Irradiance Effect on the Bifaciality Factors of Bifacial PV Modules

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***Abstract*—Bifacial photovoltaic (PV) modules are seen as a promising way to increase the power density and output of solar PV systems. Since a relatively new technology, there is little knowledge on the electrical model of bifacial modules and its dependence on operating conditions. This paper looks into the bifaciality factors of such a module by means of several experimental measurements in controlled environment. It is found that, contrary to the common assumption of constant values, the bifaciality factors in fact vary with the solar irradiance. This irradiance effect is approximated via a linear model and a newly introduced irradiance coefficient. A comparative assessment to the bifaciality factors provided in the datasheet shows that the proposed model more accurately provides these values both at STC and other conditions.**

***Index Terms*—Bifacial modules, bifaciality factors, Photovoltaic (PV) systems**

NOMENCLATURE

bPV	Bifacial Photovoltaics
STC	Standard Testing Condition
RMSE	Root Mean Square Error
MAX	Maximum Error
MPP	Maximum Power Point
I_{sc}	Short Circuit Current
V_{oc}	Open Circuit Voltage
P_{mp}	Maximum Power at MPP
I_{mp}	Current at MPP
V_{mp}	Voltage at MPP
ϕ	Bifaciality factor
ϕ_{Isc}	Bifaciality factor for I_{sc}
ϕ_{Voc}	Bifaciality factor for V_{oc}
ϕ_{Pmp}	Bifaciality factor for P_{mp}
ϕ_{Imp}	Bifaciality factor for I_{mp}
ϕ_{Vmp}	Bifaciality factor for V_{mp}

I. INTRODUCTION

THE photovoltaic (PV) industry is primarily focused on increasing efficiency, scaling up manufacturing volumes, and developing low-cost materials for solar cells and modules in order to lower the cost of solar power generation. By transforming solar energy from both sides of the PV module into electrical, bifacial modules can generate more energy. *Bifacial PV* (bPV) modules are an effective way to lower the price of PV electricity since they can convert light from both sides of the module into electricity. The power density (power per unit area on the front surface) of the bifacial modules can be increased, which lowers the cost of area-related expenses like land, cabling, installation structure, etc. [1]. Several studies [2], [3] have examined the energy gain of bPV modules in comparison to monofacial modules in various installation configurations and climatic situations. Results and studies have shown that bifacial modules can produce additional power between $10-20\%$ over monofacial panels. If conditions are optimized and single axis trackers adopted, the additional power can be as high as $30-40\%$ [4].

An open issue with regards to bPV modules at the moment is how to accurately model them and quantify the energy gain over their monofacial counterparts, which in turn complicates the cost-benefit analysis when comparing the two module types. Most bPV module manufacturers provide the front side monofacial electrical parameters under STC in the absence of standards and norms, while they tabulate the power with a linear addition of the front and rear side efficiencies for specific rear side irradiation conditions [5]–[7].

The only relevant standard is the technical specification (TS) IEC TS 60904-1-2 [8] issued by the International Electrotechnical Commission (IEC) in 2019. This standard outlines recommended practices in measuring and characterizing bPV modules, but goes as far as introducing the bifacial factors for short circuit current I_{sc}, open circuit voltage V_{oc} and maximum power P_{mp} at STC. No discussion on whether these parameters, referred to simply as *bifacialities* hereinafter, vary with the operating conditions takes place in that standard.

Research on experimental evaluation of the bifacial PV systems can be found in [9]–[13]. In [9] an equivalent single-side illumination method is proposed to measure the bPV Module, which aims essentially at modeling I_{sc}, V_{oc}, and P_{mp}. Penalty-based differential evaluation is employed to further extract the one-diode model circuit parameters of bifacial single cells. [12] identifies a relation between rear and front sides' I_{sc} and V_{oc}. The former feature relates linearly in the two sides, whereas the latter in a logarithmic manner. This analysis shows that the relevant state of the art explores some electrical features of bPV modules, but not the bifacialities and their dependence on operating conditions.

To shed some light into this open issue, this paper focuses on the irradiance effect of bifaciality factors. The study presents and processes a series of experimental measurements taken on a bPV module in a controlled environment over a wide range of irradiance from 600 to 1000 W/m^2. In addition to the three bifaciality factors established in IEC TS 60904-1-2, we introduce the bifaciality factors for MPP current I_{mp} and MPP voltage V_{mp} as well. The findings indicate that the five bifacialities are not constants and in fact depend on the operating irradiance in a seemingly linear manner. This relationship is subsequently modeled via a simple linear equation that employs the nominal bifacialities at STC and the newly introduced *irradiance coefficients*. The comparative assessment that follows concludes that the irradiance effect on bifacialities is not substantial but also not negligible, and that the bifaciality values provided in the datasheet may deviate by more than 10% from the actual values.

The specifications of bifacial PV modules, how they are described in the datasheet, and an overview of bifacialities are discussed in Section II of the study. In Section III, the indoor conceptualization and bifaciality calculations are covered. Section IV then offers a summary of the entire investigation.

II. Bifacial Photovoltaic Module Parameters

All bPV module datasheets provide the following electrical parameters for the *front side*:

- Maximum Power
- Short circuit current
- Open circuit voltage
- Maximum system voltage and current
- Current bifaciality
- Voltage or Power bifaciality

These front side parameters are given almost always at STC, i.e. cell temperature 25^oC and irradiance 1000 W/m^2 at a solar spectral content of 1.5 air mass. The combined bifacial parameters are given based on the percentage of ground albedo [14].

A. Bifaciality Determination

A bPV device's bifaciality is an intrinsic attribute that expresses the ratio between the key features on its front and rear sides at the same illumination. IEC TS 60904-1-2 [8] introduces the three bifacialities:

- Short-circuit current bifaciality ϕ_{Isc}
- Open-circuit voltage bifaciality ϕ_{Voc}
- Maximum power bifaciality ϕ_{Pmp}

ϕ_{Isc} is denoted as the ratio of short-circuit current generated solely by the rear side I_{scr} (with the front side covered) to the one generated exclusively by the front side I_{scf} (with the rear side covered):

$$\phi_{Isc} = \frac{I_{scr}}{I_{scf}} \tag{1}$$

The bifaciality factor is usually expressed as a percentage (%). Fig. 1 illustrates the characterization process.

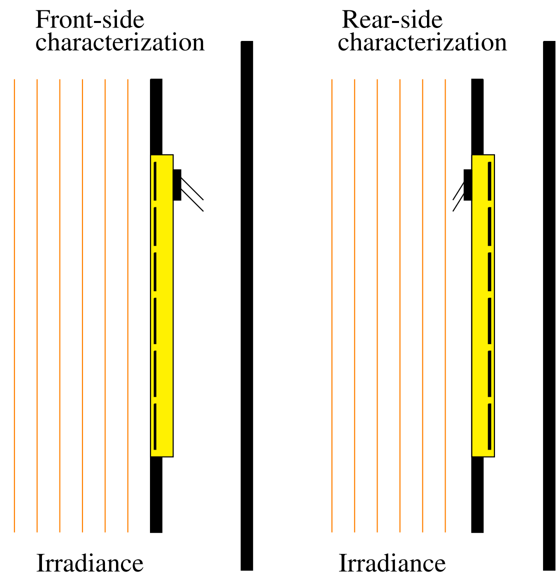


Fig. 1: Front and rear side characterization for bifacialities.

The remaining four bifacialities studied in this paper involve ϕ_{Voc} and ϕ_{Pmp} as specified in IEC TS 60904-1-2, and the relevant extensions to the MPP current and voltage, ϕ_{Imp} and ϕ_{Vmp}:

$$\phi_{Voc} = \frac{V_{ocr}}{V_{ocf}} \tag{2}$$

$$\phi_{Pmp} = \frac{P_{mpr}}{P_{mpf}} \tag{3}$$

$$\phi_{Imp} = \frac{I_{mpr}}{I_{mpf}} \tag{4}$$

$$\phi_{Vmp} = \frac{V_{mpr}}{V_{mpf}} \tag{5}$$

where the subscripts "r" and "f" indicate feature referring solely to the rear and front side respectively. ϕ_{Imp} and ϕ_{Vmp} introduced in this paper for the first time allows better understanding on how the current and voltage at different operating points differs in the two module sides.

The bifacialities are dimensionless numbers always lower than 1, depending on the feature they refer to and the technology. This is due to the rear side performing worse than the front side, because of less effective light conversion capacity as well as inferior optical characteristics, worse glass and coating features (e.g. no AR coating, higher IAM losses), and the junction box casting shadow to part of the rear side. Datasheets specify usually ϕ_{Isc} around $70 \pm 5\%$ [6], [14], [15] and ϕ_{Pmp} in the range of $70-80 \pm 5\%$ [5], [7], [16], [17]. ϕ_{Voc} is more rarely provided and it gets values slightly less than 100%, while ϕ_{Imp} and ϕ_{Vmp} are not available at any commercial datasheet.

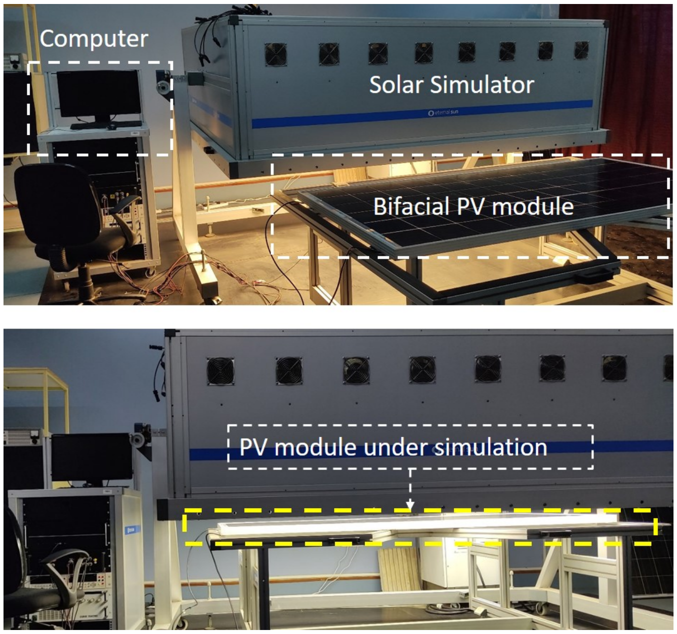


Fig. 2: Indoor Solar Simulator Lab.

TABLE I: Technical specification of bifacial PV module

Electrical Parameters	Front	Bifacial
P_{mp}	$380\ W_p$	$416\ W_p$
V_{mp}	$39.5\ V$	$41.6\ V$
I_{mp}	$9.64\ A$	$10.02\ A$
V_{oc}	$47.77\ V$	$48.14\ V$
I_{sc}	$10.11\ A$	$11.02\ A$
ϕ_{Isc}	0	0.7
ϕ_{Voc}	0	0.99
ϕ_{Pmp}	0	0.665
α_{Isc}	$0.065\ \%/^oC$	$0.065\ \%/^oC$
β_{Voc}	$-0.31\%/^oC$	$-0.31\%/^oC$
γ_{Pmp}	$-0.40\%/^oC$	$-0.40\%/^oC$

III. Indoor Measurement of Bifacial PV Modules

Fig. 2 depicts the setup used in this paper, comprising a standard monofacial indoors solar simulator able to emulate different illumination conditions and record the respective $I-V$ curve. The study-case bPV module is Adani HIP-195DA3 [14], which has 72 monocrystalline P-type PERC solar cells connected in series with the primary electrical parameters given in Table I.

The experiment measured the aforementioned module's front and rear sides independently to perform characterization of the two sides separately and infer the bifaciality factors. First, the front side was subject to 20 different irradiance levels in the range 650 to 950 W/m^2 while the rear side was in the dark (no illumination) and the respective $I-V$ curves were captured. Subsequently, the process was repeated with the rear side under illumination at 14 different levels in the same range, while keeping the front side in the dark. An example set of $I-V$ curves from the two sides at the same irradiance 751 W/m^2 is shown in Fig. 3. As expected, the rear side $I-V$ curve is inferior in terms of current, voltage and power. Please note that the setup did not have temperature control, and therefore the temperature was not kept constant during the experiment. The recordings of the experiment are given in the Appendix.

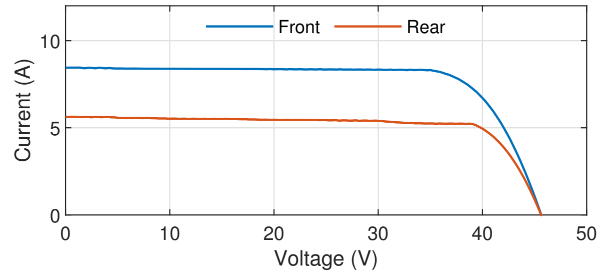
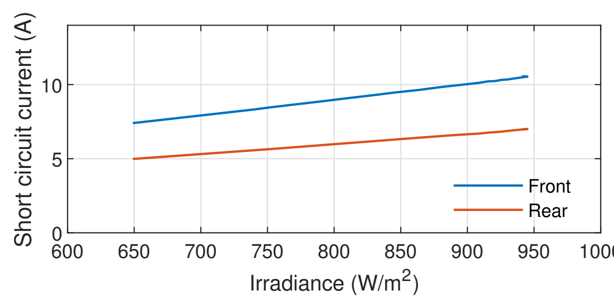
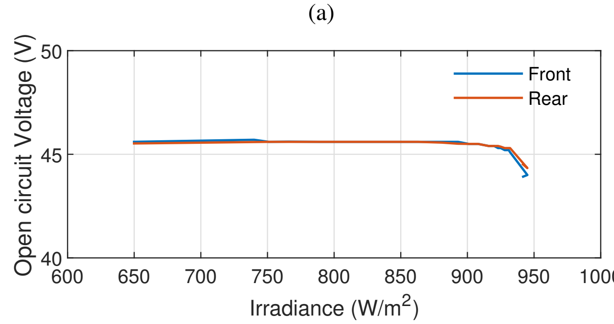


Fig. 3: $I-V$ curve from the two sides at irradiance level 751 W/m^2 at solar simulator lab

A. Results and Discussion



(a)



(b)

Fig. 4: Comparison of front and rear sides (a) short circuit current, (b) open circuit voltage, with change in irradiance.

Fig. 4a, 4b, 5a, 5b, 5c illustrate the five key features of the bPV module as they vary with irradiance for the two sides. As expected, V_{oc} changes slightly with irradiance, V_{mp} has a limited dependency, and I_{sc}, I_{mp} and P_{mp} exhibit a strong proportional irradiance effect. All the parameters attain lower values on the rear side compared to the front side due to the inferior light generating capacity and other factors, as discussed previously. It is worth noting, however,

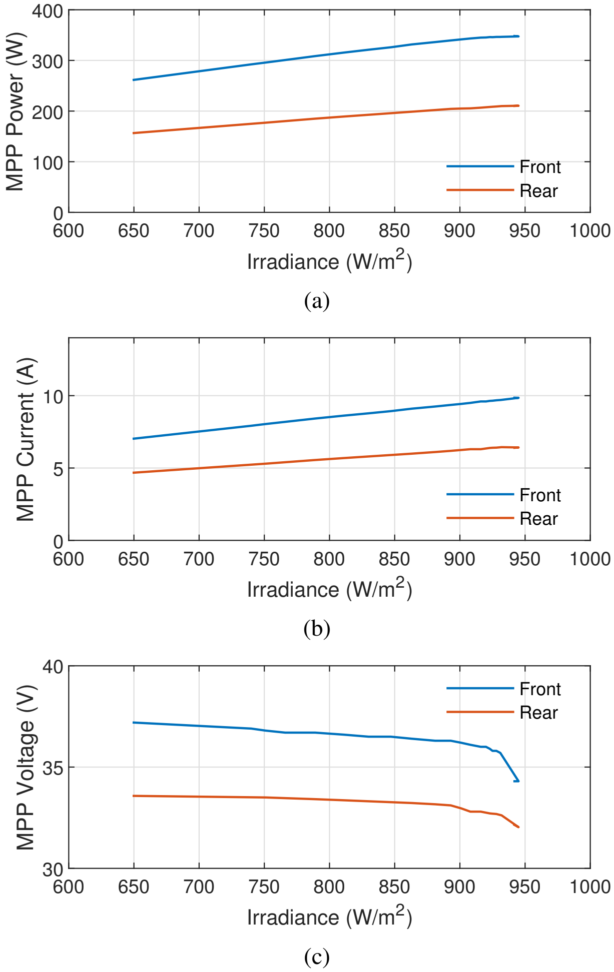


Fig. 5: Comparison of front and rear sides (a) MPP Power, (b) MPP Current and, (c) MPP Voltage, with change in irradiance.

that this deviation greatly differs from feature to feature; in V_{oc} for example it is almost imperceptible. The bifaciality investigation that follows delves into this aspect in more detail.

B. Calculation of Bifacialities

The approach described in IEC [8] and Eqs. $(1-5)$ are used to calculate all five bifaciality factors form the measured data. The measured bifacialities are plotted versus irradiance with circle markers in Fig. 6a, 6b, 6c, 6d and 6e. As a measure for comparison, the respective datasheet values are also shown with continuous horizontal lines when they are available (ϕ_{Isc}, ϕ_{Voc} and ϕ_{Pmp}), implying that they are constant irrespective of the conditions. There are a few eye-catching observations:

- None of the measured bifaciality factors are constants, but they all change with irradiance
- The irradiance effect is sufficiently linear, with few outliers and distortions probably due to the temperature factor that is neglected here
- This trend is sometimes negative (ϕ_{Isc}, ϕ_{Imp}) and sometimes positive (ϕ_{Voc}, ϕ_{Pmp}, ϕ_{Vmp})
- The datasheet values deviate somewhat from the measured ones even at close to STC irradiance

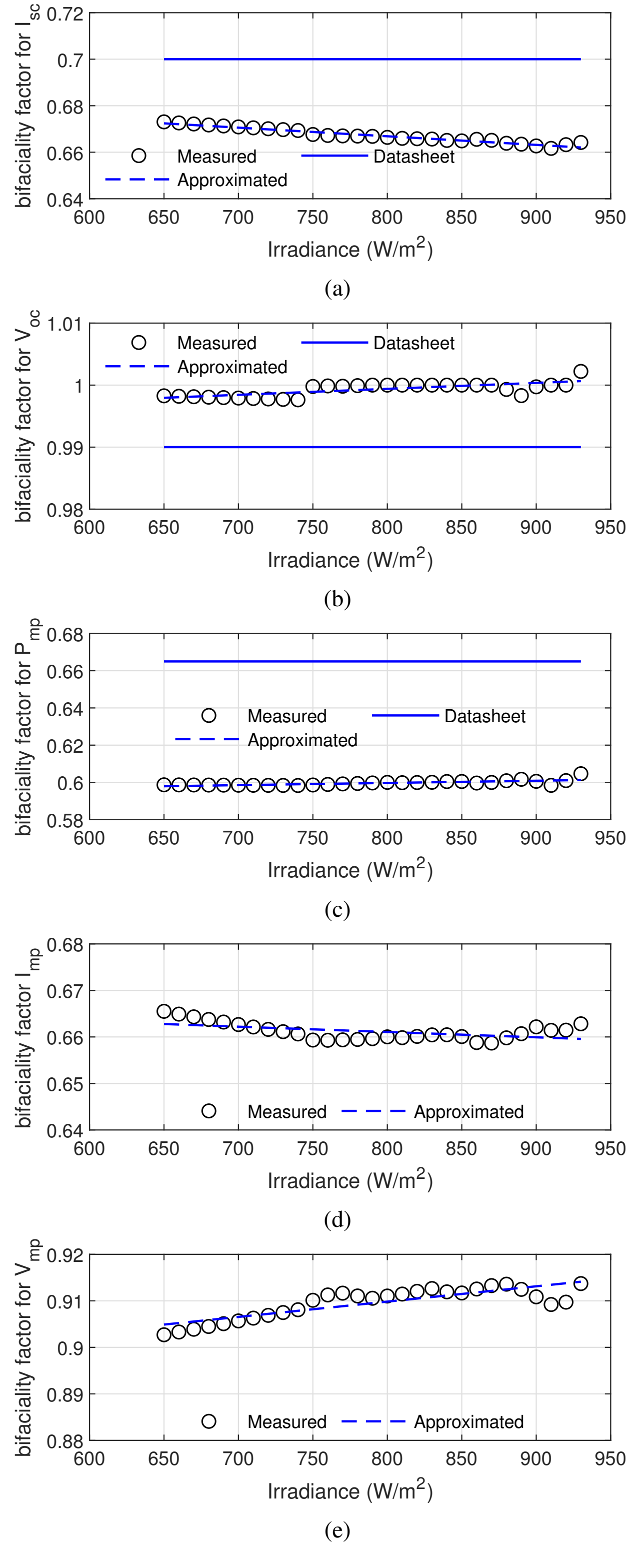


Fig. 6: Bifaciality factors (a) ϕ_{Isc}, (b) ϕ_{Voc}, (c) ϕ_{Pmp}, (d) ϕ_{Imp}, and (e) ϕ_{Vmp} from measurements, datasheet and approximation model.

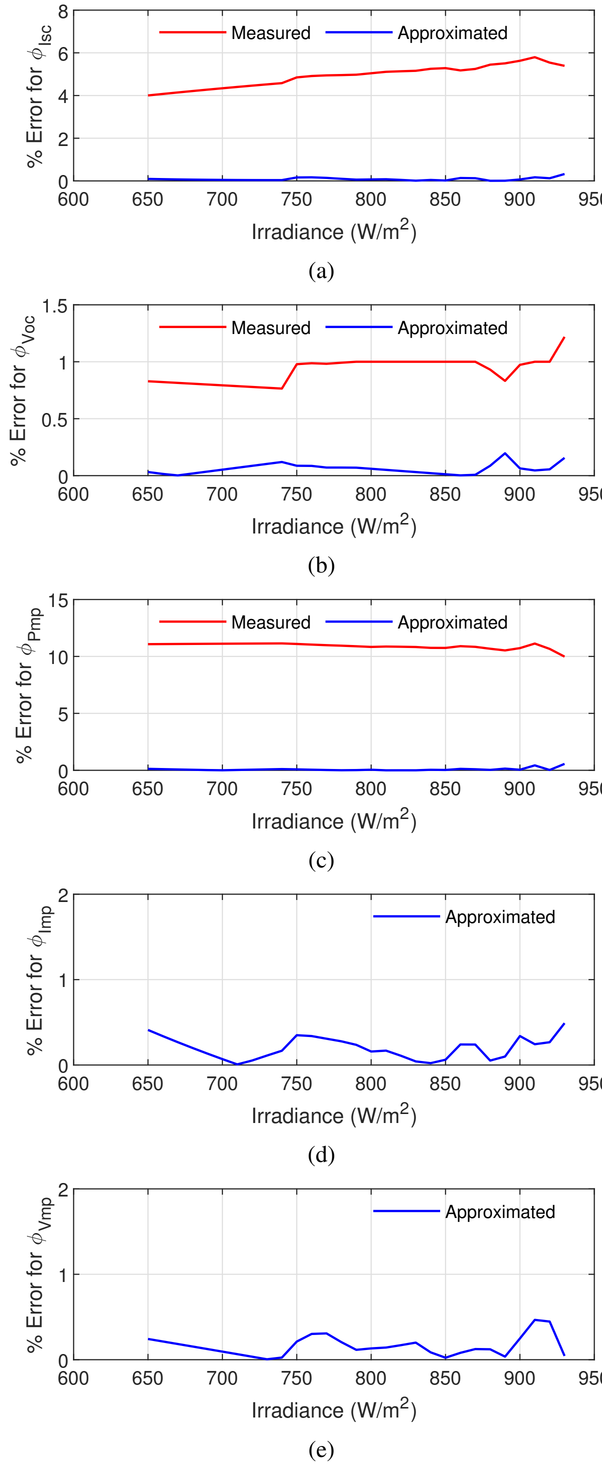


Fig. 7: Estimation errors for (a) ϕ_{Isc}, (b) ϕ_{Voc}, (c) ϕ_{Pmp}, (d) ϕ_{Imp}, and (e) ϕ_{Vmp} via the datasheet and approximation model.

To study these patterns further, a linear regression model is fitted on the measured bifacialities according to (6).

$$\phi = \phi_0 \left(1 + \delta \left(G - 1\right)\right) \tag{6}$$

TABLE II: Bifacialities Measured vs. Modeled

Bifacialities	**Datasheet**	**Modeled**	
	ϕ_{nom}	ϕ_0	δ (%)
ϕ_{Isc}	0.70	0.69	-0.005
ϕ_{Voc}	0.99	0.99	0.001
ϕ_{Pmp}	0.66	0.59	0.002
ϕ_{Imp}	-	0.67	-0.002
ϕ_{Vmp}	-	0.88	0.004

TABLE III: Bifaciality Estimation Errors

Bifacialities	**Datasheet**		**Modeled**	
	RMSE (%)	MAX (%)	RMSE (%)	MAX (%)
ϕ_{Isc}	3.3	5.80	0.07	0.32
ϕ_{Voc}	0.93	1.22	0.07	0.20
ϕ_{Pmp}	6.54	11.14	0.09	0.56
ϕ_{Imp}	-	-	0.16	0.49
ϕ_{Vmp}	-	-	0.18	0.47

where, ϕ is the bifaciality factor at an arbitrary irradiance level G, ϕ_0 is the nominal bifaciality at STC and δ the newly introduced *irradiance coefficient* which quantifies the irradiance effect. The fitted results shown with dashed lines in Fig. 6 clearly demonstrate that such a linear model approximates the irradiance effect very effectively.

The extracted coefficients are given in Table II and are compared to the datasheet nominal values. As already highlighted, the nominal bifaciality from the datasheet ϕ_{nom} and from the fitted model ϕ_0 differ more or less depending on the specific factor; note that for ϕ_{Pmp} the difference in more than the 5% tolerance given in the datasheet. As for the irradiance effect, the respective δ coefficients are relatively small, but they differ in sign: negative for the currents and positive for the voltages and power.

Fig. 7 graphically illustrates the performance of the two bifaciality approximations, i.e. via the datasheet or the fitted model, using the measured values as a benchmark. Clearly, the datasheet constant-value approach results in estimation errors that range from 1% to more than 10% depending on the factor. This seems to be mainly due to two reasons:

- The actual nominal (STC) bifacialities deviate from the datasheet
- The irradiance impact is neglected, as very visibly seen for ϕ_{Isc}

These observations are further solidified in Table III which shows the RMS and MAX errors for the five bifacialities and the two methods. With RMS and MAX errors of less than 0.2% and 0.6% respectively, the fitted model bifacialities are unquestionably far more accurate than the datasheet for all five bifacialities. Of course this is expected since the aforementioned model is trained on the samples, but it also reaffirms that the relation between bifacialities and irradiance is linear and it should be modeled as such.

IV. Conclusion

This study shows that the five bifaciality factors all depend on irradiance: the currents in a negative manner, the voltages and power in a positive way. Although the irradiance impact is not tremendous, it is sufficiently large to require modeling and it should not be ignored. This relationship is found to be linear, and therefore a linear model should suffice to this end. It is also concluded that the datasheet values for the bifaciality factors may be quite inaccurate, and it is advisable to be updated from measurements on the bPV module of interest.

Future work involves accounting for the temperature effect as well, which would require a much wider experimental dataset across various irradiance and temperature conditions. The resulting model should be validated on several bPV modules from different manufacturers. It would be also very interesting if the irradiance coefficients could be related to other module characteristics available in the datasheet to allow determination of the former without measurements, an investigation left also for future work. Furthermore, there are many unanswered questions in the electrical modeling and equivalent circuit of bPV modules which warrant answers.

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Appendix

Measured experimental data from the front and rear side of the Adani HIP-195DA3 bPV module.

TABLE IV: Front side experimental datasets

Sl. No.	Irradiance (W/m^2)	I_{sc} (A)	V_{oc} (V)	P_{max} (W)	I_{mp} (A)	V_{mp} (V)	Temp. (^oC)
1	649	7.4	45.6	261.3	7.02	37.2	38
2	740	8.3	45.7	292.2	7.92	36.9	41
3	751	8.4	45.6	295.8	8.04	36.8	42
4	766	8.6	45.6	300.8	8.19	36.7	43
5	789	8.8	45.6	308.6	8.42	36.7	44
6	811	9.1	45.6	315.5	8.62	36.6	44
7	830	9.3	45.6	321.1	8.78	36.5	45
8	847	9.5	45.6	326.0	8.93	36.5	45
9	863	9.6	45.6	331.6	9.1	36.4	46
10	881	9.8	45.6	336.2	9.25	36.3	46
11	893	9.9	45.6	339.5	9.36	36.3	47
12	901	10.0	45.5	341.5	9.43	36.2	47
13	908	10.1	45.5	343.3	9.5	36.1	48
14	916	10.2	45.4	345.0	9.6	36.0	48
15	920	10.2	45.4	345.3	9.6	36.0	49
16	923	10.3	45.3	346.1	9.6	35.9	49
17	925	10.3	45.3	345.9	9.6	35.8	50
18	928	10.3	45.2	346.4	9.6	35.8	50
19	931	10.4	45.2	346.6	9.7	35.7	50
20	932	10.4	45.1	346.6	9.7	35.6	50

TABLE V: Rear side experimental datasets

Sl. No.	Irradiance (W/m^2)	I_{sc} (A)	V_{oc} (V)	P_{max} (W)	I_{mp} (A)	V_{mp} (V)	Temp. (^oC)
1	621	4.8	45.5	150.8	4.5	33.6	35
2	751	5.6	45.6	177.1	5.3	33.5	37
3	796	6.0	45.6	186.5	5.6	33.4	38
4	873	6.5	45.6	200.6	6.0	33.2	40
5	895	6.6	45.5	204.7	6.2	33.1	40
6	908	6.7	45.5	205.4	6.3	32.8	41
7	916	6.8	45.4	206.7	6.3	32.8	41
8	924	6.8	45.4	208.3	6.4	32.7	42
9	927	6.8	45.3	208.9	6.4	32.7	42
10	933	6.9	45.3	210.1	6.4	32.6	42
11	935	6.9	45.0	209.3	6.4	32.4	44
12	943	7.0	44.4	236.2	6.4	37.1	45
13	946	7.0	44.3	236.7	6.4	37	47
14	950	7.0	44.0	237.3	6.5	36.6	54

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