Bifacial Photovoltaic Modules and Systems: Experience and Results from International Research and Pilot Applications

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Executive Summary

Bifacial photovoltaic cells and modules

Bifacial photovoltaic cells, modules, and systems are rapidly overtaking the market share of monofacial PV technologies. This is happening due to new cell designs that have replaced opaque, monolithic back surface foil contacts with isolated contacts, which allow light to reach the cell from the rear side. Minor adjustments to cell processing steps have resulted in bifacial solar cells with rear side efficiencies from >60% to over 90% of the front side efficiency. Bifacial cells now come in many varieties (e.g., PERC+, n-PERT, HIT, etc.) and many cell lines have converted to producing bifacial cells.

P-type solar cell limitations are driving the PV industry's attention toward high efficiency n-type solar cells, including n-PERT solar cells, which are promising for two reasons: (1) their process sequence calls for machinery that is generally compatible with current solar cell production lines; (2) the n-PERT cell concept permits very high bifaciality, up to 95%.

Today, busbarless heterojunction (HJT) cells fabricated in a pilot line on mass production equipment can reach efficiencies greater than 24%. With its high efficiency potential and lean manufacturing process flow, HJT cell technology is expected to gain greater global photovoltaic market share in the coming years. Even multijunction designs for bifacial cells are being considered. A multijunction bifacial cell based on a perovskite top cell and silicon HJT bottom cell appears promising.

Bifacial cells have valuable applications in both monofacial and bifacial modules. Placing bifacial cells in a monofacial package with white back encapsulant or a reflective backsheet results in a significant boost to frontside module rating and several companies are investigating this application. However, most bifacial cells end up in bifacial double-glass modules or bifacial modules with a transparent polymer backsheet. **Rating and safety standards are actively being updated to account for differences in the behavior and performance of these modules.** A new IEC Technical Specification IEC TS 60904-1-2 was released in 2019 that guides the measurement of the electrical characteristics of bifacial modules. Additional product certification requirements for bifacial PV modules are mainly related to the higher operating currents of these modules and the associated potential safety issues.

As bifacial modules have been deployed in the field, several bifacial-specific degradation issues have been discovered and are actively being researched. Light and elevated temperature induced degradation (LeTID) can specifically affect PERC cells if a stabilization process during cell manufacturing is not followed. The addition of isolated metal contacts on the rear side of bifacial cells may expedite hydrogen induced degradation processes. Potential induced degradation (PID) results from the migration of ions within the module package. When there is a potential gradient in the module, sodium ions from the glass can migrate to the cell surface and interfere with cell operation at stacking faults. A buildup of ions can also lead to surface passivation loss which results in degraded performance. Use of polyolefin encapsulants largely prevents PID. Double-glass bifacial modules using EVA encapsulant can be more susceptible to PID due to the increased availability of sodium ions from the glass.

Bifacial photovoltaic systems

Bifacial cell and module innovations have led to new optimized bifacial system designs. The reflectivity of the ground (albedo) is one the most important site characteristics influencing bifacial PV performance. Sites that experience significant snowfall typically benefit from bifacial PV because of the increased albedo during these periods. Bifacial PV performance advantage is expressed as "bifacial gain", which is the additional fraction of total energy that a bifacial PV system will produce compared with a monofacial system of the same orientation and size. Bifacial gain increases with albedo, diffuse fraction, array height, row spacing, and space between modules. The light received on the rear side of the array is much more nonuniform than light hitting the front. This nonuniformity leads to some electrical mismatch within each module and can also affect strings of modules depending on their configuration. Another characteristic of bifacial arrays is that they operate at higher DC current levels than monofacial arrays; therefore, system designers may need to adjust calculations for wire, fuse, and inverter sizing. International electrical design and safety codes are actively being reviewed to account for bifacial PV technologies.

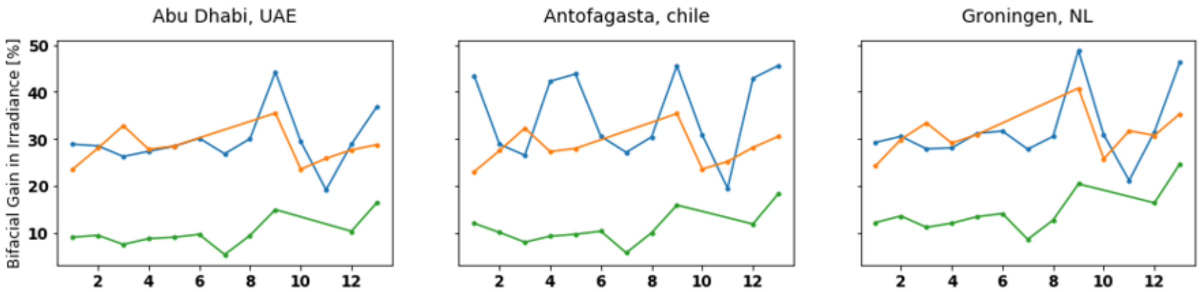
Bifacial systems come in many forms. Many are nearly identical to monofacial designs such as fixed-tilt and single-axis trackers. Performance gains of bifacial over monofacial for these system designs vary depending on site conditions and system design details. Ground reflectance or albedo and the bifaciality of the modules are generally the most important factors. Bifacial modules on single-axis tracker fields over typical natural ground covers (albedo = 0.2 to 0.3) generally see bifacial gains less than 10%. These values increase significantly when the ground is covered with snow. Other system designs, such as east-west vertically orientated arrays, are especially suited to bifacial PV technologies and offer some unique advantages such as a wider period of power generation that better matches typical load profiles, very low soiling rates, and such designs leave much of the land available for other uses, such as livestock. In addition, vertical bifacial PV has performance advantage at high latitudes due to the large variation in solar azimuth angle during the summer. In all cases, bifacial modules near the edge of rows will receive an extra amount of light due to the fact that there are fewer nearby modules and structures that shade the nearby ground. Such "edge effects" can be especially important for smaller arrays or arrays that are separated from one another. For example, elevated parking structures, fixed-tilt arrays on flat white roofs, and vertical sound barriers all benefit from the additional energy available near the edge of the array. Despite this benefit, economies of scale are also important. A recently published global analysis of bifacial PV economics determined that **bifacial PV installed on single-axis trackers resulted in the lowest levelized cost of electricity for the vast majority of potential PV sites on the planet** (93% of the Earth's land area)[1].

Surveys, comparisons, and test sites

A survey of field performance measurements from 27 different bifacial PV test systems compared bifacial gains with an array of design and site parameters and found that none of the parameters alone correlated well with the bifacial gain. A major limitation of small bifacial research systems is that their performance is dominated by edge effects. Therefore, one should not expect the same performance measured on a small system when planning for a larger system. Instead, comprehensive performance models are required to understand these relationships. These models differ primarily in how they calculate the amount of light that reaches the rear side of the array. There are two main types of bifacial models: (1) models based on view factors and (2) models that use ray-tracing. View factor models are less numerically expensive and generally assume infinitely long rows due to their two-dimensional formulations. As such view factor models are unable to represent detailed geometries. For detailed evaluations, ray-tracing models are recommended despite the computational challenges.

[1] C. D. Rodríguez-Gallegos et al., "Global techno-economic performance of bifacial and tracking PV systems," Joule, vol. 4, pp. 1–28, 2020.

A bifacial PV modelling comparison was organized to evaluate the state of the art of bifacial PV performance models. Four hypothetical system designs and two designs based on field measurements were defined and the necessary input parameters and weather files were provided to volunteers from 13 different research and commercial entities, each with their own bifacial PV performance model. These models are described in detail in this report. The comparison showed that the current bifacial models result in a range of results, with some models being unable to simulate all of the scenarios. **The resulting predicted bifacial gains varied by as much as a factor of two.** This exercise demonstrated the value of defining standard test cases to verify and validate bifacial performance models.



Modelled annual mean bifacial gain values (rear / front irradiance) for three different climates. System design 1 (blue) is fixed tilt equator facing, system design 2 (orange) is fixed tilt west facing, and system design 3 (green) is single-axis tracking. The x-axis denotes the number of the model. For any given climate or system design, predicted bifacial gains vary by up to a factor of two between the models.

The last section of this report provides a **summary of eleven bifacial field test sites around the world along with examples of field results.** Many of these sites include a variety of bifacial test arrays with different orientations, designs, and site conditions. Many test labs are experimenting with enhancing albedo using white rocks or reflective cloths. These tests have been instrumental in validating performance models and better understanding the important role of albedo in bifacial performance. Measured bifacial gains from fixed tilt sites from sites in the US and France demonstrate how bifacial gains vary with season due to the changing sun path, with the highest gains in the summer when the solar elevation reaches it maximum. In the winter, the lower solar elevation angles result in more of the ground being covered in shadows and less light reaches the rear side of the array.