Energy Science & Engineering

Open Access

RESEARCH ARTICLE

Amorphous single-junction cells for vertical BIPV application with high bifaciality

Nies Reininghaus, Clemens Feser, Benedikt Hanke, Martin Vehse & Carsten Agert

NEXT ENERGY EWE Research Centre for Energy Technology, University of Oldenburg, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany

Keywords
a-Si, bifacial, multijunction solar cell, PECVD, thin film

Correspondence
Nies Reininghaus, NEXT ENERGY EWE Research Centre for Energy Technology, University of Oldenburg, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany.
E-mail: nies.reininghaus@next-energy.de

Funding Information
No funding information provided.

Received: 12 January 2016; Revised: 17 February 2016; Accepted: 22 February 2016

Energy Science and Engineering 2016; 4(3): 183–189

doi: 10.1002/ese3.116

Abstract

Solar cells used in building integration of photovoltaic cells (BIPV) are commonly made from crystalline wafer cells. This contribution investigates the challenges and benefits of using bifacial solar cells in vertical installations. We show that those cells get up to 13% more irradiance compared to optimum tilted south facing monofacial modules in Germany. The role of the n-layer in thin amorphous bifacial single-junction cells intended to be used as bifacial cells in BIPV applications is investigated. In contrast to the superstrate cell design, a transparent n-layer and back contact play a key role to achieve high bifaciality. We therefore increased the transparency of the n-layer by adding CO_2, increasing the PH_3 flow in the deposition gas and tested different thicknesses. With those measures, we reached a bifaciality of 98% for short-circuit current density and 99% for open-circuit voltage.

Introduction

The changing situation in the social awareness of climate change and the resulting need for renewable energy facilitates the intention to implement photovoltaic devices into already established products to generate additional benefit. Especially, the thin film silicon solar technology has some great advantages compared to conventional silicon wafer solar cells concerning the integration into existing products:

- Large area with homogenous optical appearance
- Nonvisible circuitry by laser interconnection
- Can be deposited on different substrates (glass, ceramic, plastic, metal, etc.)
- Small temperature coefficient
- Very short energy payback time
- Nontoxic in case of recycling

An area with huge potential which has seen almost no attention until now [1], is the integration of solar cells into the traffic infrastructure. This would have the benefit of no additional intrusion into nature because the traffic infrastructure already exists. Cost-cutting efforts in the area of infrastructure in the EU lead to a lack of investments that have to be redeemed in the future. Adding photovoltaic modules to building elements in traffic infrastructure has the benefit of return of those investment costs in the long term, making them viable investment projects.

Bifacial cells in vertical installation on highways and rail ways have the potential to generate 42 TWh/a [2] without changing the appearance of the landscape because the noise barrier walls already exist.

The combination of sustainable energy generation and noise barriers next to highways would increase the public acceptance of structural modifications as an additional benefit.

Integrating photovoltaic power generation into noise barrier walls has been tested before [3] by integrating silicon wafer modules. The bifacial concept leads to an increase in power generated per module [4]. It also pointed out some disadvantages of using silicon wafer technology: They cannot be integrated in every object and every position because of the restricted dimensions of those modules. Integrating semitransparent wafer modules has the optical disadvantage of casting a shadow like a chess board [4] that can be very distracting.

With wafer technology, it is therefore not possible to use an existing substrate.

As we demonstrated in a previous paper [5], there is more than one way to fabricate functional bifacial thin film silicon solar modules. As we have shown, multijunction cells are not feasible in bifacial applications. On the other hand, single-junction thin film solar cells do not suffer from this problem. Compared with μc- silicon thin film modules, amorphous silicon thin film modules have some advantages:

- Higher absorption coefficient makes very thin cells and short fabrication times possible
- Stable deposition regime

These are the reasons why we believe that amorphous silicon thin film modules are a promising technology for this application.

Irridiance and Bifaciality

Using a conventional wafer-based solar cell in vertical configuration has the disadvantage of using only one-half space and therefore only a reduced part of the incoming sunlight.

The efficiency characterization of solar modules is dependent on the solar spectrum. The solar spectrum can be divided into three parts: The direct, indirect (diffuse), and reflected solar irradiance. The direct sunlight reaches the module surface after crossing the atmosphere with no further changes. Indirect sunlight is scattered on clouds or particles and far away objects before reaching the solar modules. The reflected part of the irradiation spectra results from the reflection of the near environment and back scattered sunlight of the ground. For monofacial modules on slanted rooftops, the reflected sunlight of the near environment does not play a significant role. Figure 1 depicts the composition of those parts for three German cities. Even the southernmost city Munich has an indirect solar irradiance of over 50% in average over the year. This is true for the northern European area in general.

To get a deeper understanding, in what way the mounting orientation affects the module generation, we calculated the irradiance on a plane in relation to the angle of tilt and orientation. Data for this simulation was extracted from the meteonorm [6]. The results are depicted in Figure 2. To get the optimum yield in the yearly average for a conventional one-sided module in Oldenburg Germany, it should face to the south and slightly to the west. In this optimum tilt, the average irradiance would reach 1137 kWh/m²/a.

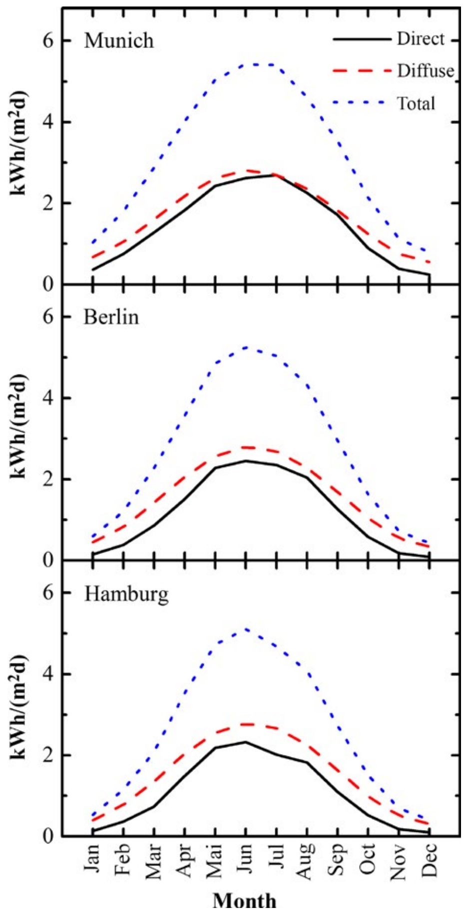

Figure 1. Composition of the solar spectrum in terms of direct and indirect irradiance for three German cities.

The same calculation can be done for a vertical plane facing east, south, west, and north. Because of the before mentioned diffuse irradiation, the average irradiance on those vertical planes per year is still very high. The results of the calculations can be seen in Figure 3. A vertical one-sided module facing south would generate the highest average yearly yield with an irradiance of 844 kWh/m²/a, which is 74% of the irradiance of the optimum tilted installation.

We propose to use bifacial modules for the vertical installation. Those modules are able to use both half spaces of the light hitting the back- and the front side of the module and are able to compensate the negative effect of partial shadowing to a certain extent. Furthermore, the vertical installation increases the naturally occurring cleaning effects and reduces the negative soiling problems caused by leaves, bird drops, and similar impurities. Thinking about noise barrier walls lining the motorways and railways going from north to south, we can use the data of Figure 3 to calculate the irradiance shining on a

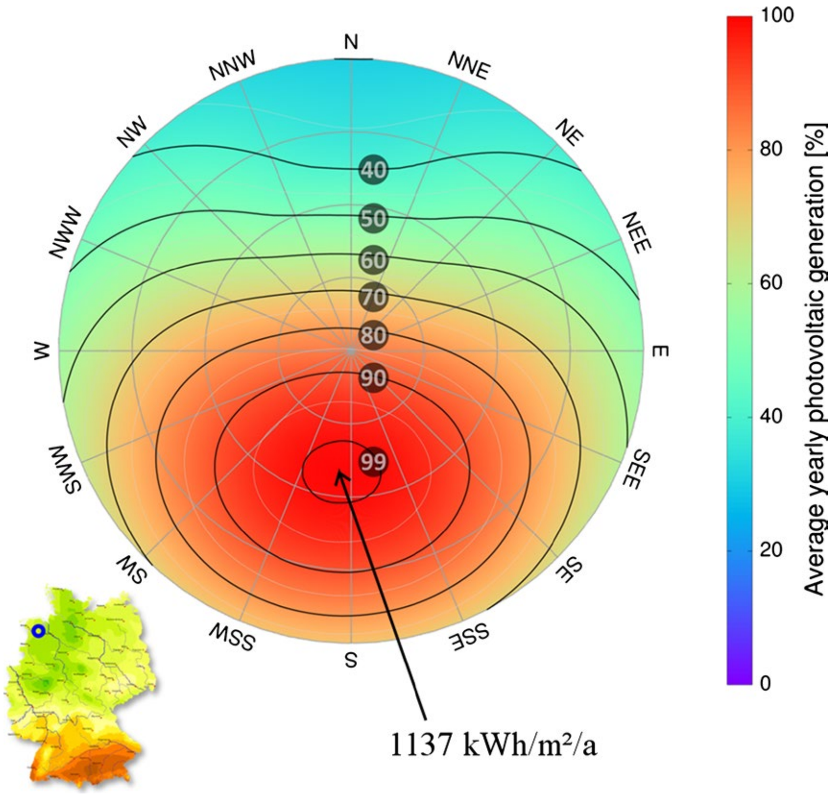

Figure 2. Tilt in relation to average yearly photovoltaic irradiance for Oldenburg, Germany. Black lines represent the isoline in percentage from the maximum irradiance.

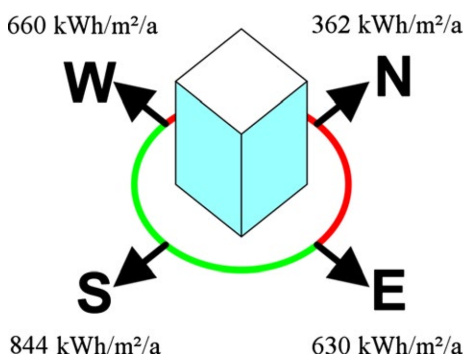

Figure 3. Photovoltaic yearly average irradiance for vertical planes facing north, east, south and west in Oldenburg with an albedo of 0.25.

bifacial module (100% bifaciality, vertical installation facing east and west) which it could convert to power. In yearly average it would face 1290 kWh/m²/a, which is 113% of a conventional module in the optimum tilt position would face. Even for transport infrastructure going from east to west the yearly average irradiance is still higher than for the modules in optimum tilt position (1206 kWh/m²/a vs. 1137 kWh/m²/a).

When using modules in vertical installation, the daily generation profile also changes. To give an example, we used measured irradiance data to simulate the irradiance on different planes of orientation and tilt on an average day in July. The results are depicted in Figure 4.

Using bifacial solar cells in vertical installation could shift the power generation peaks to the morning and evening hours. This would reduce the demand for power storage and increase the self-consumption rate since the demand profile for northern European regions is not dominated by air-conditioning.

The shift in the irradiance profile exists also on a yearly timescale. Using the same irradiance data, we calculated the same graph for those tilts and orientations on a monthly timescale. The results are shown in Figure 5.

Bifacial cells facing in north/south direction have the benefit of being able to generate more power in the winter month because of the sun being lower in the sky. In contrast, bifacial modules facing east and west could generate more power in the sunny months compared to conventional tilted modules.

Experimental

The ratio between rear- and front-side efficiency, and therefore the current generation density, is called bifaciality

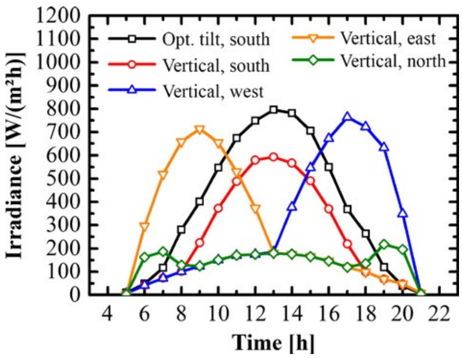

Figure 4. Simulated irradiance of an average day in July in Oldenburg for different tilts and orientations of the module plane.

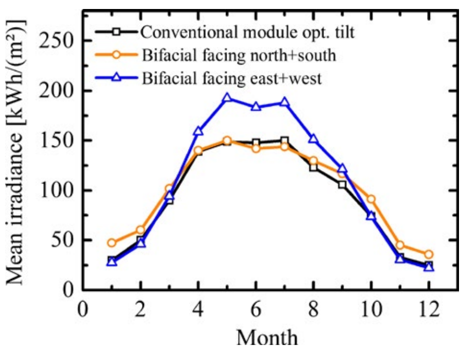

Figure 5. Monthly irradiance for three different planes in Oldenburg in different orientations.

[7]. In our previous work, we reached a bifaciality of 50% using a standard process [5] for the deposition of single a-Si thin-film solar cells in combination with a transparent back contact. The i-layer thickness was fixed at 250 nm and showed the expected light-induced degradation of 8% in average (1000 h, @STC). No further optimizations where done. To improve the bifaciality of our single-junction amorphous solar cells, we focused on the n-layer of the cell-stack. In superstrate pin configuration, amorphous silicon thin film solar cells see light only from the p-side. Therefore, there was no need for blue transparent n-layers. In the situation of a high bifaciality, the n-layer has to fulfill the same requirements as the p-layer. This means, a high transparency, high doping, less surface recombination, and good enough cross conductivity [8].

To improve the transmittance of the amorphous n-layer for low wavelengths, we varied:

- the CO_2 concentration
- the doping concentration
- the layer thickness

We decided to use an amorphous n-layer instead of the commonly used μc-$Si_{1\text{-}X}O_X$:H layer [9,10] because we expected a better long-term stability of highly doped amorphous n-layers compared to highly doped μc-$Si_{1\text{-}X}O_X$:H layers [work in prep.]. Furthermore, the process stability is better.

All presented samples were produced with a LEYBOLD Phoebus three chamber cluster PECVD-System (plasma enhanced chemical vapor deposition) at 13.56 MHz under a pressure of 4 mbar and substrate temperature between 190° to 220°. As substrates, glass with rough etched commercial sputtered ZnO:Al from the company Solayer were used. We also tested (results not shown) our cells on flat substrates and found no difference in terms of efficiency. In all samples the hydrogen flow (300 sccm), the silane flow (37.2 sccm), and the plasma power (70W) were the same. All samples were prepared with ITO-back contacts and the cell area of 1 × 1 cm² was defined by a laser isolation process.

IV-curves of solar cells under illumination (AM 1.5 g, 1000 W/cm², 25°C) were measured under a continuous light (DC) sun simulator of class A (WACOM WXS-155S-L2-AM1.5GMM). For determining the external quantum efficiency (EQE) of the solar cells, monochromatic probe beams using RERA System equipment with wavelength from 300 to 800 nm were used. Data for the irradiance graphs were extracted from the meteonorm [6].

Bifaciality Optimization

CO_2 variation

To increase the transparency of the n-layer, especially in the 300–500 nm wavelength regime, a common approach is to alloy the layer by adding CO_2 to the deposition gas mixture [9,10]. When adding too much CO_2 gas to the mixture, a decrease of the n- conductivity [8] can be observed. To prevent such an effect, we increased the CO_2 flow in small steps until we reached a gas flow of 10 sccm. As shown in Figure 6, the addition of CO_2 did not change the behavior of the cell when illuminated from the p-side. Therefore, we conclude that the used max gas flow of 10 sccm is small enough to neglect the influence on the n-layer conductivity. In contrast to the results of the p-side illumination, the short circuit current density increases slightly with the increasing gas flow. As expected, an increase in the transparency of the n-layer can be observed by increasing the CO_2 proportion at the n-layer. The maximum benefit of 0.6 mA/cm² is reached by adding a flow of 10 sccm CO_2 to the deposition gas mixture. To see where the additional current is generated, we measured the external quantum efficiency and extracted the results depicted in Figure 7. The reflectance (not shown) does not change measurably for all samples.

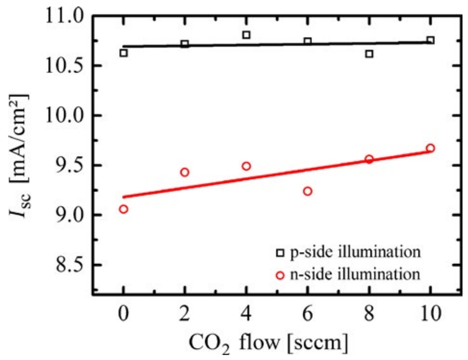

Figure 6. Short circuit current density of amorphous single-junction cells with oxygenated n-layers. Lines are fits of the measurement points.

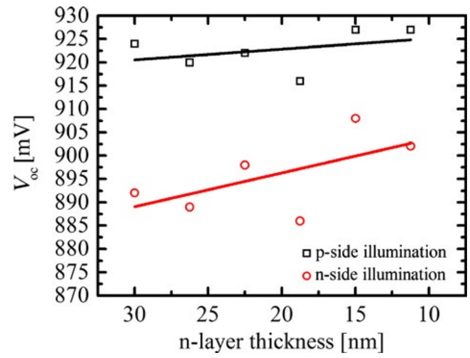

Figure 8. Open circuit voltage values of bifacial amorphous single-junction cells with decreased n-layer thickness. Lines are fits of the measurement points.

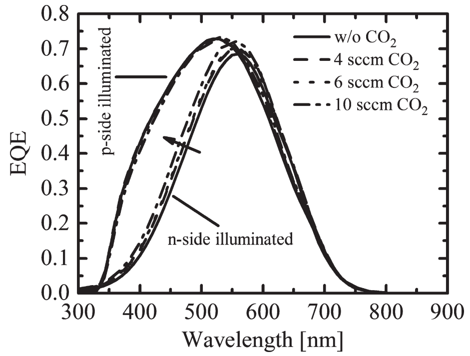

Figure 7. External quantum efficiency measurement of bifacial amorphous single-junction cells with CO_2 doping in the n-layer. The arrow indicates the tendency.

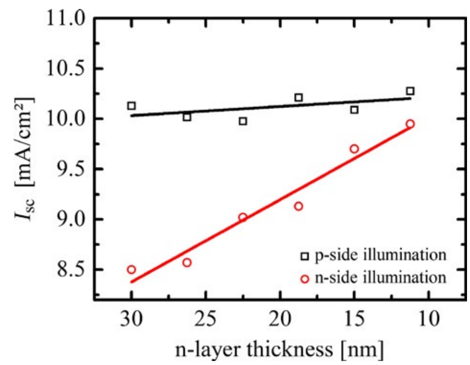

Figure 9. Short circuit current density of bifacial amorphous single-junction cells with decreased n-layer thickness. Lines are fits of the measurement points.

While the addition of CO_2 to the n-layer did not change the behavior, a distinct increase in conversion efficiency in the wavelength area between 400 and 600 nm can be observed (indicated by the arrow), when the cells are illuminated from the n-side. This can be attributed to the increased transparency due to the incorporation of oxygen and/or carbon to the layer. V_{oc} is not affected by the variation and remains nearly constant at an average of 920 mV for p-side illumination and 900 for n-side illumination.

Thickness variation

Besides mixing the n-layer deposition gas with CO_2 to increase its transparency, a thickness variation in the n-layer was performed to investigate the influence of the n-layer thickness on the absorption behavior, cell efficiency, and the bifaciality. The standard p-layer used in our cells is between 5 and 10 nm thick, whereas the default n-layer is 20–30 nm thick to ensure a strong built-in field for the improved carrier extraction and the homogeneity of the field. Figure 8 depicts the V_{oc} values of the series, proving that the used n-layer of approximately 10 nm is thick enough to conserve the strong built-in field.

As shown in Figure 9, the decreasing thickness of the n-layer does not influence the current generation density when the cell is illuminated from the p-side.

In case of the illumination from the n-side, an increase in short-circuit current density generation can be observed, reaching a short-circuit current generation bifaciality value of 96% for the cell with an n-layer of approximately 10 nm thickness.

As demonstrated in Figure 10, the additional current generated originates from the short wavelength regime. Compared to the CO_2 variation and the doping gas variation, the thickness variation shows the highest impact on the transparency for small wavelength.

The observed improvement in conversion efficiency for light from the high-energy regime is caused by a reduced absorption in the n-layer. Light absorbed in the n-layer does not contribute to the photocurrent. By reducing the

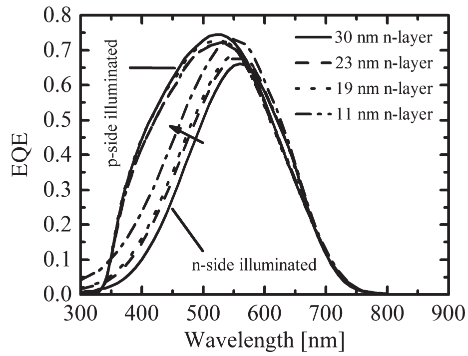

Figure 10. External quantum efficiency measurement of bifacial amorphous single-junction cells with reduced n-layer thickness. The arrow indicates the tendency.

thickness, more high energy light passes the n-layer to reach the i-layer where it is absorbed and converted into photocurrent.

Doping variation

Because a variation in the thickness of the n-layer might reduce the strength of the built-in field generated by the phosphorus doping, we deposited our bifacial a-Si:H cells with an increasing amount of PH_3 doping gas. For a better comparability to the other experiments, we used the same n-layer as a starting point as in the experiments before. The results of the doping variation are depicted in Figure 11.

With n-side illumination, an increase in the short-circuit current density of 0.4 mA/cm^2 can be seen when an additional gas flow of 5 sccm is added to the deposition gas mixture. The p-side formed by short-circuit current does not show such dependence.

The V_{oc} is not affected by the variation and remains constant at an average of 925 mV for p-side illumination and 900 for n-side illumination, respectively.

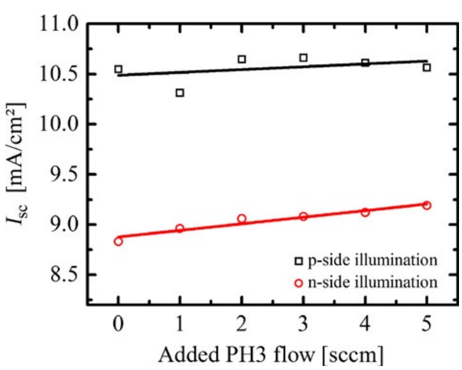

Figure 11. Short circuit current density of bifacial amorphous single-junction cells with increased doping gas flow. Lines are fits of the measurement points.

This asymmetric behavior is in good accordance to theory. The built-in field of amorphous silicon thin film cells largely originates from the boundary between i-layer and adjacent doped layer. Free charge carriers excited by absorption of light at the i-layer are forced toward the contacts by the built-in field (p for holes, n for electrons). Because of their lower mobility, free holes have a higher recombination probability in the i-layer compared to electrons [11]. This is why conventional a-Si:H modules are built in superstrat configuration, where the light enters the cell through the p-layer and the high density of exited holes on the first few nanometers can reach the contact before recombining.

The depicted n-doping increase in Figure 11 influences mainly the hole transport in the area of the n-i junction. This is why, only the short circuit current generation under n-side illumination increases. A faster excited charge transport has the additional benefit of removing the holes faster from the area where the highest concentration of free carriers is located in case of illumination from the n-side. This improved charge separation behavior resulted in a reduced recombination probability and consequently in an improved fill factor we also observed.

Combination of variations

The reference cell at the start of the investigations had a bifaciality in short-circuit current generation of only 77%. Due to a combination of the discussed improvements, we were able to fabricate a bifacial amorphous single-junction cell with improved bifaciality. This cell incorporated a 40% thinner n-layer an increased PH_3 and CO_2 deposition gas flow rate and was deposited on rough etched commercial ZnO:Al substrates. With that n-layer we managed to reach a bifaciality of 98% for short-circuit current density and 99% for open circuit voltage. The EQE in Figure 12 depicts the spectra of the optimized and the reference cell. The optimization leads to an increased

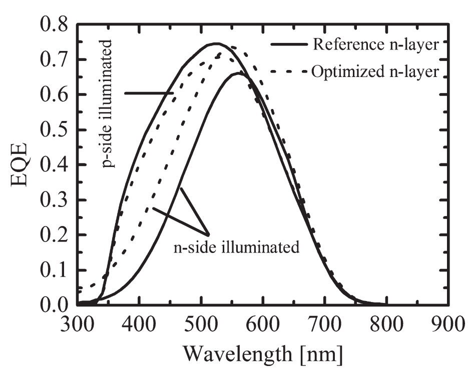

Figure 12. External quantum efficiency measurement of bifacial amorphous single-junction cells with reference and optimized n-layer.

conversion efficiency up to a wavelength of 600 nm when illuminated from the n-side while maintaining the performance when illuminated from the p-side.

The average power conversion efficiency of the monofacial reference cells was 7.0% while the optimized bifacial cells reached an efficiency of 7.4%.

Since the deposition time of the final n-layer is less than half of the deposition time of the reference layer and the only additional gas is cheap CO_2, the new n-layer would cost even less in industrial production than the reference n-layer.

Conclusion

Simulating the irradiance on different planes, we demonstrated that bifacial modules in freestanding vertical installation face more irradiance than monofacial modules in optimum tilt and orientation, regardless of the modules facing east-west or north-south.

We could show that a slight tuning of the n-layer of a standard amorphous single-junction cell in combination with the removal of the reflecting layer (Ag/white light reflector) can produce a cell with a bifaciality of 98%. Our improved bifacial amorphous single-junction solar cells show the same efficiency as our conventional cells under STC. Due to their bifacial nature this could lead to twice the output power generated under optimum conditions. We estimate that they could reach 40% to 70% improved power generation in a yearly average compared to monofacial solar cells under real-life conditions.

Outlook

To make measurements of bifacial modules comparable under STC, additional conditions like the reflectivity of the measurement block are being proposed [12]. To gage the performance of a plant with bifacial cells, additional measurement standards have to be defined [13]. To determine the plant yield, new factors like the albedo and the ratio between direct and indirect sunlight have to be taken into account.

Bifacial solar cell applications differ from classic rooftop or power plant installations demanding new solutions and different circuitry to compensate for shadowing by moving objects for example.

Current building material regulations hinder the incorporation of solar cells in building materials. To establish solar cells as part of building materials different hazards have to be evaluated:

- Danger of electrocution
- Fire hazards (ignition and toxicity)
- Blinding of vehicle drivers by reflections
- Breakage of glass

Since building material glass is a different type of glass compared to solar-grade glass, it has to be investigated how combination of thin film silicon solar cells and the building type glass used in noise barrier walls performs.

Conflict of Interest

None declared.

References

1. http://www.theguardian.com/environment/2014/nov/05/worlds-first-solar-cycle-lane-opening-in-the-netherlands (accessed 09.07.2015).
2. Quaschning, V. *Systemtechnik einer klimaverträglichen Elektrizitätsversorgung in Deutschland für das 21 Jahrhundert*. Fortschritts-Berichte, VDI Reihe 6, 2000; Nr. 437.
3. Pukrop, D. *Zur Modellierung großflächiger Photovoltaik-Generatoren* 1997; These; Carl von Ossietzky University Oldenburg.
4. Duran, C. *Bifacial Solar Cells: High Efficiency Design, Characterization, Modules and Applications* 2012; These; University Konstanz.
5. Reininghaus, N., C. Feser, and K. von Maydell. 2014. Investigation of bifacial thin-film silicon solar cells for building integration. Proc. EUPVSEC 29th:3837–3841. doi:10.4229/EUPVSEC20142014-6AV.5.39.
6. http://meteonorm.com (accessed 09.07.2015).
7. Kopecek, R., Y. Veschetti, E. Gerritsen, A. Schneider, C. Comparotto, V. D. Mihailetchi, et al. 2014. One small step for technology, one giant leap for kWh cost reduction. Photovolt. Int. 26:32–45.
8. Cuony, P. *Optical Layer for Thin-film Silcion* 2011, These, Ecole polytechnique federale de Lausanne.
9. Smirnov, V., A. Lambertz, and F. Finger. 2014. Bifacial microcrystalline silicon solar cells with improved performance due to μc-SiOx: H doped layers. Can. J. Phys. 92:913–916.
10. Veneri, P. D., L. V. Mercaldo, and I. Usatii. 2011. Improved micromorph solar cells by means of mixed-phase n-doped silicon oxide layers. Prog. Photovolt. Res. Appl. 21:148–155.
11. Shah, A. 2010. Thin-film silicon solar cells. EPFL Press, Switzerland.
12. Hohl-Ebinger, J., and W. Warta. 2010. Bifacial solar cells in STC measurement. Proc. EUPVSEC 25th:1358–1362. doi:10.4229/25thEUPVSEC2010-2CO.4.1.
13. Singh, J. P., A. G. Aberle, and T. M. Walsh. 2014. Electrical characterization method for bifacial photovoltaic modules. Sol. Energy Mater. Sol. Cells 127:136–142.

