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ANALYSIS OF BACKSHEET AND REAR COVER REFLECTION GAINS FOR BIFACIAL SOLAR CELLS

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ABSTRACT: Bifacial solar cells are known to increase module power and performance. Due to their active rear side additional gains are possible from internal reflections. Existing models to analyze cell-to-module (CTM) gains need to be extended. We analyze reflection within modules with bifacial cells and establish a system and a nomenclature for gains resulting from internal reflection. Transmission through the cell, subsequent reflection on module cover layers and a second absorption of light in the solar cell leads to additional gains in the range of 0.5 – 0.8% for bifacial cells in modules with reflecting rear cover materials (i.e. white backsheets) under STC conditions. We present models to calculate gains and perform measurements on bifacial modules with different backsheets and covers. Cover coupling gains for bifacial cells are higher compared to monofacial cells (20%$_{rel}$ in modules with white backsheets).

Keywords: Photovoltaic Module, Optical Gains, Simulation, CTM, Cell-to-Module, Bifacial, Backsheet Coupling

1 INTRODUCTION

Today, photovoltaic modules mainly use monofacial solar cells [1] that are only capable of converting irradiance from the front side into electrical power. Bifacial solar cells are a promising technology, which allows additional gains from rear irradiance [2]-[6]. By introducing bifacial cells into photovoltaic modules, existing models for cell-to-module (CTM) efficiency analysis or yield prediction [7] are no longer sufficient due to additional optical effects within the photovoltaic module such as additional relevant internal reflections [8].

Conventional solar modules with monofacial cells are known to profit from reflections from the modules rear cover (“backsheet gain”) [9]. Previous research shows that these power gains are in the range of 1 to 3% [7][10] for common module setups and components. Since monofacial cells are only capable of using light irradiant from the front side, only a fracture of possible gains from internal reflection of light can be realized. Bifacial cells have additional electrically active surfaces on the cell rear side and therefore higher reflective gains are possible [11]. Results regarding the magnitude of reflection gains have been presented [9][12].

We conduct an analysis of factors that allow reflection gains from the module covers for bifacial cells and present a nomenclature as well as models for calculation. We manufacture several modules of different setups and measure the effects of front side irradiance on modules with bifacial solar cell.

2 GAINS BY INTERNAL REFLECTION

Monofacial solar cells in modules with a reflecting (opaque) rear cover profit from reflection of light within the module. Rays incident on the opaque backsheet may be reflected onto the front glass and afterwards may again be reflected on active solar cell area (Figure 1). We will use the description “k_{11}” for this effect in accordance to the methodology of Hädrich et al. [7] to analyze the cell-to-module (CTM) ratio and influencing effects.

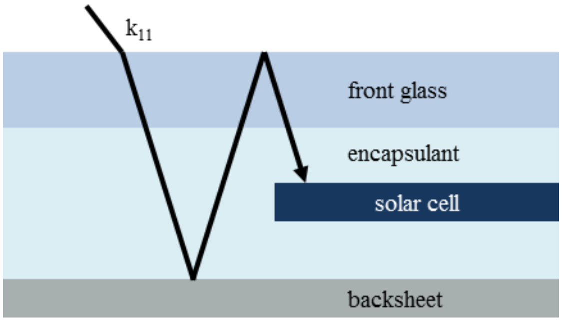

Figure 1: schematic drawing of backsheet reflection gains in modules with monofacial cells and opaque rear cover [13]

By introducing transparent backsheets and double-glass-modules an extension of the nomenclature is necessary. We therefore rename the k_{11} gain factor to “cover coupling” and extend it by using additional indices to allow a further distinction between different separate contributors. The first index letter describes the origin of the incident light (module front “f” or module rear “r”) and the second letter names the cell side receiving the ray. Figure 2 shows the extended model for transparent rear cover materials (monofacial cell).

The introduction of transparent module rear covers not only affects the internal gains and losses but also module power characterization. Reflections from measurement chucks or surrounding equipment have to be considered for cell and module measurements [14][15]. In this work we do not consider irradiance from the module rear side as models for front side irradiance may be applied accordingly.

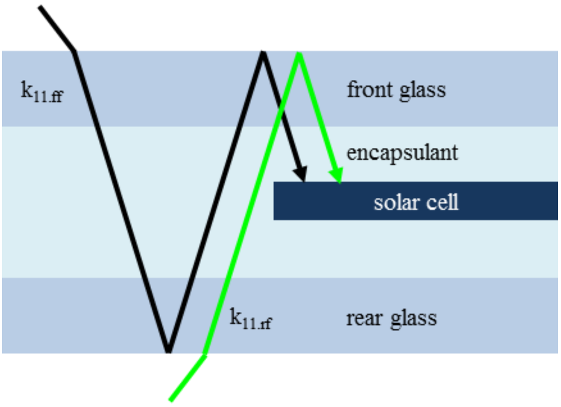

Figure 2: Schematic drawing of cover reflection gains in modules with monofacial cells and transparent rear cover

An additional extension is necessary if bifacial cells are introduced into modules since a second active cell surface has to be considered. Figure 3 shows the additional gain mechanisms $k_{11.fr}$ and $k_{11.rr}$.

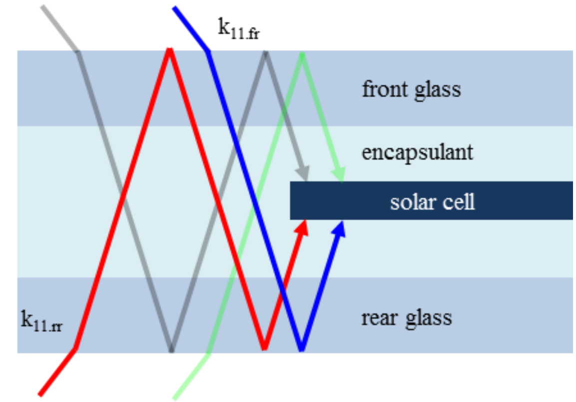

Figure 3: Schematic drawing of cover reflection gains in modules with bifacial cells and transparent rear cover

Additional reflectors in cell and string spacing areas have been presented to increase the module power in bifacial modules [8][16]. Our system and nomenclature can also be applied to categorize these gains (Figure 4).

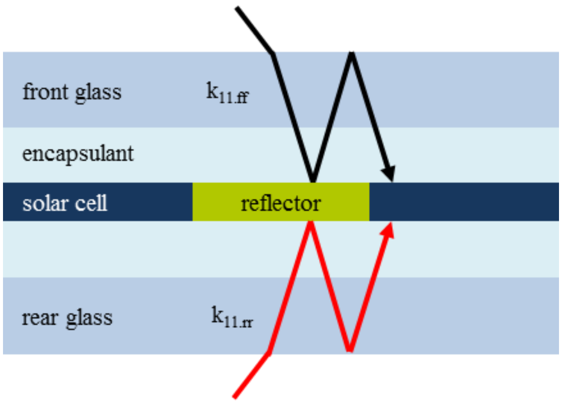

Figure 4: Schematic drawing of cover reflection gains in modules with bifacial cells, transparent rear cover and additional reflectors in the cell/string spacing area

3 GAINS BY TRANSMISSION THROUGH SOLAR CELLS AND SUBSEQUENT REFLECTION

Another possible gain mechanism is described by Singh et al. [10]. Bifacial cells are translucent in wavelengths > 1000 nm. Light transmitted through the solar cell may be afterwards reflected at a module cover and subsequently be absorbed by the solar cell (Figure 5).

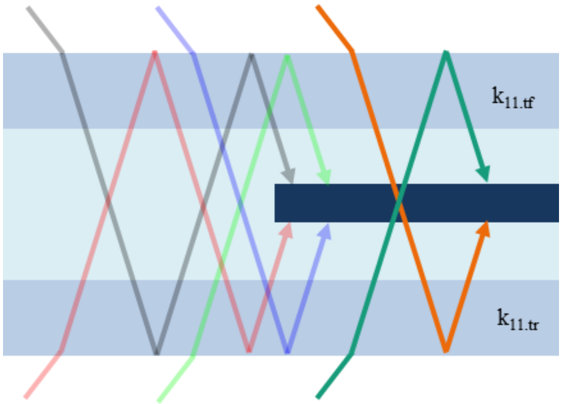

Figure 5: Schematic drawing of cover reflection gains resulting from transmission of light through the solar cell and subsequent reflection

We create a calculation model and perform optical measurements (Figure 6, Figure 7) to quantify transmission gain effects ($k_{11.tx}$).

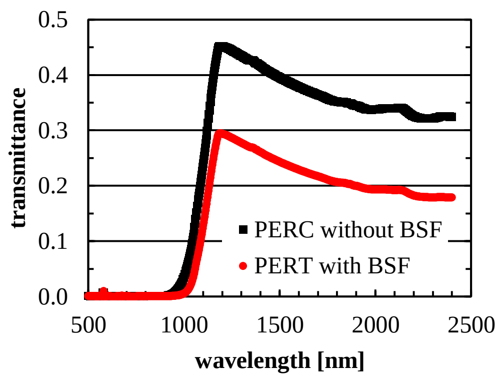

Figure 6: Measured transmittance of different bifacial solar cells

Neglecting multiple reflections or total reflection, we assume light irradiant from the module front has an AM1.5g spectrum and is partially reflected at the front glass. It passes through EVA three times in total and is being transmitted through the cell. Reflection on a rear cover material (such as a backsheet or a glass) is considered. If the rear cover is transparent (i.e. a glass) we include another pass through the transparent cover and a reflection on the outer module interface (i.e. $k_{11,tr}$). The additional irradiation on the cell rear side can be estimated using the following equation:

$$E_{cellrear} = E_{AM1.5} \cdot (1 - r_{glassfront}) \cdot t_{glassfront} \cdot (3 \cdot t_{EVA}) \cdot t_{solarcell} \cdot r_{rearcover}$$

The cell features a spectral response (SR) which has to be considered in the calculation of electrical gains.

We perform a measurement of all parameters. Selected results are displayed in Figure 7. Transmission gains are caused by light with a wavelength between approx. 1000 and 1200 nm (below blue and red curve).

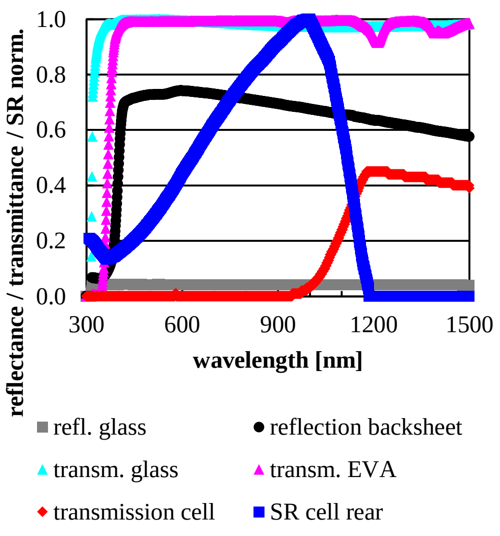

Figure 7: Measured optical properties of module materials and a bifacial solar cell

We calculate the transmission gain to be 0.4% for an exemplary monofacial module setup using bifacial solar cells, low-iron glass without anti-reflective coating and a white TPT-backsheet. We calculate the transmission gains of a double-glass module as well as a module with black backsheet and find them to be neglectable (0.03%). Multiple reflections, total reflection or additional effects have not been considered.

To estimate the influence of the transmission gains, power measurements on samples using commercial bifacial cells and white as well as highly absorbing backsheets are measured. The initial cell power is measured and module results are corrected according to differences in initial cell power. We find the difference in I_{SC} measurements between modules with black and white backsheets to be 0.5 to 0.8% which can be associated to transmission gains. We therefore conclude that transmission gains are a relevant factor for monofacial modules with bifacial solar cells.

Considering these results we further extend the CTM model [17][18] and nomenclature for gains resulting from transmission of light through the solar cell, reflection on module cover interfaces and consequent absorption. Gains after transmission are marked as $k_{11.tx}$ with *x* describing the direction of incidence on the solar cell after internal reflections (Figure 5).

4 MODELLING OF COVER COUPLING GAINS

Cover coupling gains depend on:

- Cell and string spacing
- Optical properties of module materials (i.e. reflection, absorption)
- Module setup (i.e. layer thickness)
- Cell edge length and cell size

An empirical model to describe backsheet gains has been presented by Haedrich et al. [7] which is based on measurements and an exponential fit to describe the coupling gain as a function of the cell distance *d*:

$$I_{SC\,gain} = a \cdot \exp\left(\frac{d}{b}\right) + c = \frac{I_{SC}(0mm) - I_{SC}(d)}{I_{SC}(0mm)}$$

Gains modeled with this equation that are based on measurements using shading masks (Figure 8) or LBIC (Laser Beam Induced Current) [9] already include the optical properties of module materials and the module setup.

This model is also valid for bifacial solar cells. The short circuit current at 0 mm and any other cell distance is higher for bifacial cells due to transmission gains and therefore $I_{SC\,gain}$ is changed for bifacial cells. If an estimation of the transmission gains is performed a correction of I_{SC}(0mm) may be performed.

Effects of varying cell edge lengths (i.e. for halved cells or shingles) can be considered based on measurements on full-size cells and a linear correction [19].

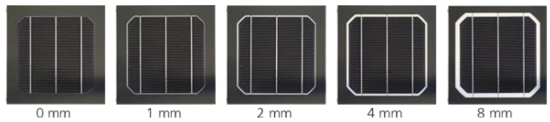

Figure 8: measurement setup using masks to determine cover coupling gains for different cell spacings

5 INFLUENCE OF DIFFERENT COVERS ON MODULE POWER

We build and measure single-cell modules of different setup to compare the cover coupling gains for different rear cover materials. All modules contain the same commercial EVA, glass and interconnector ribbons. Commercially available monofacial as well as bifacial cells are used. Modules are measured at Fraunhofer ISE Module-TEC and coupling gains for different cell/string spacing are determined. The modules contain different rear cover materials. We use a flash sun simulator with IV-curve measurement system and shading masks to vary cell and string spacing (Figure 8).

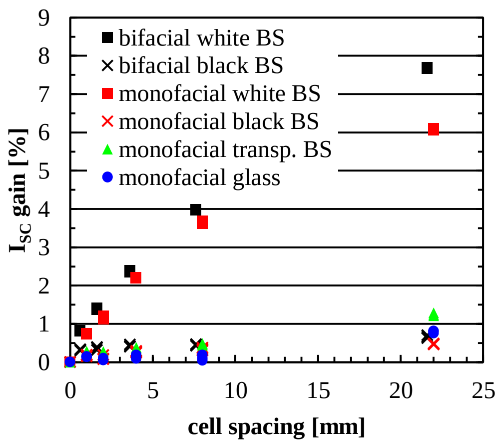

Figure 9: cover coupling gains of modules with different rear cover materials at different cell/ string distances, mono- and bifacial cells, mask measurement

Coupling gains of black or transparent rear cover materials are small compared to reflective covers such as white backsheets. Figure 9 shows increased coupling gains for reflective rear covers both for monofacial and bifacial cells. Measurements are performed with front side irradiance only. Bifacial cell cover gains are higher compared to monofacial cells. We find them to be approx. 20% higher compared to monofacial cells in modules using white backsheets.

It can be concluded that the power of modules with bifacial cells can be increased with reflecting rear covers if only front side irradiation is considered. Gains from additional irradiation from the module rear side have not been considered within this study.

To confirm the increased cover coupling gains for bifacial cells in monofacial module setups with reflecting rear covers (Figure 9), we build additional 4-cell modules (2 mm cell spacing, 600x400 mm², one sample per setup) with black, white and transparent backsheets as well as with a rear glass cover and measure the short circuit current I_{SC} at Fraunhofer ISE CalLab PV Modules. Results prove the increased optical gains for bifacial solar cells (Figure 10).

The strong influence of the rear cover on module power proves the necessity to consider the background in the measurement of bifacial modules (if a single-side-irradiation measurement setup is used).

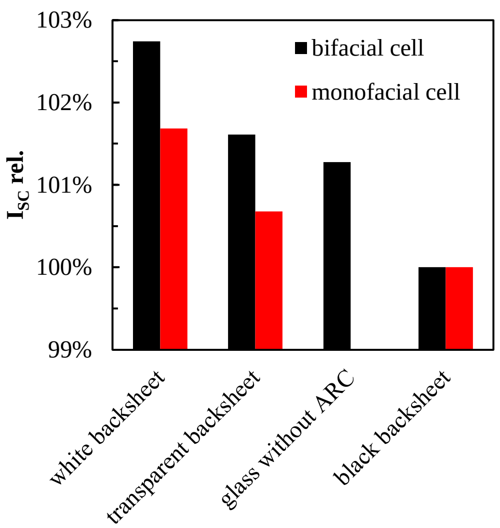

Figure 10: Short circuit current gain of monofacial and bifacial solar cells (different manufacturer) in 4-cell-modules with different rear cover materials; 2 mm cell spacing; front side irradiation only, mask used, normalized to I_{SC} measured with black blacksheet

Due to the lost bifaciality of the module itself, monofacial module setups with opaque rear covers might not be preferred. Applying reflective elements in the cell spacing area but not behind the cell provides a solution [9]. Bifaciality is preserved and cover coupling gains can be observed.

We build additional 4-cell modules with reflectors in the cell spacing area using a white polymer coating or a white tape on the inside of the rear glass (4 mm cell spacing) and measure the change in short circuit current compared to an uncoated glass.

The I_{SC} of a bifacial module increases by 1.5% compared to an uncoated glass without reflective elements (Figure 11, front irradiation only). The white tape that is usually used to cover string interconnector ribbons raises the I_{SC} by 1.1%.

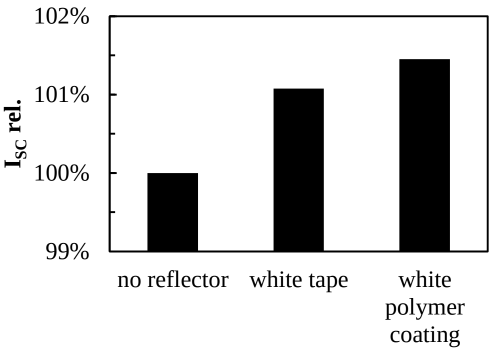

Figure 11: Short circuit current of bifacial solar cells in modules with different reflectors compared to an untreated rear glass (no reflector), 4 mm cell spacing, front irradiance only, mask used

6 SUMMARY

Module efficiency analysis and cell-to-module calculations require new models for bifacial cells due to additional optical gain mechanisms related to the second active cell side. We analyze possible gain mechanisms and identify three additional light paths compared to monofacial cells.

Bifacial cells are partially transparent in wavelengths between 1000 and 1200 nm. Transmission, subsequent reflection on module cover layers and a second absorption of light in the solar cell leads to additional gains in the range of 0.5 – 0.8% for bifacial cells in modules with reflecting rear cover materials (i.e. white backsheets). Transmission gains in modules with absorbing or transparent rear covers can be neglected.

We model cover coupling gains and perform measurements on modules of different setup and confirm the predicted additional gains for bifacial cells.

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