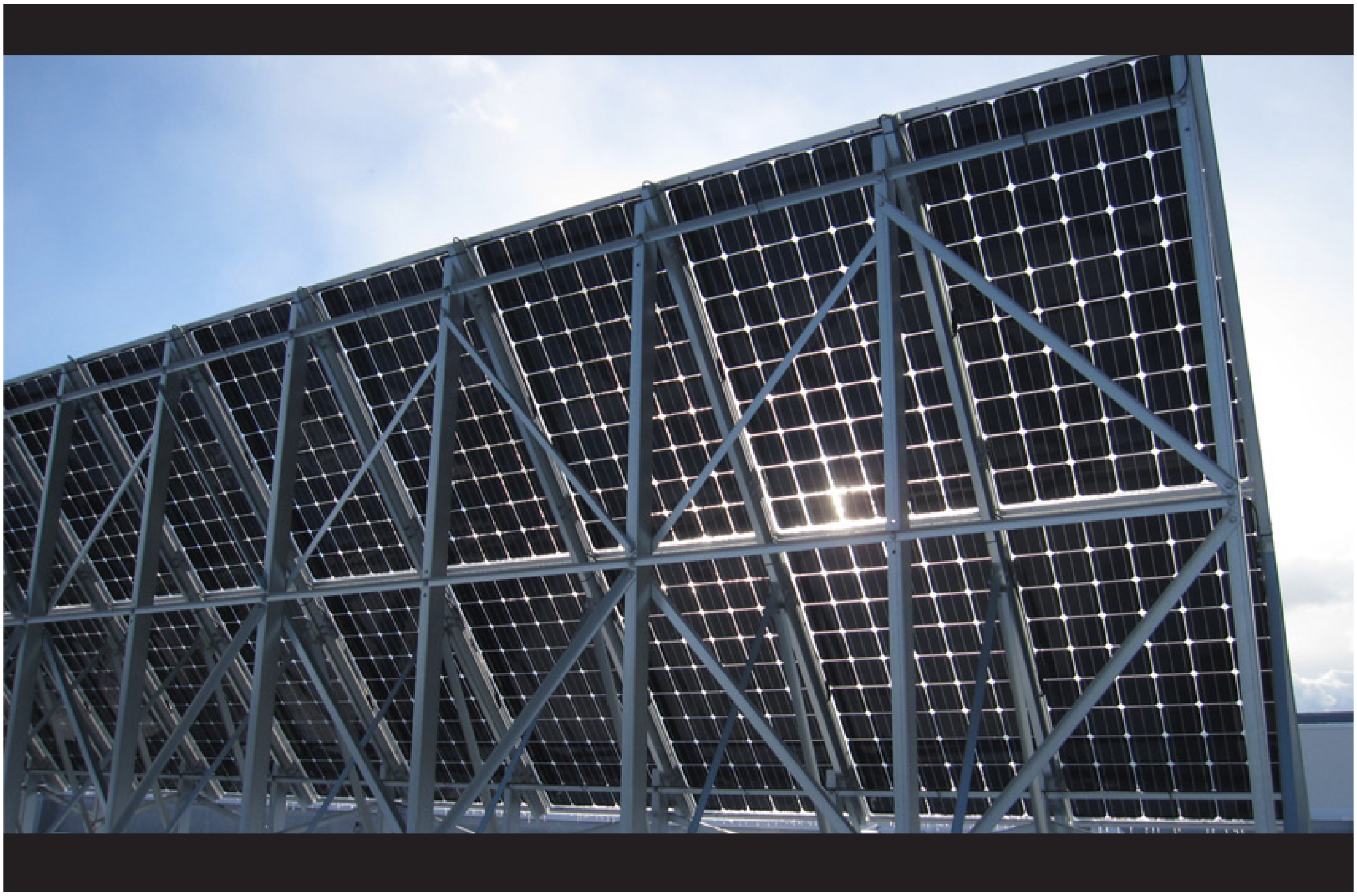
ELECTRIC POWER
RESEARCH INSTITUTE

BIFACIAL SOLAR PHOTOVOLTAIC MODULES

Program on Technology Innovation



September 2016

Executive Summary

The on-going aim to reduce the Levelized Cost of Electricity (LCOE) of photovoltaics (PV) can be achieved by: (1) reducing a plant's lifetime cost, primarily its upfront capital cost; and (2) increasing a system's lifetime generated electricity. Reduction in upfront capital cost has historically been driven by economies of manufacturing scale, improvement in manufacturing technology and processes, reduction in material cost and usage, and increases in device efficiency. The solar industry continues to pursue these avenues to improve the cost competitiveness of PV systems. Meanwhile, LCOE reductions are also being achieved through measures that increase system performance and/or energy yield, such as those which reduce module degradation rates, increase light capture via module coatings, or enhance cell and module architectures.

Bifacial modules represent a promising technology for increasing a PV system's lifetime generated electricity. Their core innovation is the ability to capture and utilize light from both sides of the module.[1] As with today's common monofacial modules, bifacial technology, depicted in Figure 1, converts sunlight to electricity that shines directly on the frontside of the module; but it also harvests sunlight, reflected from the ground, a rooftop surface, or neighboring PV modules, that shines on the rearside of the module. As a result, overall power generation can be boosted by as much as 50% in highly-controlled test conditions compared to monofacial modules.

Real world testing and demonstration sites are being established to better understand short- and long-term energy gains. Initial field testing suggests that a more moderate energy boost of 5–30% can be achieved depending on site conditions. Beyond measuring energy yield, monitoring and analysis efforts are also examining the extent to which glass-glass bifacial modules may also benefit from lower degradation rates, lower impact from potential induced degradation, and greater fire protection.

Bifacial technology has been researched since the mid-1980s, and early applications of the technology have been documented since the mid-1990s. But over the ensuing decades, interest in commercializing bifacial modules has ebbed and flowed. To achieve more widespread use and greater market adoption of the technology, stakeholders will likely need to:

Figure 1. Example illustration of a bifacial system
Source: Nikkei BP (Asahikawa Hokuto Solar Power Plant)

Note: Picture taken from the rearside of an array of modules

Table of Contents

This white paper was prepared by Michael Bolen, Nadav Enbar, and Luis Cerezo of the Electric Power Research Institute.

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[1] The majority of today's bifacial modules have a glass-glass configuration, in which the embedded solar cells are sandwiched between two pieces of glass. An alternative approach involves a glass-backsheet configuration, in which the backsheet is made transparent. (In conventional monofacial PV modules, the backsheets are typical dyed white or black.)

- Develop a standardized approach for rating a bifacial module's nameplate power;
- Devise a method for accurately predicting and modeling real-world energy gains;
- Address key manufacturing challenges—stemming from the use of non-standard manufacturing equipment, materials, and processes—that result in higher $/W cell and module costs; and
- Garner bankability for the modules themselves, as well as the non-standard balance of plant equipment (e.g., module mounting hardware) and/or designs associated with bifacial PV systems to optimize power output (e.g., racking choices, row spacing or orientation).

Technology Overview

Bifacial PV modules offer enhanced power output of 5–50% over conventional panels due to their ability to harvest light reflected onto their backside.[2] The backside light can emanate from a variety of sources, such as reflection from the ground or from a neighboring row of PV modules. The ratio of light reflected from these various sources compared to incoming irradiance is called "albedo." Figure 2 shows albedo ranges across a variety of surfaces, where 0% equates to no reflected light, and 100% represents a perfect reflector.[3] The more light that shines onto the backside of a bifacial module (i.e., higher albedo) the more power that is generated.

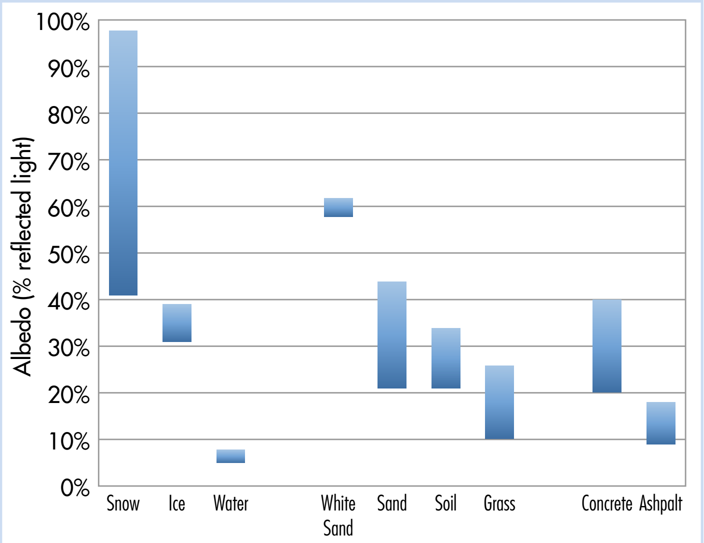

Figure 2. Albedo ranges for a variety of surfaces
Sources: Helmholtz Alfred-Wegener Institut and the National Renewable Energy Laboratory (NREL)

The solar industry's interest in bifacials—which spans over 30 years—emanates from the technology's potential to increase module power output at lower manufacturing cost. Historically, the largest cost component of a monofacial crystalline silicon (c-Si) module, the incumbent commercial solar technology, has been associated with the cell itself. Until recently, the polysilicon feedstock, wafering, and cell production comprised approximately two-thirds of a module's overall cost. Today, industry efforts have reduced cell costs to nearly 50% of overall module costs. To further enhance the cost competitiveness of PV, manufacturers are now looking for ways to increase module power density, reduce non-cell related module costs, and increase module lifetime energy production. Bifacial modules show promise to address each of these goals. Cell and module manufacturers are positioned to internally address the first two aims, but the third, lifetime energy quantification, will require extensive field testing and analysis by both public and private stakeholders.

The earliest well-documented installation of bifacial modules was sited in Zurich, Switzerland along the A1 motorway in 1997. The

Figure 3. One of the first commercial applications of bifacial PV modules: noise barriers along roadways in Switzerland
Source: TNC Consulting AG

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[2] The wide range in the observed increase in power output is due to a variety of factors including lab vs. field setting, cell type, system design, ground surface material and its albedo effect, shading, etc.

[3] Albedo is not wavelength-specific. It is based solely on cumulative irradiance (i.e., $W \cdot m^{-2}$) across the entire solar spectrum. For instance, white surfaces reflect all colors of light equally well and give them a higher albedo than, say, grass that predominantly reflects green light.

10-kW array involved vertically oriented modules that produced power and also served as noise barriers. Similar installations were deployed over the next decade along additional Swiss and German motorways and train tracks (see Figure 3). In 2003, Hitachi started manufacturing bifacial modules at the rate of 6 MW per year. Soon after, SunPower and Sanyo, among others, began producing their own bifacial cell and module lines. As discussed further below, manufacturing and product testing activities in the space have surged particularly over the last 5–7 years.

Despite the many known and purported field tests of bifacial modules, little performance data has been published within the broader solar industry. The scarcity of published findings is a likely contributing factor behind the intermittent interest in the technology. The current renaissance in bifacial research is better documenting and broadly disseminating results.

The market share of bifacial modules today is insignificant, owing to the limited amount of commercially available products. Only a small number of manufacturers are currently producing bifacials modules or developing them for future commercial fabrication. Overcoming the following key challenges will go a long way towards enabling market share growth:

- *Manufacturing Cost:* Non-standard manufacturing equipment, materials, and processes, along with low financial returns on manufacturing asset investments, stand in the way of mass produced bifacial modules at lower $/W costs.
- *Standardized rating of nameplate power:* No standard method is available to rate bifacial cell and module power using indoor measurements.
- *Field tests for bankability and design optimization:* Bifacial modules may benefit from innovative plant designs that enhance rearside light capture; however, pursuing non-standard designs and/or balance of plant equipment comes with risk.
- *Energy yield predictions:* Module performance is installation-dependent which is creating uncertainty in predicting energy yield.

Basic Science

Cells

The opportunity for bifacial cells depends on both its technical and economic upsides. Today's crystalline silicon and thin-film monofacial PV cells commonly use a fully metallized backside. This feature involves a moderately thick metal contact for reduced series resistance and is relatively inexpensive to produce. By contrast, bifacial cells incorporate selective-area metallization schemes to allow light between the metallized areas. The lower amount of metal changes how cell performance is optimized, potentially requiring tighter (i.e., more expensive) specs on the silicon and thin-film material used and also increasing series resistance concerns. Furthermore, bifacial cells may employ different metals, such as copper and nickel, and/or deposition methods, such as plating or inkjet printing, which, in part, requires different equipment and entails a potentially more complex manufacturing process. Consequently, the backside metal represents a non-trivial impediment to manufacturing bifacial cells with high performance and low cost. This added complexity and cost needs to be offset by the performance gain from increased light collection.

Specifically for monofacial crystalline silicon cells, the backside metal is typically composed of aluminum, which reflects approximately 90% of the light that reaches it. A selectively metallized bifacial cells needs to employ other means for effectively trapping light in the silicon, thus allowing for the greatest chance of turning a photon into an electron.[4]

Meanwhile, thin-film PV technologies need to overcome fundamental materials science issues before they can be adapted to bifacial applications. Cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) absorbers lack a p-type contact material that is sufficiently transparent and conductive while being low cost enough to manufacture.[5] As a result, opaque metal contacts will likely be used on the p-type side of thin-film cells for the foreseeable future.

A zoo of silicon bifacial cell architectures have been developed and tested in research labs with fitting acronyms, including BiSoN, ZEBRA, and PANDA.[6] Each cell design aspires to lower the $/W

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[4] The backside metal is more important for silicon than thin film materials. Silicon is an indirect bandgap material, which, in practical terms, means it is less efficient at capturing longer light wavelengths and benefits from a second chance at photon absorption. By contrast, thin films are direct bandgap materials and are efficient at capturing photons with energies at and above the semiconductor's bandgap energy.

[5] "N-type" and "P-type" describe an abundance or deficiency, respectively, of available electrons in a semiconductor. The wafers, as a result, have different chemical potentials. PV cells exploit this difference to assist the collection of photogenerated electrons.

[6] BiSoN = Bi-facial Solar cell on N-type silicon; ZEBRA uses stripes of n-type and p-type doping on the cell's backside; PANDA was a project code-name for the academic and corporate partnership that developed the cell.

costs associated with cell production. Costs can be lowered through reduced manufacturing steps and complexity, as well as avoided use of expensive (sometimes custom) manufacturing equipment and/or expensive bill-of-material items. These architectures seek to balance increased power output with cell manufacturing cost by, for example, pursuing cost competitive ways to selectively metallizing the backside and use purer input materials.

To date, the cell architecture that has garnered the greatest adoption uses a “heterojunction” approach.[7] Most commonly, the heterojunctions are formed by depositing layers of amorphous silicon onto the frontside and backside of a mono-crystalline silicon wafer. Then a transparent conducting layer is uniformly deposited, followed by metal contact deposition on selective areas of the cell. This cell architecture is the premise behind Panasonic’s commercially-available “Heterojunction with Intrinsic Thin layer” (HIT) cell technology and bifacial modules. Figure 4 provides a side-by-side comparison of the heterojunction cell architecture and the standard silicon monofacial cell that uses an Aluminum Back Surface Field (Al-BSF) architecture.

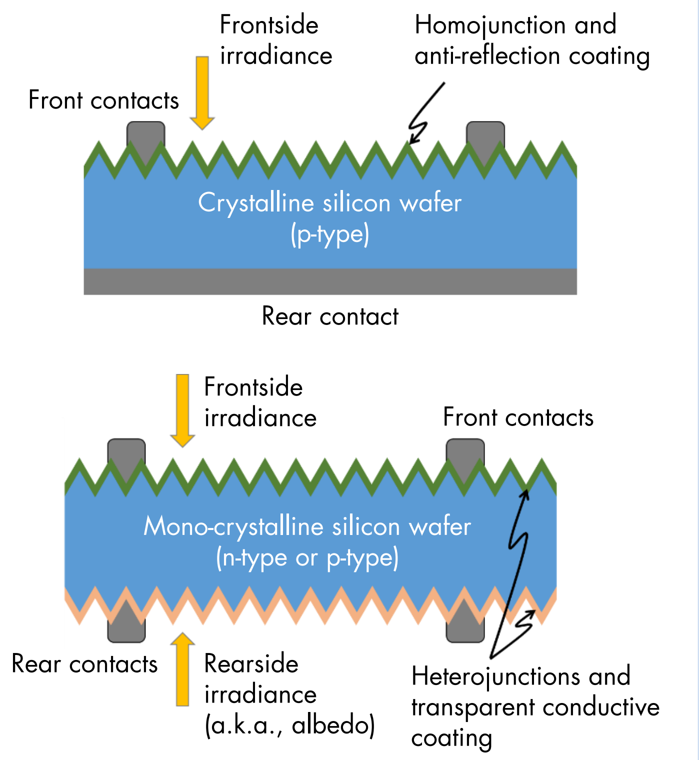

Figure 4. Industry standard crystalline silicon Al-BSF cell (left) and bifacial hetereojunction cell (right)
Source: EPRI

Fabrication of bifacial cells may require 2 to 5 extra steps compared to monofacial solar cells designs, depending on the architecture and type of wafer (n-type or p-type) used. These additional steps add manufacturing cost that likely need to be offset by higher nameplate power to make bifacials market competitive.

Modules

The working principle of a bifacial module is similar to that of a monofacial one. In a monofacial module, light enters through the frontside glass (i.e., the glass facing the sun), is absorbed by the cell, and converted into electrons that are used for electrical power. In bifacial modules, the same frontside light collection process happens and, in addition, light is absorbed from the backside of the module. This backside light can come from a variety of sources, such as reflection from the ground or a neighboring row of PV modules. The additional light generates more electrons in the cells which primarily increases the current of the module. The voltage of the cell also increases slightly due to its logarithmic proportional relationship to current.

Most commonly, bifacial modules have a glass-glass configuration. There are multiple reasons why this is beneficial from a near- and long-term energy production standpoint:

- Glass is less permeable to water and moisture ingress than other materials such as polymers. Lower permeability and lower overall steady-state water content may reduce metal corrosion, which is especially important for busbars[8], and may, in turn, reduce the annual degradation rate.
- Glass is (currently) less expensive than commonly used brand-name polymer backsheets, such as Tedlar.
- Placing the cells between two rigid surfaces reduces their induced stress from module flexure (e.g., during handling, installation,

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[7] Most commercially-available silicon cell architectures, such as those that integrate backside contacts (Al-BSF) or passivate emitter rear contacts (PERC), form an electronic junction by intentionally adding elemental impurities into the silicon. Both sides of the junction are crystalline silicon, which is called a “homojunction”. A “heterojunction” is formed by bringing materials together with different bandgaps, such as crystalline silicon and amorphous silicon.

[8] The busbar in a PV module is the strip of tin-dipped copper that carries electricity between cells. The maximum amount of direct current that can be safely carried is determined by the size of the busbar. Water ingress provides a pathway for galvanic corrosion between the multiple metals used in the module, such as tin, lead, silver, and copper.

wind or snow loading), thereby lowering cell damage and concomitant power losses.

- A limited number of racking clips helps reduce the potential induced degradation inflicted on a bifacial module compared to others framed with aluminum, which are common to today's conventional crystalline silicon modules.

Alternatively, it is possible to create a bifacial glass-backsheet module. Backsheets are usually dyed white or black (the cheapest come white), but can be made transparent by, among other things, excluding the dye during the manufacturing process. Importantly, the dye also provides chemical stability against ultraviolet light. Transparent backsheets need to overcome this potential durability limitation. Further, transparent backsheets can cost 20%+ more than glass.[9] Although relatively uncommon to date, suppliers are developing more rugged and robust clear backsheets based on evolving materials and patterning techniques that are intended to lower costs and increase their appeal.

Nameplate Rating

The industry currently lacks a method of rating nameplate power for bifacial modules. Two pressing issues are how to measure module power and how much bifacial power gain to assign to the nameplate. The industry standard method of measuring power shines a normally-incident, highly-calibrated flash of light onto the front surface of a module. Only the light striking the front matters since, for monofacial modules, the backsheet is opaque. Bifacial modules complicate the measurement since surfaces behind the module now make a difference (and not all test chambers are the same) and a single front side flash does not credit the rearside power boost. Under laboratory-controlled conditions, a bifacial module may have a 50% power boost, but in the field, it may only be 3–5% due to plant-specific factors, discussed below.

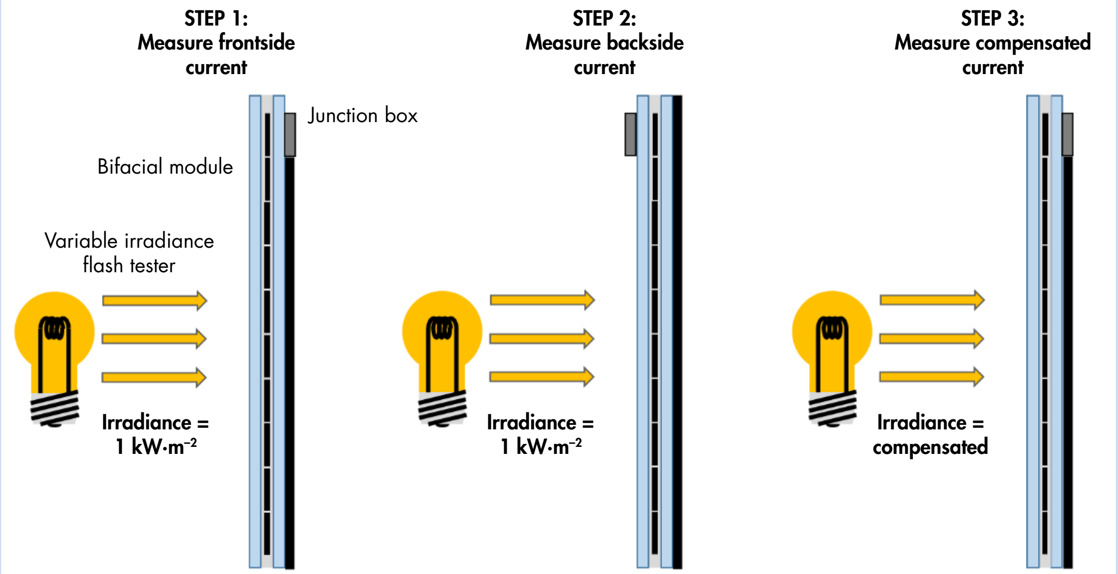

Figure 5. Example proposed method for measuring the nameplate rating of bifacial modules
Source: EPRI

The International Electrotechnial Commission (IEC) is developing a new technical specification, IEC 60904-1-2, which aims to address the measurement method and nameplate rating challenges. As of this writing, there is no clear pathway forward; however, one method being discussed involves three measurement steps (versus one step for monofacial modules) as shown in Figure 5. First, the frontside current, I_{front}, is ascertained by flash testing at the usual standard test condition of 1 $kW{\cdot}m^{-2}$ and with a black covering directly on the back of the module. Second, the backside current, I_{back}, is obtained at the same 1 $kW{\cdot}m^{-2}$ irradiance and a black covering on the frontside. Third, a "reflectivity compensated" current, I_{comp}, is measured by varying irradiance until $I_{comp} = I_{front} + 0.2{\cdot}I_{back}$. The 0.2 coefficient represents a middle ground estimate for how much additional power a bifacial module may produce in the field. The compensated irradiance could be used to measure bifacial modules in a single flash test, similar to the one-step monofacial measurement.

Debate is ongoing as to what factor (or factors) should be reported on a module datasheet. Of utmost concern is how to report nameplate power. Some module manufacturers' datasheets report nameplate power across 4 different flash conditions: frontside power-only,

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[9] P. Grunow. "Bifacial Modules – Promises and Challenges." Photovoltaik-Institut Berlin, Bifacial PV Workshop, 2012.

and backside gain coefficients of 0.1, 0.2, and 0.3. This complicates bifacial pricing and comparison with monofacial modules on a $/W basis. For instance, Panasonic's "HIT Double" module promotes a power density of up to 207.9 W·m^{-2}, which, under standard irradiance test conditions of 1000 W·m^{-2}, implies an efficiency of 20.8%. However, digging deeper into the product datasheet reveals that the 207.9 W·m^{-2} value includes a 30% backside power boost. Under only frontside illumination the module produces a more modest 160.7 W·m^{-2}.

Resolving the nameplate rating issue is important for furthering the market adoption of bifacial modules. Stopgap measures such as using the terms "equivalent efficiency" or "equivalent power" are currently being used in attempts to compare bifacials with monofacial modules (a.k.a., the "reflectivity compensated" method from the IEC). Monofacial modules have a single price, regardless of installation location, and are often compared on a $/W basis. This pricing and comparison construct is difficult to use with bifacial modules since plant specific factors play a large role in power production.

There are two simplistic extremes that highlight the conundrum of using a single price for bifacial modules. A manufacturer could include the upper end rearside power boost as nameplate, which would enable the lowest $/W price. If field performance is worse than rated, there may be performance guarantee contracts and/or underperformance warranty concerns. Alternatively, bifacial modules could be rated at the 1-sun frontside nameplate, which would carry the highest $/W price. This may make bifacials appear less price competitive to monofacial modules and, furthermore, the manufacturer would not be credited for rearside power gains generated in the field. Finding a balance to the rating and pricing conundrum is important for enabling the technology's market growth.

Plants

The energy gain from a bifacial module over a monofacial module is due to the additional albedo collection on the rear side of the module. The formula that governs the additional rear collection power is:

$$\text{Rear collection} \propto (1 - \cos(180^\circ - \alpha)) \cdot \text{albedo} \cdot \text{GHI},$$

where α is the module's tilt angle. Calculating the overall energy boost requires integrating power over time. The simple formula belies the fact that, in practice, energy gain depends on a number of complicated installation-specific factors.

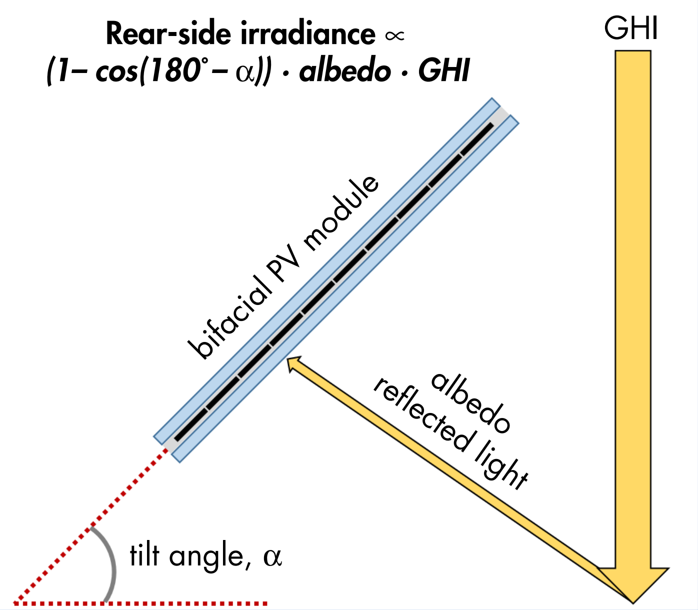

Figure 6. Rear collection power gain of a bifacial PV module
Source: EPRI

For example, the installation surface has a large effect on albedo. Highly reflective white surfaces, such as snow, white EPDM (ethylene propylene diene monomer) synthetic rubber membranes on building rooftops, and white sand deserts such as those in New Mexico or the Atacama in Chile, have the highest albedos. Meanwhile, white surfaces reflect light of all color, but colored surfaces (e.g., green grass) reflect light preferentially, which affects light absorption. Also, cells do not collect nor uniformly convert all wavelengths of light into electrons equally well, which impacts power production.

Equipment and plant design have different ramifications on plant production as well. Modules can have different internal cell spacing, allowing different amounts of light to pass through them; wider cell spacing means greater light transmittance. The installation height of the module can likewise affect output; those that are higher off the ground capture more ground-reflected light. Placing the modules too close to the ground creates self-shading that reduces the available albedo light reflected to the backside.[10] In addition, the manner in which the module is secured to the racking can influence losses from shading. Glass-glass modules do not have an aluminum frame for rigidity; instead, they rely on four (or more) clamps around the module's perimeter to secure them into place, which reduces shading.

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[10] S. Sciara, et. al., *Characterizing Electrical Output of Bifacial PV Modules by Altering Reflective Materials*. Western Carolina University, March 2016.

Related, a plant's tracking method, fixed-tilt versus single-axis, can affect how shadows are cast throughout the day and, in turn, impact backside irradiance collection. For example, a fixed-tilt system's more open backside design may create less shading than a common single-axis tracking design that incorporates a drive shaft plus racking behind the modules. Furthermore, the way in which shadows change throughout the day affects power output. The albedo for each module's backside is unlikely to be constant throughout a season, day, or even hour. Non-uniform illumination across the backside of a single and/or string of modules may prevent the realization of expected power gain.

How individual modules are oriented within an array, spaced, and wired may also impact power output. Output current, which is where most bifacial gain happens, is limited by the worst performing module connected in series (up to the point where the bypass diode turns on). Bifacial modules still rely on the same bypass diode scheme used in monofacial modules. Orienting the modules in a landscape versus portrait mode provides an extra lever (and degree of complexity) for controlling how shading impacts bypass diode behavior. The distance between modules and reflectors strongly influences the output of bifacial PV modules. The available albedo light that hits the back of the module is directly related to the height and tilt of the module installed over the surface. There is a complex relationship between costs and potential energy gains from varying ground coverage ratio.

Due to the various factors affecting the energy yield of a bifacial PV module, the end-use of the module compared to a common monofacial module cannot be easily quantified. Higher gains are possible if the installation conditions are optimized for a particular location. One of the major challenges with bifacial plants is predicting and modeling the energy output. Work is on-going within the industry to develop a robust modeling package towards this end.

Applications and Potential Impact

Conventionally configured to exploit albedo-derived photon collection advantages, bifacial modules can be used in traditional power plant applications (usually at the commercial- or utility-scale), as illustrated in Figure 7. They can also be employed as noise barriers along highways in fence integrated PV systems, incorporated into building architectures, paired with solar concentrators, and utilized as multi-functional sun shading elements (e.g., awnings, greenhouses, canopies, carports, etc.).

Figure 7. Bifacial PV on white reflective rooftop
Source: Prism Solar 5th PVPMC Santa Clara CA 2016

PV Power Plants

The use of bifacial modules for terrestrial albedo collection applications is advantageous for both sunny and cloudy climates since the scattered light from the sky and ground can be collected. Bifacial modules tend to benefit from regions with a higher percentage of diffuse light, as compared to direct light (e.g., cloudy places). The rearside power gain has shown to increase in such conditions.[11] With albedo collection, a power gain of ~20% has been reported without special installation configuration.[12] Additional details on demonstration and commercial plants is described further below.

Use of trackers in combination with bifacial PV modules is being pilot tested to evaluate tracking strategies and potential reductions in LCOE. Électricité de France (EdF) researchers, for example, recently developed a model for assessing the additional gain derived from bifacial modules mounted on horizontal single axis trackers. The model considers the impact of season, ground-coverage ratio, diffuse/global horizontal irradiance ratio, and ground albedo.[13] In comparison to standard monofacial PV modules, estimated gains in

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[11] J. P. Singh, et. al. *Performance Investigation of Bifacial PV Modules in the Tropics*. Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Volume: 27, September, 2012.

[12] S.A. Sciara, et. al. *In Situ Performance Testing of Bifacial PV Panels*. Appalachian State University, 2012.

[13] A. Lindsay, et. al. *Modelling of Single-Axis Tracking Gain for Bi-facial PV Systems*. European Photovoltaic Solar Energy Conference (EU PVSEC). June 2016.

production (kWh/kW_p) were calculated to be 5–15% and 3–11% for bifacials mounted on fixed-tilt racking and horizontal solar trackers, respectively, across a range of albedos (0.2–0.5).

In locations with high Direct Normal Insolation (DNI) where horizontal solar trackers have an economic advantage, bifacial PV can be the most cost-effective LCOE option. Consequently, EdF's analysis concludes that there are benefits in switching from monofacial to bifacial for areas with high albedo and low land costs.

Vertically Mounted Bifacial PV Modules

Bifacial modules allow a unique vertical mounting configuration. Often, the modules are aligned north-south to capture morning and evening sun, as shown in Figure 8. Real-world applications have coupled power production with other benefits. For instance, vertically installed PV systems have been installed as noise barriers along railway tracks and highways, fencing, and building components. Various studies indicate that vertically installed bifacial PV modules in higher latitude locations produce energy which is comparable to monofacial modules installed at conventional latitude tilt, and significantly higher than that of vertically mounted monofacial modules.

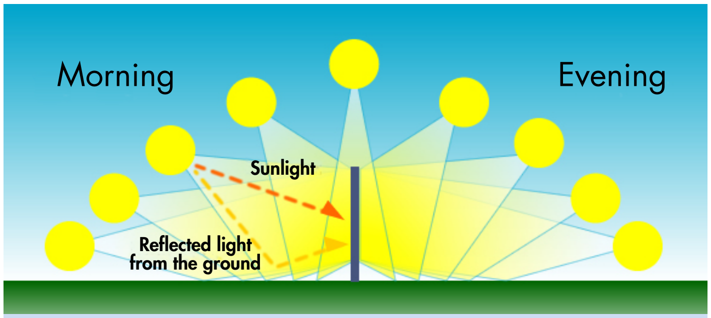

Figure 8. Rear collection power gain of a vertically mounted bifacial PV module
Source: Natural Energy Yasukawa

For example, researchers at the University of Grenoble have analyzed the potential benefit that vertically installed bifacial modules can realize with respect to reduced soiling and snow coverage as well as orientation.[14] Mixing east/west- and north/south-oriented vertical modules may, for example, better align energy production to demand, as depicted in Figure 9. Findings from a comparative analysis of vertically-mounted bifacial modules versus a mix of equator-oriented tilted monofacial and bifacial modules at high (>40 degree) northern latitude and Polar Regions indicates greater energy production (+10% to +30%) for both sets of bifacials compared with monofacial tilted. Also, large semi-arid regions at < 20 degree latitude are identified as optimal for vertical bifacial east/west installations due to the high albedo in these areas. The relative importance of tilt angle and albedos depends on the latitude/orientation of the modules and ground albedo at each specific site. The University of Grenoble study found that reduced soiling of vertical modules may bring an additional 10–20% energy gain particularly in dusty desert areas.

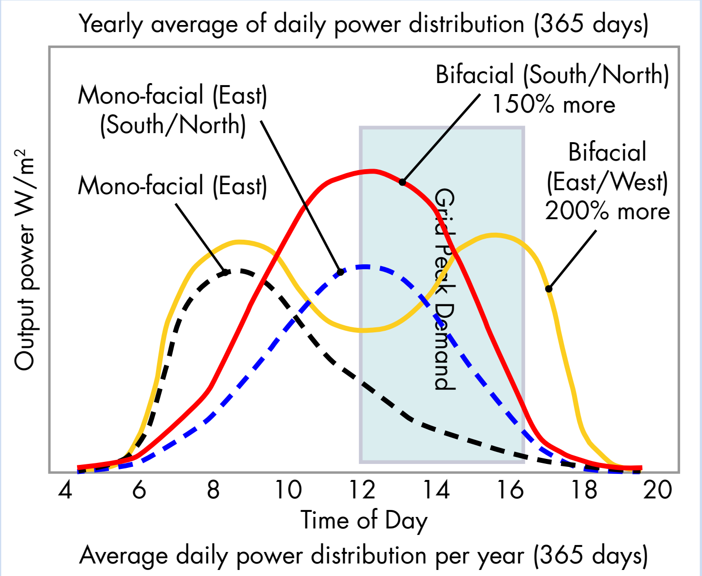

Figure 9. Bifacial vertical installation
Source: Gamma Solar via NREL

Building Integrated PV Applications

Building Integrated Photovoltaics (BIPV) represent an alternative approach to traditional rooftop PV. Rather than mounting modules on external racking, BIPV combines the functions of traditional building materials, such as roofing, glazing, cladding, and other surfaces, with the added role of producing electrical power. Although the technology accounts for less than 1% of global PV installations—largely due to their higher upfront cost relative to conventional rack-mounted, building applied (or added) PV products, as well as the complexity introduced by the requisite involvement of architects and building designers—policy initiatives, particularly in Europe, are catalyzing the introduction of new BIPV products into the market.

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[14] M. Ito, et. al. *Geographical Mapping of the Performance of Vertically Installed Bi-facial Modules*. European Photovoltaic Solar Energy Conference (EU PVSEC). June 2016.

Within the BIPV market segment, bifacial PV modules are being employed as exterior walls, either over entire façades or for specific accents. They are also being utilized as solar awnings to provide shade while converting sunlight to energy, as skylights and windows that allow for daylighting but also reduce glare and heat loading, and for greenhouse applications. Figure 10 depicts a bifacial module displayed on the tradeshow floor of 2016 Intersolar Europe conference that is intended for greenhouses.

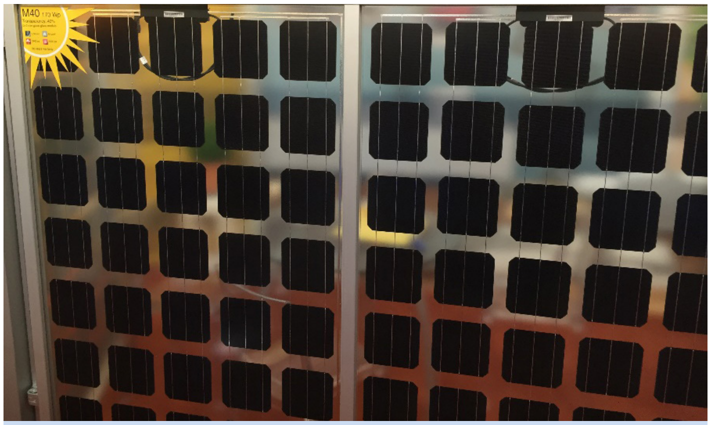

Figure 10. Bifacial module designed for greenhouse applications
Source: EPRI

State of the Technology

The variation of bifacial cell architectures that have been developed in the lab is formidable.[15] To date, however, only a few have proceeded to manufacturing. But as the solar market continues to mature, near-term innovations are expected to increasingly focus on squeezing more efficiency out of conventional silicon solar cells. To this end, cell and module manufacturers are likely to more aggressively pursue and improve upon high-efficiency structures that can aid bifacial development, such as passivated emitter, rear contact (PERC) cells, passivated emitter, rear locally-diffused (PERL) cells, heterojunction technologies (HJT), among others. While the number of active bifacial module manufacturers is limited, other producers may, in the future, enter the marketplace by adapting their existing cell architectures where R&D budgets permit, either by working with third-party R&D organizations such as universities or national labs, or through merger and/or acquisition routes.

Currently, bifacial PV modules, depending on their application, are at a Technology Readiness Level (TRL) of 6–8 (Early Demonstration/Demonstration/Early Commercial). For example, bifacial PV modules for carport and other BIPV applications—such as awnings and canopies—have been in the market for a number of years but adoption has been measured. They have additionally been vertically installed on a limited basis as railings or sound barriers at highways and railways or other places where space for installing standard PV modules is constrained.

Meanwhile, as ground-mounted power generating systems, bifacial PV has been deployed in a growing number of smaller demonstration projects, and in several instances, in full-blown utility-scale plants. Table 1 (on page 11) provides an overview of representative bifacial cell and/or module fabricators that are supplying product for testing and evaluation in both experimental and commercial settings.

Bifacial Deployments

Small-Scale Demonstrations

Today, much of the segment is engaged in small-, and to a lesser extent, large-scale field testing, to prove out early as well as more mature bifacial technologies. Multiple testbeds have been setup over the years, often operated by non-profit research or academic institutions, to measure actual system performance. These facilities, some of which are identified in Table 2 (on page 12), are providing critical data about real-world electrical performance of small-scale systems and are helping to validate and refine developed software models. Note: Beyond the testbeds listed in Table 2, all of the bifacial module manufacturers are also conducting laboratory and/or field testing of their products; few are, however, publishing their results for proprietary reasons.

These testbeds often operate under highly-controlled conditions, and vary test parameters, such as cell type, module orientation, ground or rooftop albedo, fixed-tilt angle, single-axis tracking, number of neighboring module rows, and so on. Although the variable conditions at each of the testbeds make exact comparisons of results difficult, the collective research is providing deeper understanding and insights to the solar industry.

Within the U.S., a DOE SunShot project is, in particular, pursuing cutting-edge research intended to introduce useful insights into the public domain about the real-world performance of bifacial PV. Undertaken collaboratively by Sandia National Laboratories (San-

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[15] S. Glunz, A. Cuevas. "Bifacial Silicon Solar Cells – An Overview." Bifacial PV Workshop. Konstanz, Germany, 2012.

Table 1. Bifacial PV Module Manufacturers

Company	Technology/ Design	Rated Module Efficiency*	Notes
bSolar	p-type crystalline silicon	>22% "equivalent efficiency" (cell)	Cells and modules produced in Germany
LG Electronics	n-type mono-crystalline	18.8%	Uses transparent backsheet (not glass)
MegaCell	n-type mono-crystalline, BiSoN	21% (cell)	Pilot manufacturing in northern Italy. 60-cell bifacial module with 300 W nameplate, frontside only illumination.
Neo Solar Power	n-type mono-crystalline heterojunction	~22.2% (cell)	One of the largest cell and module manufacturers globally, operating primarily in Taiwan. Constructing a 50-MW pilot-production line as 2Q16.
Panasonic	HIT; n-type mono-crystalline heterojunction	19.7%	Developed by Sanyo (which was acquired by Panasonic in 2012). Sales predominately in Japanese market. Low product demand, manufacturing capacity recently reduced from 900 MW to ~600 MW per year.
Prism Solar	co-diffused n-type silicon	17.7%/22.5%**	Among industry pioneers, have offered products with bifacial cells since 2008. Working with NREL/Sandia to standardize bifacial performance testing and modeling. Only company to offer power warranty on backside module production.
PVG Solutions	n-type mono-crystalline	16.1%	35 MW of "EarthON" cell and module manufacturing in Seijo, Japan.
RCT	p-type multi-crystalline	19% (cell)	Pilot production of "Multi PERCT" cells in China averages 18.5% efficiency.
Silfab Solar	co-diffused n-type mono-silicon	18.4%	Silfab X glass-glass Series debuted in Feb 2016; developed in partnership with the ISC Konstanz and MegaCell. 300-MW capacity production in Toronto.
SolarWorld	p-type mono-PERC	16.1%	Bisun modules have clear backsheet and contain p-type cells, which offer ~60% bifacial ratio (vs. 85–95% for n-type cells), but at reduced price point. Leverages existing company fab lines that are tooled for p-type cell manufacture.
SolarCity (Silevo)	Triex technology; n-type crystalline/a-Si hybrid cell	18.5%	Glass-glass, frameless bifacial module under development and intended to be mass-produced at 1-GW plant in Buffalo, NY.
Sunpreme	HIT; cell consists of thin film p-n junction formed by four a-Si depositions	19.1%	Underlying platform: SmartSilicon Hybrid Cell Technology (HCT). In lawsuit with U.S. Dept. of Commerce to vacate ruling to impose anti-dumping and countervailing duties on c-Si wafers imported from firm's Chinese fab plant. The trade tariffs apply to c-Si cells, unclear if they also apply to Sunpreme's silicon wafer substrate upon which silicon layers are mounted.
Yingli Green Energy	n-type mono-PERT cells	17.0%	TwinMAX product series based on PANDA cell, launched in 2011 with white backsheet, and since adapted to include glass/glass and anti-reflection on both sides of the cell. 30-year linear warranty offering.

Notes: HIT = Heterojunction with Intrinsic Thin layer; PERC = Passivated Emitter Rear Contact; PERT = Passivated Emitter, Rear Totally diffused
** Module efficiencies are STC; to convey bifacial power boost, most manufacturers advertise between a 5–30% additional increase from backside sunlight conversion.*
***Prism Solar's 17.7% module efficiency is based on frontside-only STC, while its 22.5% module rating is based on a bifacial STC rating = cell temp 25°C, AM1.5, 1000W/m^2 (FRONT) + 300W/m^2 (BACK).*

dia) and the National Renewable Energy Laboratory (NREL), the multi-year project aims to collect performance data from bifacial PV systems, develop international power rating standards for bifacial PV modules, and validate bifacial performance models.

As part of the initiative, Sandia is field testing multiple bifacial module types, albedo values, and racking configurations (both fixed-tilt and single-axis tracking) at its campus in Albuquerque, NM (see Figure 11 on page 12). Initiated in March 2016, testing includes comparative performance measurement of bifacial and monofacial modules at south-facing 15˚ fixed tilt on white ground cover, south-facing 30˚ fixed tilt on natural ground cover, west-facing 15˚ fixed tilt on white ground cover, and west- and south-oriented vertical mount (90˚) on natural ground cover.[16]

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[16] Baseline irradiance measurements were made prior to module installation and the monitoring system was calibrated with respect to STC-traceable reference modules.

Table 2. Bifacial PV module testbeds

Primary Project Manager	Testbed Notes
International Solar Energy Research Center Konstanz (ISC-Konstanz)	3 sites setup globally to test the research center's BiSoN cell architecture: Italy in 2014, Egypt in 2015, and Chile in 2015.
Institut National de l'Energie Solaire (CEA-INES)	Modules under evaluation in the institute's Building Energy Lab in Le Bourget-du-Lac, France.
Energy research Centre of the Netherlands (ECN)	The Dutch center's n-PASHA cell architecture being tested in modules sited on main campus in Petten, Netherlands and at the Solar Energy Application Centre in Eidhoven, Netherlands.
Fraunhofer Institute	A several-kW fixed-tilt array being assessed at the Institute for Solar Energy Systems (FhISE) campus in Freiburg, Germany. Two modules on dual-axis tracking sited at the Center for Silicon PV (FhCSP) campus in Halle (Saale), Germany.
PVG Solutions	Two 3-kW arrays of the company's EarthOn bifacial products have been assessed in Kitami, Japan since 2012.
Électricité de France (EdF)	Forty 72-cell bifacial modules (4 rows of 10) in fixed-tilt configuration and twenty 72-cell modules in SAT configuration being tested in Cairo, Egypt. A fixed-tilt string of 8 bifacial modules also under examination since 2014 at EdF's R&D site in France.
Electric Power Research Institute (EPRI)	8-kW HIT array in fixed-tilt configuration installed and under evaluation at the Solar Technology Acceleration Center (SolarTAC) in Aurora, CO, since 2012.
National Renewable Energy Laboratory (NREL)	Multiple bifacial module types installed in fixed-tilt configuration on NREL's campus in Golden, CO. Funding provided by U.S. DOE's SunShot Initiative.
Sandia National Laboratories	Multiple bifacial module types, albedo values, and racking configurations (both fixed-tilt and single-axis tracking) installed on campus in Albuquerque, NM. Funding provided by U.S. Dept. of Energy's SunShot Initiative.
Prism Solar	Manufacturing and field-testing bifacial modules since 2012 with test locations at production facilities in Highland, NY and Tucson, AZ. Independent testing occurring in Albuquerque, NM, potentially soon in Upstate NY and VT.
bSolar	Manufacturer of bifacial modules, pursuing fixed-tilt rooftop and ground-mounted testing in Germany (Geilenkirchen, Berlin, Saxony) and Eilat-Eilot, Israel.

Figure 11. Module-scale bifacial PV test bed at Sandia National Laboratories
Source: Sandia National Laboratories

Preliminary data suggest that standalone bifacial modules, which are able to better capture the surrounding light, generate 20–35% more power than monofacial alternatives. Gains average 20% across all test modules, increase to over 30% for bifacials on white ground cover, and are highest for those in vertical orientations.[17] Though results appear promising, Sandia researchers qualify that the achievable power boost for larger bifacial systems will likely be lower due to the impact of inter-row shading on rear-side irradiance.[18] Sandia is also installing several fixed tilt and tracking bifacial arrays, expected to be commissioned by end-2016 to further explore string- and system-level performance.

NREL is, meanwhile, measuring the backside irradiance of a handful of monofacial and bifacial modules and arrays sited side-by-side on a grassy field at its Golden, CO campus. (NREL had previously measured backside irradiance of modules located on a carport structure, rooftop array, and open field array.[19, 20]) This effort aims to determine the level and effect of rear-side irradiance drops on larger systems due to inter-row shading and other factors to inform

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[17] J. Stein. *Performance Models and Standards for Bifacial PV Module Technologies*. Quarterly Project Report, U.S. DOE SuNLaMP 30286, August 2016.

[18] Personal Communication. Joshua Stein, Sandia National Laboratories, August 2, 2016.

[19] C. Deline, et. al., *Evaluation and Field Assessment of Bifacial Photovoltaic Module Power Rating Methodologies*, 43rd IEEE PVSC, 2016, preprint.

[20] C. Deline, et. al., "Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out", *Journal of Photovoltaics*, 2016. (Submitted)

bifacial performance modeling guidelines. Early results specify a 10% energy boost for bifacials over monofacials. However, project investigators caution that initial findings may be somewhat skewed by the asymmetric proximity of neighboring solar arrays (i.e., a solar array exists to the west of the bifacial installation, but not to its east, thus potentially enabling the array to receive greater backside irradiance).[21] In parallel, Sandia and NREL are working with the University of Iowa to develop ray tracing methodologies for estimating backside irradiance in multiple PV array environments.

Altogether, research out of the DOE SunShot project is intended to directly and indirectly help further develop and codify the draft rating standard, IEC 60904-1-2, described earlier. Sandia and NREL have, for instance, set up module test racks for measuring outdoor IV curves along with front and back irradiance. These measurements have been compared with indoor flash tests following the draft IEC rating standard and have produced results showing maximum power differences within 2% of simulator accuracy. Ongoing work is identifying components of current-voltage (I-V) curve measurement that contribute to uncertainty in bifacial module measurement.

Large-Scale Demonstrations

Two larger scale, 1-MW+ demonstration plants are also expected to provide a growing understanding of bifacial PV performance: a 1.25-MW system in Asahikawa, Japan, situated on the northern island prefecture of Hokkaido; and a 1.7-MW system in northern Chile near the Atacama Desert. The former installation is currently operating in sun, while the latter is under construction. Following are further details on each installation.

(Note: other larger-scale commercial plants are in various stages of development. Two being built by Prism Solar in Update New York—a 150-kW rooftop array and a 500-kW ground mount system—are anticipated to be the first larger-scale commercial systems to be monitored by a third party. The performance data collection, expected to commence by end-2016, will be undertaken by Sandia and is meant to validate Prism Solar's performance monitoring techniques, perhaps helping to incorporate them into a universally-accepted industry standard.)

1.25-MW Asahikawa Hokuto PV Plant

The 1.25-MW system, commissioned in late 2013, uses 5,320 bifacial modules with EarthOn cells made by PVG Solutions. The modules have a nameplate rating of 254 W (though, as described above, there is ambiguity in bifacial nameplate rating). The site has fixed-tilt racking at 40 degrees, which is commensurate with the high latitude of the location, and the modules sit 1.8 m above ground. The rows are spaced 10 m apart. Overall, the plant's ground surface coverage is 35,140 m^2, equivalent to 8.7 acres. This equates to nearly 7 acres/MW. For comparison, a plant using monofacial modules, deployed at the same time as the Asahikawa Hokuto system, would have had a ground coverage ratio of 4.8 acres/MW.[22]

Figure 12 shows the energy production from the first year of the plant's operation and reveals a couple of interesting insights. First, the overall energy production for the year is approximately 1,722 MWh, which equates to a yield of 1378 kWh/kW—and, according to the module manufacturer, reflects a 21.9% energy boost compared to monofacial products.

Second, the rearside energy contribution is relatively higher during the winter months, almost twice that of the spring months (15% vs. 30%). There are a handful of possible explanations for this disparity, including increased albedo from snow covered ground, rearside energy production when the frontside is covered with snow,[23] and/or beneficial rearside production at lower sun angle due to the plant design.

1.7-MW La Silla PV Plant

At the start of 2016, Enel Green Power announced its intention to commence construction of a 1.7 MW$_{dc}$ bifacial solar PV plant near the La Silla Observatory in the Chilean Atacama desert. Construction is estimated to cost $ 3.4M and commissioning is expected sometime in the third quarter of 2016. When operational, the plant is predicted to produce 5% to 10% more energy than a "traditional" PV plant of equal size. More specifically, Enel believes the system will be able to generate approximately 4.75 GWh/year, equating to an energy yield of 2,794 kWh/kW.[24]

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[21] Personal Communication. Chris Deline, NREL, August 1, 2016.

[22] *Solar Energy Technology Guide*. Electric Power Research Institute, Palo Alto, CA: 2014. 3002001638.

[23] Interestingly, bifacial modules shed snow earlier than monofacial modules because they heat up from the rearside energy production.

[24] PV Magazine, "Enel Green Power Begins Construction of Innovative PV Plant at La Silla Observatory in Chile." February 11, 2016. www.pv-magazine.com/news/details/beitrag/enel-green-power-begins-construction-of-innovative-pv-plant-at-la-silla-observatory-in-chile_100023169.

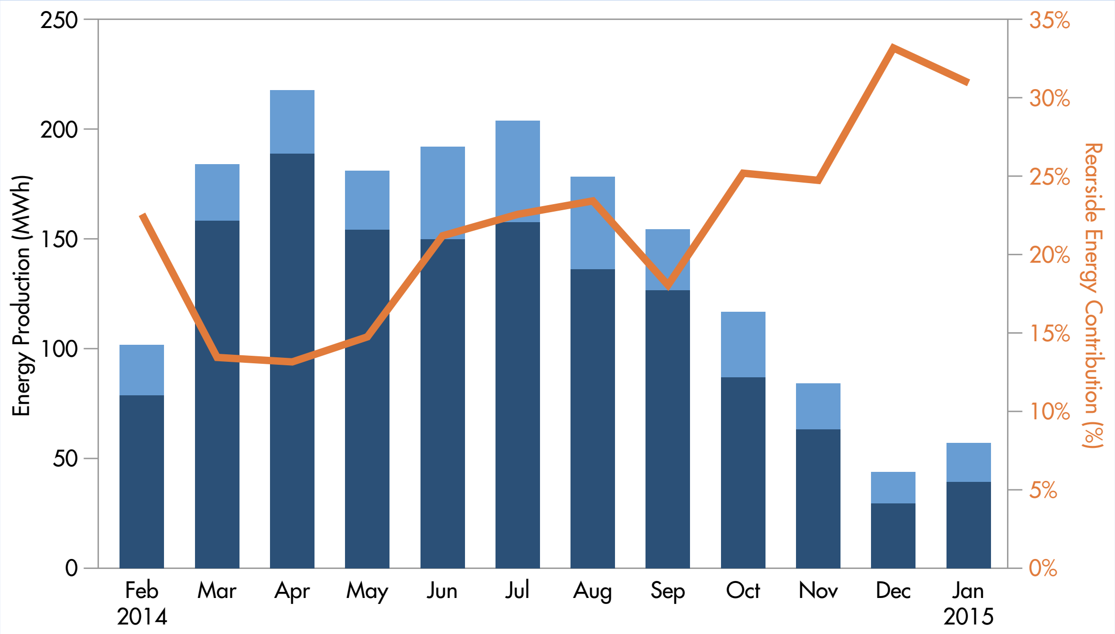

Figure 12. Monthly energy production from 1.25 MW Asahikawa Hokuto PV Plant
Source: KTH Royal Institute of Technology

EPRI modeling suggests that a 12 MW_{dc} plant in Antofagasta, Chile with multi-crystalline silicon modules at a fixed-tilt would produce 2.1 GWh/year or, with single-axis tracking, 2.4 GWh/year. The result: energy yield of 1,750 kWh/kW for fixed-tilt and 2,000 kWh/kW for single axis tracking.

Commercial Pricing and Market Outlook

Commercial pricing of bifacial modules is highly variable based upon their application, composition, and the market context under which they are being manufactured. Moreover, pricing is further complicated by the non-uniform manner in which bifacial module manufacturers rate their products. Although most producers currently use frontside-only STC flash ratings to determine module pricing, some also include estimated backside module contributions. And even among those that rely on frontside-only flash ratings, some use white backgrounds behind the modules which increases the apparent frontside flash STC rating, in effect adding some of the backside into the rating. The result is a hodgepodge of module price points that are often not comparable.

As discussed earlier, the development of a technical specification is underway that aims to standardize the method for measuring and assigning bifacial module power to module nameplate. As part of this effort, industry stakeholders expect flash test conditions governing the measurement of bifacial STC ratings to be better defined, and for the pricing per watt to more consistently reflect the true potential of the technology.

That said, nearly all bifacial products in the U.S. market are today estimated to predominately range between $0.70/W and 1.35/W, based on loosely defined frontside-only STC flash ratings. They are generally more expensive than conventional monofacial panels. However, their price premiums are often justified by the purported boosts in solar generation that bifacials can command—a supposition complicated by fluctuating bifacial module performance across different designs, scant field data, and an inconsistent method for measuring performance.

Bifacials have been sold into architectural BIPV installations, in which aesthetics are an important price driver, for upward of $1.20–1.65/W. The higher price point is largely based on the technology's ability to displace another similarly high priced material input, such as architectural glass. Meanwhile, for traditional power projects, bifacial modules need to hover around $0.95–$1.35/W to be competitive in commercial-scale PV system projects, and at $0.70–$0.95/W for utility-scale projects, according to one manufacturer.[25]

The range in pricing is a reflection of variable factors such as project size, module technology/construction (e.g., p-type vs, n-type, glass-glass vs. backsheet), and bifacial ratio.[26] Among bifacial module

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[25] Personal communication. Jose Castillo and Paul Hauser, Prism Solar Technologies, August 4 and August 30, 2016.

[26] The lowest priced bifacial modules are typically those that are constructed out of p-type polycrystalline cells, have lower bifacial ratio (50%-65%), and use a traditional backsheet.

types, there is a $0.10–0.20/W price difference between products that employ p-type polycrystalline technology versus those that utilize more expensive n-type monocrystalline wafers, which typically command a higher bifacial ratio as well as lower/negligible light induced degradation. Meanwhile, glass-glass bifacial modules tend to command a $0.05–$0.15/W premium over more traditional bifacial builds that contain a backsheet. (Anecdotally, for a 2012 EPRI PV field demonstration project at the Solar Technology Acceleration Center, bifacial technology cost twice as much as monofacial on a $/W basis.)

To increase the value proposition of bifacial systems, a growing number of product manufacturers are exploring the merits of pairing their modules with single-axis tracking (SAT) equipment. Initial cost models suggest ground coverage ratio, albedo, and amount of diffuse and direct irradiance are important economic considerations. A hypothetical case study on Cairo, Egypt found the bifacial production gains to be larger for fixed-tilt over SAT systems on a relative percentage basis; though overall energy production favored the bifacial module and SAT pairing.[13] The extended solar profile enabled by SAT along with its falling costs, coupled with the enhanced diffuse and direct light collection capability of bifacials, potentially extends the economic applicability of tracked bifacial plants to a wider latitude of locations. For monofacial modules, tilt-angle becomes a stronger driver of energy production than east-west tracking at increasing latitudes.[27] It remains to be seen how the tilt versus tracking trade-off impacts bifacial modules.

All told, some analysts and industry groups anticipate market growth for bifacials. For instance, a PV technology road mapping group led by SEMI, the global industry association serving the manufacturing supply chain for the micro- and nano-electronics industries, predicts that bifacial modules will comprise 30% of the crystalline silicon module market by 2026, significantly up from today's low single digit levels (see Figure 13).[28] Of note, the group expects most bifacial cells to be initially be incorporated into monofacial modules through 2020, and for more rapid adoption of bifacial modules to ensue thereafter.

There are, of course, a number of barriers constraining bifacial PV adoption. In particular, the bifacial cell and module manufacturing process is unique, which requires a relatively high amount of capital to setup a new manufacturing facility. Moreover, low-to-negative operating margins also currently exist for manufacturers.

Most bifacial manufacturing processes simply cannot leverage the same toolsets used for the industry standard monofacial Al-BSF or PERC cells. As a result, bringing more bifacial cells to market requires removing existing manufacturing lines or creating a separate suitable manufacturing facility. The uniqueness of bifacial equipment means it cannot fully leverage existing economies of scale. Additionally, there is currently an oversupply of module manufacturing capacity compared to demand, creating stiff headwinds to contribute even further to the oversupply. This is likely to exacerbate the already slim-to-negative return on assets module manufacturers have experienced over the past few years. Raising financing in such an environment will likely be challenging.

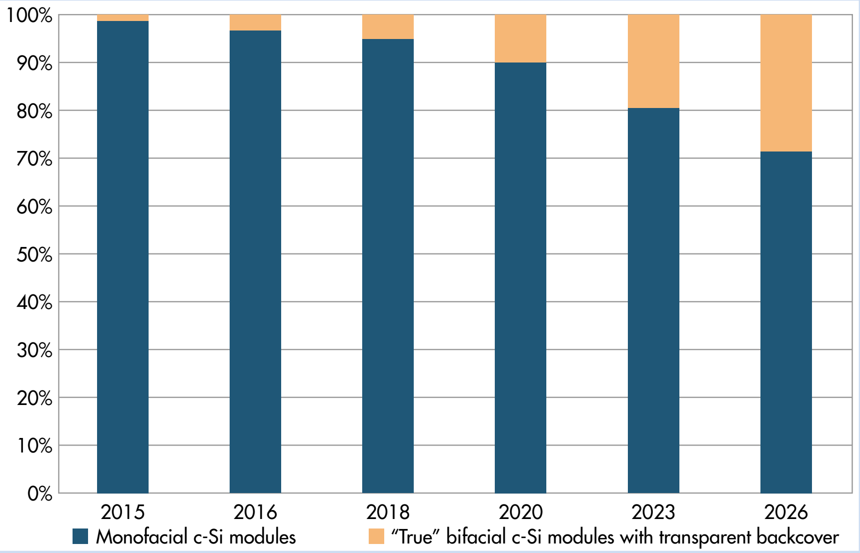

Figure 13. Market adoption forecast for bifacial modules
Source: International Technology Roadmap for Photovoltaic (ITRPV), 7th edition, March 2016

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[27] E. Drury, et. al. *Relative performance of tracking versus fixed tilt photovoltaic systems in the USA*. Prog. Photovolt: Res. Appl. (2013).

[28] *International Technology Roadmap for Photovoltaic* (ITRPV). 7th edition, March 2016.

EPRI Engagement

EPRI is engaged in bifacial PV assessment, and intends to grow its activities in the research area going forward. Field study has thus far been exclusively tied to a larger, multi-year supplemental project analyzing and comparing the performance of a range of flat-plate PV technologies— including mono- and multi-crystalline silicon, as well as thin-films—sited at the Solar Technology Acceleration Center (SolarTAC) in Aurora, CO. As part of this effort, which successfully concluded in Summer 2016, a single array of bifacial HIT modules was evaluated. (Performance monitoring and analysis of the PV systems, including the bifacial array, will continue indefinitely under EPRI's 193C Solar Generation R&D program.)

Research results were grouped into five main categories:

1. *Reliability and O&M*, including equipment warranties, maintenance activities, and I-V curve results;
2. *Solar Resource*, including monthly insolation, irradiance profiles, and resource variability metrics;
3. *Energy Performance*, including seasonal performance ratio profiles, and module temperature impacts on daily performance ratio, and system efficiency;
4. *Annual Degradation*, including first year and long term degradation (up to 3 years); and
5. *Financial Performance*, including seasonal variation in simple annual return.

The field test also allowed side experiments and built collaboration with NREL. For instance, part way through the project, silicon-based reference cells, akin in purpose to a pyranometer, were installed on the back of the racking to measure albedo, as shown in Figure 14. Initial experimental results indicate a modest rearside irradiance of less than 10% of the frontside irradiance. When there is grass behind the modules, which is the majority of the year, rearside irradiance is between 4% to 6% of frontside, depending on sensor location. When the ground is snow covered, the percentage increases to 7% to 10%.

Interestingly, the high side of the grass covered range (i.e., 6%) was measured by the bottom sensor and the low end of the range was seen by the top sensor (i.e., 4%). Under snowy conditions the situation flipped, with the top sensor measuring the highest rearside gain and bottom measuring the lowest. This is insightful because it provides initial guidance on how rearside irradiance changes with season, ground conditions, and perhaps most importantly, is non-uniform across the back of the array.

SolarTAC is a well-established venue that has broad opportunities for future PV testing. In the context of this report, it would be possible to develop and analyze larger-scale bifacial demonstration projects. Most of the testbeds previously described above have only one or two rows of bifacial modules and array sizes in the single digits of kW. This is not large enough to realistically test how bifacial modules will perform at utility-scale. As discussed, there are many design options and a complicated interplay of variables that affect performance, such as inter-row shading and reflectance, racking choices, and module orientation that demands greater testing and evaluation.

Figure 14. Silicon reference cells installed on the back of one a PV array at SolarTAC to measure albedo
Source: EPRI

Conclusions and Future Opportunities

Bifacial modules are an illustrative example of an innovative technology that has unique potential, but that is misaligned with the solar industry's status quo business model. The technology's challenges and opportunities can be framed and analyzed according to common solar industry metrics.

- *Cost of a bifacial module, $/m^2$*

  Bifacial modules face multiple cost challenges that are hindering their greater embrace by product manufacturers. Specific to the manufacturing process, more cost effective means to metallize the cell are needed, likely requiring refinements to the material used and to the process in which the material is deposited. As a result, customization will, to some extent, be required by future bifacial manufacturing tools. The level of necessary customization will impact the expense and relative ability to leverage the scale economies provided by the existing supply chain.

  In addition, the bifacial PV sector will be required to weather the tough macroeconomic conditions surrounding aggressive PV module pricing and near-term oversupply. Low pricing reduces revenue and leads to low-to-negative operating margins for most module manufacturers. It is financially difficult to sustainably grow manufacturing capacity of existing products, let alone a more innovative concept such as bifacial modules. This issue is exacerbated by the more expensive manufacturing tooling and processes required to product bifacial modules today. The high capital expense and low returns on cell and module production is a bottleneck for adoption by manufacturers.

- *Cost of a bifacial plant, $/m^2$*

  Fully utilizing all of the performance benefits of bifacial modules may require some hardware changes to the PV plant itself that consequently impact costs. For instance, guidance from future performance data analysis may determine that the way in which modules are held in the racking and/or how the strings are arranged should be altered to minimize shading. Increasing inter-row spacing may separately boost rearside irradiance and associated power output. Vigilance will be required by stakeholders to determine the tradeoff in performance versus the costs of increased land and wiring.

- *Module nameplate power rating, W/m^2*

  The power output of bifacial modules is plant-specific. Power gains in the field have varied from 5% to 30%. There is no consensus on how to measure, rate, and then monetize this power boost. Currently, the international community is developing IEC 60904-1-2, which would provide guidance on how to measure the power output of a bifacial module under standard test conditions. It is left to the manufacturer on what power number to list as nameplate (as is the case for monofacial modules too).

- *Price of a bifacial module, $/W*

  Monofacial modules have a single price, regardless of installation location, and are often compared on a $/W basis. This pricing and comparison construct is difficult to use with bifacial modules since plant specific factors play a large role in power production. Finding balance in the rating and pricing conundrum is important for fairly compensating all parties along the PV supply chain and fostering market growth.

- *Lifetime energy output, kWh*

  Bifacial modules have shown increased generation on an energy yield (kWh/kW) basis compared to monofacial modules. They may also have lower degradation rates due to lower susceptibility to cell microcracking and water ingress. Existing testbeds and demo projects are proving out these value propositions and aiding with technical bankability.

  For larger-scale bifacial plants, it remains challenging to predict and model their energy production. The development and verification of bifacial modeling software is non-trivial, but critical for wider adoption of bifacial modules. Willingness to finance larger-scale bifacial PV plants will require more upfront due diligence than what currently exists. Targeted, well-coordinated, and collaborative activities amongst industry researchers have made incremental progress towards this goal.

Future Opportunities

Other potential pathways to explore bifacial modules include (in order of least to most effort):

- Observe the development and pilot testing of enhanced bifacial cells and modules as well as early field demonstrations to validate performance.
- Collaborate with organizations, such as NREL and Sandia, in the field testing of modules, creation of rating standards, and/or development of predictive computer models for the design of PV plants utilizing bifacial modules.

- Perform more in-depth assessment of existing data around bifacial module performance for side-by-side comparison against monofacial modules.
- Develop new field-test projects that focus more exclusively on bifacial modules to validate and/or demonstrate unique performance opportunities, such as bifacial modules on single-axis trackers and/or larger field demonstrations of various racking and design configurations. These efforts can potentially be coupled with other research goals.

Recommended Reading

Research Reports and Papers

J Castillo-Aguilella, et. al. "Multi-Variable Bifacial Photovoltaic Module Test Results and Best-Fit Annual Bifacial Energy Yield Model." *IEEEAccess*, Vol. 4. March 2016.

C. Deline, et. al., *Evaluation and Field Assessment of Bifacial Photovoltaic Module Power Rating Methodologies*, 43rd IEEE Photovoltaic Specialists Conference (PVSC), 2016, preprint.

C. Deline, et al., "Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out", *Journal of Photovoltaics*, 2016. (Submitted)

F. Fertig. Et. al. Economic Feasibility of Bifacial Silicon Solar Cells." *Progress in Photovoltaics*, Vol. 24, Issue 6 (pp 800–817). June 2016.

P. Grunow. "Bifacial Modules – Promises and Challenges." Photovoltaik-Institut Berlin, Bifacial PV Workshop, 2012.

R. Guerrero-Lemus, et. al. "Bifacial Solar Photovoltaics—A Technology Review." *Renewable and Sustainable Energy Reviews*, Vol, 60, pp 1533–1549. July 2016.

R.Hezel. "Novel Applications of Bifacial Solar Cells." *Progress in Photovoltaics: Research and Applications*, Vol. 11, 2003.

M. Ito, et. al. *Geographical Mapping of the Performance of Vertically Installed Bi-facial Modules*. EU PVSEC. June 2016

A. Lindsay, et. al. *Modelling of Single-Axis Tracking Gain for Bi-facial PV Systems*. European Photovoltaic Solar Energy Conference (EU PVSEC). June 2016.

P. Ooshaksaraei, et. al., *Terrestrial Applications of Bifacial PV Solar Panels*. Solar Energy Research Institute, 2016.

J. Prakash. *Characterization and Performance Analysis of Bifacial Solar Cells and Modules*. Masters Thesis, National University of Singapore. 2014.

A Schmid, et. al., "Realistic Yield Expectations for Bifacial PV Systems." European Photovoltaic Solar Energy Conference (EU PVSEC), September 2015.

J Singh. "Comparison of Glass/Glass and Glass/Backsheet PV Modules Using Bifacial Silicon Solar Cells." IEEE Journal of Photovoltaics, Volume: 5 Issue: 3: pp 783-791. 2015.

S. Sciara, et. al., *Characterizing Electrical Output of Bifacial PV Modules by Altering Reflective Materials*. Western Carolina University, March 2016.

Additional Information

PV Performance Modeling Collaborative: https://pvpmc.sandia.gov.

Design Guide for Bifacial Solar Modules (Rev 4). Prism Solar Technologies: http://www.prismsolar.com/pdf/Design_guide.pdf.

Prism Solar installation Manual. Prism Solar Technologies: http://www.prismsolar.com/pdf/install.pdf.

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