  | n-type PERT BBr3 diffused/ Phos Implanted |
|                               |         | cells: max:.19.3% (6") |
|                               |         | R&D [xxii] |
| Inventec Solar                | Taiwan  | n-type PERT BCl3 diffused/ Phos Implanted |
|                               |         | cells: max:.19.7% (6") |
|                               |         | Max: 18.9% (monolike) |
|                               |         | R&D, [xxiii] 330 W (72 cells) |
|                               |         | bifacial module presented on SPI 2013, cell in industrial production |
| CSUN                          | China   | n-type PERT with P + B implanted |
|                               |         | cells: >20% |
|                               |         | R&D with Intevac [xxiv] |
| ET Solar                      | China   |                         |
|                               |         | bifacial modules with NSP cells [xxv] |
| SI Module                     | Germany |                         |
|                               |         | buys bifacial cells from other manufacturers |
|                               |         | bifacial module: "SI-Enduro B270 – bifacial"
<p>|                               |         | <a href="http://www.si-module.com/">http://www.si-module.com/</a> |
| HT-SAAE (SSNED)               | China   | n-type PERT (P doping by ion-implant ?) |
|                               |         | cells with up to 20.4% efficiency, modules (60 cells) up to 285 Pmpp (front) |
|                               |         | bifacial cell &amp; module presented at Japan PV Expo 2015 [xxvi] |
| Yingli Solar                  | China   | Panda n-type PERT BBr3 |
|                               |         | cells: max: 20.2% (6&quot;) avg.: 19.6% |
|                               |         | n-Pasha” technology transfer (ECN-NL) mass production of bifacial cells [xxviii], recently also bifacial modules available through &quot;Baoding Jiasheng Photovoltaic Technology Co., Ltd. “[xxviii] |</p>
<table>
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<tr>
<th>Company/Technology</th>
<th>Location</th>
<th>Type</th>
<th>Cells and Module Efficiency</th>
<th>Bifacial Ratio</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Solar</td>
<td>China</td>
<td>n-type PERT</td>
<td>19.0% front</td>
<td>93%</td>
<td></td>
</tr>
<tr>
<td>BOSCH Solar Energy</td>
<td>Germany</td>
<td>Hybrid (including ion-implantation) nPERT cell/ developed by Bosch R&amp;D</td>
<td>20.6%</td>
<td>90%</td>
<td>Pilot production results. Bosch withdrew in 2013 from the production of crystalline solar cells. The know-how and patent portfolio related to n-type solar cells was acquired by ISC Konstanz.</td>
</tr>
<tr>
<td>Silevo</td>
<td>USA</td>
<td>Triex™ cells &amp; modules Hybrid tunneling-junction cell architecture</td>
<td>&gt;22% cells &gt;18% modules</td>
<td></td>
<td>In industrial production capacity. 2014: 32 MW/year, 2015: 230 MW/year, 2017 (planned): 1 GW/year</td>
</tr>
<tr>
<td>Shanxi Lu’an Solar Technology Co. Ltd.</td>
<td>China</td>
<td>Bifacial PERCT on p-type mc-Si (by RCT solutions)</td>
<td>18%</td>
<td></td>
<td>Industrial pilot-production</td>
</tr>
<tr>
<td>Solarworld</td>
<td>Germany</td>
<td>Not officially announced</td>
<td>No datasheet available yet</td>
<td></td>
<td>60 cells glass-glass module presented at Intersolar 2015 [xxx] pilot-production?</td>
</tr>
<tr>
<td>ERDM Solar</td>
<td>Mexico</td>
<td>Bifacial p-type mc-Si (&quot;Geminus&quot; technology by Schmid-Group)</td>
<td>Equivalent module efficiency (assuming 30% bifacial gain): 18%</td>
<td></td>
<td>Production start planned for Q3/2015 (110/MW/year bifacial cells and modules) [xxxi]</td>
</tr>
<tr>
<td>Irysolar</td>
<td>France</td>
<td>n-type PERT cell process</td>
<td>&gt;20% cell efficiency</td>
<td></td>
<td>&quot;Fabrication laboratory&quot; of SEMCO (manufacturer of diffusion furnaces for cell production), 5 MWp (bifacial and all other technologies)</td>
</tr>
<tr>
<td>Company x</td>
<td>Asia</td>
<td>n-type PERT</td>
<td>Target: cell efficiency 21%</td>
<td></td>
<td>R&amp;D collaboration with ISC Konstanz, potential initial capacity: 120 MW/year (2017)</td>
</tr>
<tr>
<td>Adani Group</td>
<td>Asia</td>
<td>n-type PERT</td>
<td>Target: cell efficiency 20.5%</td>
<td></td>
<td>Initial capacity: 120 MW/year (2017)</td>
</tr>
<tr>
<td>INSTITUTES</td>
<td>EQUIPT. MANUFACT.</td>
<td>Germany</td>
<td>Zebra n-type IBC BBr3, POCl3, screen printing</td>
<td>cell: max: 22.0% Avg. bifacial ratio : 75% (cell)/65%(module)</td>
<td>lab-results on industrial equipment; PECVD masking &amp; laser ablation in addition to standard n-type PERT process</td>
</tr>
<tr>
<td>--------------------</td>
<td>-------------------</td>
<td>---------</td>
<td>-----------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ISC Konstanz</td>
<td>Germany</td>
<td>BiSoN n-type PERT BBr3, POCl3, screen-printing</td>
<td>cells: max: 20.8% (6&quot;) bifacial ratio : &gt;85%</td>
<td>lab results, process transferred to MegaCell</td>
<td></td>
</tr>
<tr>
<td>INES</td>
<td>France</td>
<td>n-type, PERT passivation SiO$_2$/SiN$_x$</td>
<td>cells: max:20.7% (6&quot;) bifacial ratio: 92%</td>
<td>lab results</td>
<td></td>
</tr>
<tr>
<td>INES</td>
<td>France</td>
<td>HIT</td>
<td>cells: avg.: &gt; 20% (6&quot;)</td>
<td>lab results</td>
<td></td>
</tr>
<tr>
<td>ECN</td>
<td>Netherlands</td>
<td>nPasha (industrially implemented as Panda at Yingli) n-type, BBr3, POCl3</td>
<td>max. cell efficiency: 20.3%</td>
<td>lab results (process transferred to Yingli and Mission Solar/Nexolon)</td>
<td></td>
</tr>
<tr>
<td>Centrotherm</td>
<td>Germany</td>
<td>BiSoN (process from ISC) n-type, PERT</td>
<td>Avg. &gt; 20.5%/ 6&quot;</td>
<td>technology provider</td>
<td></td>
</tr>
<tr>
<td>Schmid</td>
<td>Germany</td>
<td>bifacial multi-PERT p-type (”Geminus”- Technology) APCVD (for P and B-doping)</td>
<td>p-type mc-Si</td>
<td>Process package, presented on EUPVSEC 2014 Exhibition</td>
<td></td>
</tr>
<tr>
<td>RCT</td>
<td>Germany</td>
<td>bifacial PERT BBr3 + POCl3</td>
<td>p-type mc-Si; cells &gt; 18%</td>
<td>laboratory/pilot results [xxxii]</td>
<td></td>
</tr>
<tr>
<td>Meyer Burger</td>
<td>Switzerland</td>
<td>HJ cells with smart wire (SWCT) interconnection technology</td>
<td>60 6&quot; cells with 327W (bifacial cells in monofacial module)</td>
<td>(technology provider) [xxxiii]</td>
<td></td>
</tr>
</tbody>
</table>
3. COO FOR MONO AND BIFACIAL TECHNOLOGIES

When an investor has to decide which cell and module technology to implement in a PV system, there are mainly two criteria that will guide this decision:

- bankability: track record of the technology and of the module manufacturers offering modules based on the considered technologies
- LCOE: the levelized cost of energy (USD/kWh)

The first point is a challenge for each technology that is entering the market. For bifacial PV technology - a part from the track record of the existing bifacial cell and module manufacturers and from the specific technology to be evaluated - the most important point is the question, how much bifacial gain can be reasonably expected for a given installation. As pointed out above (section 1), for ground mounted and flat-roof top PV systems between 10% and 30% bifacial gain can be expected for nPERT and HJ technologies that feature a bifaciality higher than 90%. More than 30% bifacial gain is possible in presence of very high (artificially increased) ground albedo, while less than 10% will be achieved in configurations that are not favorable for the application of bifacial PV (e.g. dark ground surface with very low albedo or for installations where the modules are mounted very close to the ground or roof-top).

The quantitative analysis of the second point - the LCOE - requires on the one hand a reliable forecast of the total amount of electricity produced during the useful lifetime of the PV system when assuming the implementation of the various technologies under consideration. On the other hand, complete information about the module and balance of system (BOS) cost is required together with the data about the cost of financing and for operation and maintenance. While for each specific case, taxes and potential feed-in tariffs would have to be included, in the present analysis, this point has not been included as the situation varies a lot from one country to another and is also in continuous evolution.

Fig. 5 summarizes the results of our calculations for the cost of ownership (CoO) for various module technologies currently in mass production together with the respective module efficiencies (expressed as Pmpp of 60 cells modules) that have been used as input for the LCOE calculations. These CoO calculations are based on an integrated 500 MWp/year cell and module factory located in a low-cost country in Asia.

Regarding the electricity generation, a utility scale ground mounted solar farm located in an area with a yearly GHI of 1800 kWh/m2 has been considered. Such a solar irradiation level is representative e.g. for the south of Spain and of the US as well as for large parts of India.

The module lifetime is assumed to be dependent mainly on the module technology and, as glass-backsheet is applicable to all module technologies, the useful system lifetime has been set to 25 years for all of them. In addition, for bifacial technologies, glass-glass modules with a useful lifetime that can be assumed to be around 35 years and a lower yearly degradation rate (0.2% instead of 0.4%), have been included in the comparison.

In order to evaluate the LCOE of various bifacial technologies under comparable conditions, the present considerations and calculations of the LCOE are based on a bifacial gain of 20% for
PERT and HJ (90% bifaciality), while for PERC - due to its lower bifaciality of around 70% - a bifacial gain of 15% has been assumed.

Figure 12: Summary of the results of CoO calculations for monofacial and bifacial technologies (01/2017)

The results of the LCOE calculations based on the above listed assumptions are summarized in Fig 12. The outcome of this analysis shows that high efficiency but high cost monofacial technologies such as the HIT and IBC technologies currently in mass-production at large manufacturers are not competitive in terms of LCOE in case of application in utility scale systems. The results also show clearly that the mainstream monofacial technologies (mc-Si and Cz-Si Al-BSF and Cz-Si PERC) can be considered as equivalent in terms of LCOE. Bifacaility with a reasonable module and system cost, as achievable with nPERT and PERC+, is the technological factor that results in a significant (around 14%) reduction of LCOE compared to monofacial standard technology. A further strong reduction of the LCOE of an additional 25% can be achieved by the use of glass-glass modules due to the huge increase of the cumulated produced electricity during the 10 years of additional system lifetime. Regarding hetero-junction (HJ) and interdigitated back contact (IBC) solar cells, innovative cell concepts with lower cost manufacturing processes are currently entering the market. With cell efficiencies of 22.5% to 23%, a module power of 320W to 330W can be achieved, while the module CoO is expected to be significantly lower compared to today's HIT & IBC technologies. HJ as well as IBC are bifacial technologies, accordingly, the respective LCOEs of their modern versions is expected to be significantly lower than today's HIT & IBC and slightly higher compared to PERC+ and BiSoN (nPERT). In addition, e.g. the company Solaround is developing a bifacial PERT solar cell technology based on Cz-Si wafers with an anticipated manufacturing cost that is expected to be lower compared to PERC+ while featuring a bifaciality of 95% or more.
Figure 13: Summary of the results of LCOE calculations (updated in 01/2017, for yearly GHI of 1800 kWh/m² and 25 years system lifetime) and system costs for the various technologies based on module CoO shown in Fig. 12.

One example for a large bifacial PV system is the 2.5 MWp solar “BiSoN-farm” that has been installed using bifacial glass-glass BiSoN (nPERT) modules from MegaCell at Hormiga in Chile. The module design has been optimized in order to guarantee 35 years of the modules also under the harsh desert climate conditions. This type of modules combined with a yearly GHI of around 2500 kWh/m² enable an LCOE of around 23 USD/MWh.

4. BISON/ATAMO TECHNOLOGY IN 2020 AND 2025

The time has come for new technologies to enter the conservative PV market. The PERC technology has already strongly penetrated the market with a production capacity of about 15GWp in 2016 and an expected capacity of 25GWp in 2017. Fig. 8 depicts shares of cell technologies of the PV market as a function of years taken from the technology road map (international technology roadmap for PV, ITRPV). The standard Al-BSF solar cell, which was dominant for decades, is getting more and more replaced by technologies which have a rear side passivation and can be made bifacial. PERC+ is now the newest trend for PERC producers to save material and gain in power by rear side illumination. In 2026 the market will be dominated by solar cells such as PERC, PERT, HJ and IBC cells that will be made bifacial and therefore lead to lowest LCOEs. In addition a small portion of tandem solar cells are prognosed that exceed a front side efficiency of 30% - such as e.g. Perowskites on IBC cells.
Figure 14: Shares of different solar cell technologies in the coming years.

AtaMo (Atacama Module) Chile’s Roadmap

Figure 15: Roadmap for AtaMo (BiSoN) until 2025

The roadmap was made from ISC for CORFO in 2016. The module sizes were scaled up to 72 cell modules for this study. The power and prices were estimated for the future to:

- BiSoN/AtaMo 72 cell module 2017: 342Wp / 0.33ct/Wp
- BiSoN/AtaMo 72 cell module 2020: 360Wp / 0.3ct/Wp
- BiSoN/AtaMo 72 cell module 2025: 420Wp / 0.25ct/Wp
5. **PREDICTION OF ENERGY YIELD BY ELECTRICAL AND OPTICAL MODELLING OF BIFACIAL MODULES**

In this section, the bifacial simulation model and tool (MoBiDiG = Modeling of Bifacial Distributed Gain) that has been developed at ISC Konstanz is introduced and the methods used to calculate the energy output of the here considered bifacial PV systems are presented together with the obtained results.

5.1 **Introduction**

ISC Konstanz has developed a model and related software tool for the modeling of the irradiance on front and rear side of a bifacial PV module. In combination with its electrical and thermal model, the tool is capable to calculate the gain in energy yield of a bifacial module compared to a monofacial reference. The optical model for the calculation of the rear side irradiance is based on the view factor approach (Figure 16), more details can be found in [xxxiv].

![Image](Figure 16: Geometrical considerations for the determination of the view factor between the shadow region $A_{sh}$ and the module rear surface $A_{M,r}$, inclined at the angle $\alpha$. [xxxiv])

5.2 **General Assumptions**

As explained in the first part of the present report, the nPERT (BiSoN) cell and module technology is considered to be the most promising one in terms of lowest LCOE for a scenario of a utility scale ground mounted PV system from 2020 to 2025.

Accordingly for the energy yield simulations, a nPERT module with the characteristics shown in Table 2 has been assumed. The properties of the front side of the monofacial reference module have been chosen as close as possible to the bifacial module and are shown in Table 3.
Table 2: *Bifacial module characteristics.*

<table>
<thead>
<tr>
<th>Bifacial module characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1990 mm</td>
</tr>
<tr>
<td>Width</td>
<td>990 mm</td>
</tr>
<tr>
<td>Number of cells</td>
<td>72</td>
</tr>
<tr>
<td>Average cell efficiency</td>
<td>20.5%</td>
</tr>
<tr>
<td>Pmpp per cell</td>
<td>5.01 W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I/V parameters at STC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bifaciality</td>
<td>90%</td>
</tr>
<tr>
<td>Pmpp_front</td>
<td>342.7 W</td>
</tr>
<tr>
<td>Umpp_front</td>
<td>38.5</td>
</tr>
<tr>
<td>Impp_front</td>
<td>8.9</td>
</tr>
<tr>
<td>Pmpp_rear</td>
<td>310.2</td>
</tr>
<tr>
<td>Umpp_rear</td>
<td>38.3</td>
</tr>
<tr>
<td>Impp_rear</td>
<td>8.1</td>
</tr>
<tr>
<td>Temp coefficient Pmpp</td>
<td>-0.41 %/°C</td>
</tr>
<tr>
<td>NOCT</td>
<td>45°C</td>
</tr>
</tbody>
</table>

Table 3: *Monofacial module characteristics.*

<table>
<thead>
<tr>
<th>Monofacial module characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1990 mm</td>
</tr>
<tr>
<td>Width</td>
<td>990 mm</td>
</tr>
<tr>
<td>Number of cells</td>
<td>72</td>
</tr>
<tr>
<td>Average cell efficiency</td>
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</tr>
<tr>
<td>Pmpp per cell</td>
<td>5.01 W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I/V parameters at STC</th>
<th></th>
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<tbody>
<tr>
<td>Pmpp_front</td>
<td>342.7 W</td>
</tr>
<tr>
<td>Umpp_front</td>
<td>38.5</td>
</tr>
<tr>
<td>Impp_front</td>
<td>8.9</td>
</tr>
<tr>
<td>Temp coefficient Pmpp</td>
<td>-0.41 %/°C</td>
</tr>
<tr>
<td>NOCT</td>
<td>45°C</td>
</tr>
</tbody>
</table>

The geographic location of the planned PV system will be in Chile nearby the town *Diego de Almagro* (Provincia di Chañaral, Regione di Atacama) at 25.87 S, -70.33 W at an altitude of around 900m above sea level.
The following meteo data (hourly resolved - see attached file):

- ambient temperature,
- wind speed,
- global horizontal irradiance,
- direct normal irradiance and
- diffuse horizontal irradiance

has been provided by DLR and was used by ISC for calculation of the predicted electrical performance of the monofacial reference system and for the bifacial system. Based on measurements results that are at ISC Konstanz' disposal and that have been performed in another location (see Fig. 17) in the Atacama desert but with a surface morphology that is very similar to the situation on the planned installation site (see Fig 18), the ground albedo has been assumed to be 0.23.

**Figure 17**: Location of radiometer for the albedo measurement in the Atacama Desert.

**Figure 18**: Location of the planned PV system (satellite picture from Google earth).
5.3 Methods

The bifacial-simulation tool MoBiDiG is designed to accurately predict the percentage increase in energy yield (kWh/kWp) of a bifacial PV module compared to a monofacial reference module (“bifacial gain”) for each given time step (based on hourly values of irradiance, ambient temperature and wind speed), taking into account the optical shading effects of modules and module rows adjacent to the considered bifacial module. In order to obtain absolute values of \( U_{mpp} \) and \( I_{mpp} \) of a complete PV system, the commercial software PVsyst (v 6.5.3) has been used to calculate the hourly values of \( U_{mpp} \) and \( I_{mpp} \) for the complete monofacial reference system. One limitation of the current version of the software is that it is not taking into account the effect of neighboring modules rows blocking direct light incident on the rear side of the bifacial module. This effect is occurring only in summer just after sunrise and just before sunset respectively. While - due to the low absolute energy production in these times of the day - these data points do not contribute in a significantly to the energy yield, they give an incorrect picture of the instantaneous (hourly) values of the bifacial gain. Consequently, in order to take correctly into account of the blocking effect, for producing the datasets attached to the present study, single data points affected by this effect have been filtered out and have been corrected manually.

The bifacial gain for a single bifacial module depends on its position within the module field. Figure 19 (taken from [xl]) shows an example of the distribution of the bifacial gain within a small PV array with 5 rows and 11 modules in each row. As it can be seen, due to the higher fraction of shadowed ground in the surroundings of the module, the central module shows a significantly lower bifacial gain (27.72%) compared to the corner (31.41%/31.2%) or edge (31.13%) modules. For a stand-alone module installed under the same conditions (meteo, height, albedo and tilt), a bifacial gain of 34% has been calculated.

![Figure 19: Bifacial gain of all modules in a field in El Gouna with alpha = 0.5. The module height over the ground is 1 m and the modules are mounted with a fixed tilt of 25° and a row to row distance of 2.5 m](image-url)

Figure 19: Bifacial gain of all modules in a field in El Gouna with alpha = 0.5. The module height over the ground is 1 m and the modules are mounted with a fixed tilt of 25° and a row to row distance of 2.5 m
The study performed in [xxxiv] shows that - in terms of view of bifacial gain - every module that has at least 3 neighboring modules and at least 2 neighboring module rows (1 on the front and at the rear respectively) between the considered module and the edge of the array, can be considered as "central" modules featuring the lowest bifacial gain amongst all modules within the module field. Accordingly, when considering PV arrays with a nominal capacity of 1 MW or more, as done in the present study, the case of the "central" PV module is representative for more than 90% of all modules in the array. This being said, in the present simulations, it has been assumed that all modules show the same electrical performance like a "central module". As a result, this simplification leaves a slight upside potential for the actual bifacial gain of the real system where the edge modules will contribute to increase the bifacial gain compared to the central modules.

5.4 Results for fixed tilt bifacial system

Using the simulation tool, an optimization in terms of bifacial gain has been performed while maintaining the module height and row-to-row distance within certain limits; as a result, the following configuration has been chosen for the fixed tilt bifacial system:

- 3 modules (72 cells) in landscape format one above the other within each mounting rack
- row pitch: 9m
- module tilt: 25°
- azimuth: 0° (module front side is north oriented)
- height (distance from lower side of lowest module and the ground): 1 m
- total number of modules 3640
- nominal array power at STC: 1247 kW (without rear side contribution)

The monofacial reference system has been designed in PVsyst according to the parameters provided by DLR:

- 6 modules (72 cells) in landscape format one above the other within each mounting rack
- row pitch: 8.5m
- module tilt: 20°
- azimuth: 0° (module front side is north oriented)
- total number of modules 3640
- nominal array power at STC: 1247 kW
- further details: see ANNEX (PVsyst simulation report)
Based on all the above listed assumptions and input data, the tool MoBiDiG has been used to calculate the hourly values of the bifacial gains $BG_{Umpp}$ and $BG_{Impp}$:

$$BG_{Umpp} = \frac{Umpp_b}{Umpp_m}$$

$$BG_{Impp} = \frac{Impp_b}{Impp_m}$$

with $Umpp_b$ being the Umpp of the bifacial module and $Impp_b$ the Impp of the bifacial module at one given time step (and $m$ for the monofacial module respectively).

The mpp-values (DC side of the inverter) for the voltage and current of the complete monofacial 1.247 MW system ($U_{array \_m}$ and $I_{array \_m}$) have been calculated using PVSyst. From these data, the mpp-values (DC) for the voltage and current of the complete bifacial PV system ($U_{array \_b}$ and $I_{array \_b}$) have been calculated as follows:

$$U_{array \_b} = BG_{Umpp} \times U_{array \_m}$$

$$I_{array \_b} = BG_{Impp} \times I_{array \_m}$$

Figure 20 and Figure 21 show an overview of the dataset for the bifacial PV system. The complete dataset (hourly resolved values for $U_{array \_b}$ and $I_{array \_b}$, and $U_{array \_m}$ and $I_{array \_m}$) is provided together with the present report in electronic format. An overview of the simulation results is shown in fig y,x,z,q, (graphs from jmp of $U_{array \_mono}$, $I_{array \_mono}$ and $U_{array \_bifi}$, $I_{Array_bifi}$). According to these results, the yearly energy yield (kWh/kWp) of the bifacial PV system is expected to be 11.8% higher than the considered monofacial reference system.

**Figure 20:** Yearly dataset of day time dependent values of current and voltage at mpp (DC) of the 1.247 MW bifacial array with fixed tilt.
Figure 21: Yearly dataset of day time dependent values of \( P_{mpp} \) (DC) of the 1.247 MW bifacial monofacial and the 1.247 MW bifacial array - both with fixed tilt.

5.5 Assumptions for PV system with single axis tracker

Regarding the module characteristics, the same characteristics as used for the fixed tilt system (see Table 2 and Table 3) have been assumed for the modeling of the single axis tracking (SAT) scenario. The same is valid for the geographical location and the albedo of the ground surface.

For the present investigation, the so-called sun-belt tracker configuration (Figure 22) has been considered. The sun-belt tracker consists in a single axis tracking system with a horizontal, north-west oriented tracking axis. In terms of yearly energy yield, this simple tracking concept is mostly suited for PV systems located at latitudes close the equator.

Figure 22: Schematic drawing of a single axis tracker with horizontal, south-east oriented axis ("sunbelt tracker").
The following system configurations have been used for the calculation of the single axis PV system with mono- and bifacial modules:

**monofacial modules:**
- horizontal N-S oriented axis
- tracker spacing: 4.5m
- no backtracking, tracking amplitude: -60° to 60°
- Details: see ANNEX (PVsyst simulation report)
- total number of modules: 3640
- nominal array power at STC: 1247 kW

**bifacial modules:**
- same as monofacial

As in the fixed tilt scenario, the hourly values of $I_{m_{pp}}$ and $U_{m_{pp}}$ of the complete array (1.247 MW) with monofacial modules with single axis tracking have been calculated using PVsyst. In the following, using the bifacial simulation tool from ISC, the bifacial gains ($BG_{U_{m_{pp} sat}}$ and $BG_{I_{m_{pp} sat}}$) on module level have been calculated as follows:

$$BG_{U_{m_{pp} sat}} = \frac{U_{m_{pp} b_{sat}}}{U_{m_{pp} m_{sat}}}$$
$$BG_{I_{m_{pp} sat}} = \frac{I_{m_{pp} b_{sat}}}{I_{m_{pp} m_{sat}}}$$

With $U_{m_{pp} b_{sat}}$ and $I_{m_{pp} b_{sat}}$ being the current and voltage at mpp of the bifacial module with single axis tracking and $U_{m_{pp} m_{sat}}$ and $I_{m_{pp} m_{sat}}$ the respective values for the monofacial module.

The $U_{m_{pp}}$ and $I_{m_{pp}}$ of the bifacial PV system with SAT have been calculated from the above values as follows:

$$U_{array_{b_{sat}}} = BG_{U_{m_{pp} sat}} \times U_{m_{pp} m_{sat}}$$
$$I_{array_{b_{sat}}} = BG_{I_{m_{pp} sat}} \times I_{m_{pp} m_{sat}}$$

The complete dataset (hourly resolved values for $U_{array_{sat_{m}}} b_{sat}$ and $I_{array_{sat_{m}}} b_{sat}$) is provided together with the present report in electronic format. An overview of the simulation results is shown in fig 23 and fig 24.
Figure 23: Yearly dataset of day time dependent values of current and voltage at mpp (DC) of the 1.247 MW bifacial array with single axis tracking (SAT).

Figure 24: Yearly dataset of day time dependent values of Pmpp (DC) of the 1.247 MW bifacial monofacial and the 1.247 MW bifacial array - both with single axis tracking (SAT).
5.6 Summary of results

Table 4 summarizes the results of all simulations performed within the present study in terms of specific yearly energy yield on the DC side of the inverter.

Table 4 Overview of simulation results for specific energy yield of the various system configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>kWh/kWp (E at mpp)</th>
<th>gain vs. monofacial fixed tilt</th>
<th>gain vs bifacial fixed tilt</th>
<th>gain vs. monofacial SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>monofacial fixed tilt</td>
<td>2233</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>bifacial fixed tilt</td>
<td>2498</td>
<td>11.8%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>monofacial SAT</td>
<td>2806</td>
<td>25.6%</td>
<td>12%</td>
<td>-</td>
</tr>
<tr>
<td>bifi SAT</td>
<td>3230</td>
<td>44.6 %</td>
<td>29.3%</td>
<td>15.1%</td>
</tr>
</tbody>
</table>

5.7 Conclusions

As shown in section 1 with experimental data from literature (Figure 1), depending on albedo, installation configuration and technical performance (bifaciality) of the bifacial modules, 10% to 30% bifacial gain can be achieved as an average of longer time periods. Furthermore it has been shown how bifacial technologies are starting to enter the market (cell and module production as well as system installation) on a level that is demonstrating the increasing interest of the down-stream players. The technological concepts of the various, industrially relevant cell technologies have been reviewed and their updated CoO and LCOE has been indicated. Thereby, the bifacial nPERT-technology has been identified as the one with the best combination between cost (CoO & LCOE), technological risk and efficiency.

For the final part of this report (section 5), using ISC Konstanz software tool MoBiDiG for simulation of the energy yield of bifacial modules, the hourly resolved values for Umpp and Impp of a bifacial 1.247 MW system have been calculated for modules that are installed with fixed tilt as well as for single axis tracked bifacial modules. For both scenarios, an equivalent monofacial system has been simulated using PVSyst 6.5.3 and compared with the values obtained previously for the bifacial systems. As a result, using bifacial modules in the fixed tilt case will result in a 11.8% higher energy yield, while for the system with single axis tracking this gain is predicted to be 15.1%.
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ANNEXES

pdf-files:

1. PVsyst simulation report for fixed tilt monofacial system (fixed mono 1-247 MW)
2. PVsyst simulation report for monofacial system with single axis tracking (SAT mono 1-247 MW)

excel-files:

3. fixed tilt: hourly resolved data for a full year containing the meteo input data and the output data (in particular I_array and U_array) from PVsyst for the monofacial system and from ISC's tool for the bifacial module as well as the calculated values for I_array and U_array for the bifacial system
4. single axis tracking (SAT) : hourly resolved data for a full year containing the meteo input data and the output data (in particular I_array and U_array) from PVsyst for the monofacial SAT system and from ISC's tool for the bifacial SAT module as well as the calculated values for I_array and U_array for the bifacial system