IMPACT OF INHOMOGENEOUS IRRADIANCE AT THE REAR OF BIFACIAL PANELS ON MODELLED ENERGY YIELD

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ABSTRACT: The inhomogeneity of the rear irradiance of bifacial PV panels and its effect on the power loss due to current mismatch was investigated by modelling. We have found that the inhomogeneity of the rear irradiance depends on orientation, elevation, and tilt angle of the panel and on irradiance conditions. Typically the inhomogeneity of the rear irradiance is largest at a high fraction of direct light. Conversely, the inhomogeneity of the total irradiance is smallest when there is a large direct light component. The simulations indicated that the relative standard deviation (RSD) of the total irradiance will not exceed 5% even at albedo as high as 0.8, and is usually much smaller. Simulations mimicking near-field shading also showed that the RSD will be below 10% unless the beam component is small, i.e. at low light conditions. LTspice circuit simulations with an inhomogeneous current distribution showed that a current distribution with an RSD below 10% will not lead to cells going into reverse bias. This means the risk for hot-spots is small. A simple parametrization for the power loss as function of the RSD of the current distribution was established, which can be used for energy yield calculations.

Keywords: bifacial, module, simulation, shading, current mismatch

1 INTRODUCTION

By converting light falling on the rear as well as on the front of a solar panel, bifacial PV systems can produce 10-30% more electricity than conventional PV systems [1]. However, the irradiance on the rear of a solar panel is usually more inhomogeneous than on the front, i.e. the side facing the sun-light. This is first of all due to the shade created by the direct light falling on the panel, or its adjacent panels in a shed, which reduces the ground reflected irradiance on the rear [2,3]. In addition there may be near-field shade of objects at the rear such as the frame, the support of the panels, junction box, other equipment or panels in the next row of a system. These objects will block ground-reflected light as well as diffuse light falling on the rear.

Besides reducing the generated current, these shading effects induce a current mismatch between the individual cells of the panel, resulting in additional power loss. In monofacial systems the current mismatch is mostly caused by shading of the direct irradiance and is, therefore, often quite large. To avoid hot-spots, a whole group of cells is then by-passed by a diode, thereby substantially reducing the energy output of the system. Recent experimental results obtained by ECN indicated that the inhomogeneity in rear side irradiance of an equator-facing, tilted panel did not lead to cells going into reverse bias, i.e. did not cause conditions at which hotspots can occur [4]. It was found that the inhomogeneity in rear irradiance, in that study caused by variations in ground-reflected light as well as by objects at the rear, was small with respect to the total irradiance on the panel.

In this paper we first investigate the inhomogeneity of the irradiance for a wider range of conditions. Therefore, we carried out simulations with the recently developed ECN model designed to calculate the bifacial energy yield [5]. This model includes shading aspects affecting the irradiance on the rear, such as reduction of the ground-reflected irradiance by self-shading, limitations of the view factors for diffuse and reflected irradiance, and shading of the direct light on the rear. Next, we present LTspice [6] calculations to show the impact of inhomogeneous irradiation of bifacial photovoltaic (PV) panels on the expected power output. We find a simple parametrization, coupling the simulated irradiance inhomogeneity to the modelled power loss.

2 DESCRIPTION OF THE MODEL

2.1 Irradiance model

We calculated the effect of inhomogeneous irradiance on the rear for a landscape oriented, free-standing panel in Amsterdam. Meteorological data with one-hour resolution for Amsterdam were synthetically generated from monthly average values in the database PVGIS using PVSyst [7,8]. Two configurations were considered: south-facing with a tilt angle of 38° and an east-orientated vertical module. The edge of the module was 0.5 m above the ground, unless specified otherwise.

The irradiance G_{front} on the front side of the free-standing module with tilt angle β can essentially be written as [9]:

$$G_{front} = (GHI - DHI)\cdot\frac{\cos\theta}{\cos\theta_z} + DHI\cdot\frac{1+\cos\beta}{2} + \gamma\cdot DHI\cdot\frac{1-\cos\beta}{2} + \gamma\cdot(GHI - DHI)\cdot\left[\frac{1-\cos\beta}{2} - VF_{front-shade}\right] \quad (1a)$$

Here GHI and DHI are the global and the diffuse irradiance on a horizontal plane, θ is the angle of incidence of the beam on the tilted plane, θ_z is the zenith angle of the sun, and γ is the ground-reflection coefficient or albedo. $VF_{front-shade}$ is the view-factor of the front to its self-shade; this term reduces the total ground-reflected irradiance. $VF_{front-shade}$ will only deviate from zero when the beam is incident on the rear of the panel, i.e. it will usually be negligible for an equator-facing panel. For an east-facing system $VF_{front-shade}$ is non-zero as soon as here is direct irradiance from the west, i.e.50% of the time. Note that, like most other models, the ECN software actually uses a more complex equation to calculate the contribution of diffuse irradiance on the tilted plane but such details are not relevant for this study.

For the irradiance G_{rear} on the rear side a similar equation applies:

$$G_{rear} = (GHI - DHI) \cdot \frac{\cos\theta}{\cos\theta_z} + DHI \cdot \frac{1-\cos\beta}{2}$$

$$+\gamma \cdot DHI \cdot \frac{1+\cos\beta}{2} +$$

$$\gamma \cdot (GHI - DHI) \cdot \left[\frac{1+\cos\beta}{2} - VF_{rear-shade}\right] \quad (1b)$$

In this case θ is the angle of incidence of the beam on the rear of the tilted plane. $VF_{rear\text{-}shade}$ is the view-factor of the rear to its self-shade, and this term can be quite significant. As shown by Yusufoglu et al. [2,3] $VF_{rear-shade}$ does not only depend on the position of the sun with respect to the module and the tilt angle, but also on the elevation of the module. The $VF_{rear-shade}$ varies over the module surface. This makes the rear irradiance intrinsically inhomogeneous.

It must be noted that Eq. 1a and 1b only include self-shading caused by the beam. For a free-standing panel this is probably a valid assumption, unless the tilt angle and elevation are very low. In the case of a PV system consisting of many modules, the diffuse irradiance hitting the ground will also be reduced by the presence of adjacent modules or modules in adjacent sheds.

A convenient way to characterize the inhomogeneity of the irradiance of *n* cells in a panel (or cell-string) is by means of the relative standard deviation RSD:

$$\mathrm{RSD} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(G_i - G_{mean})^2}}{G_{mean}} \qquad (2)$$

Where G_i is the irradiance on cell *i* and G_{mean} the average over all *n* cells. The RSD can be calculated for the total irradiance, but also for front or rear irradiance only.

2.2 LTspice model

To investigate the effect of G_{mean} and RSD on the power loss due to current mismatch, we constructed irradiance distributions with a random generator. We selected six different values for G_{mean} and seven RSD values between 1 and 20%. An irradiance distribution for 60 solar cells was made to match each (G_{mean}, RSD) combination. This irradiance distribution was then fed to LTspice to simulate a 60-cell 240 Wp front efficiency module. The short-circuit current of each cell was taken proportional to its incident radiation. Furthermore, the module was divided in three 20-cell strings and each string was protected with a by-pass diode.

3 RESULTS

3.1 Inhomogeneity due to self-shading

Fig. 1 shows examples of inhomogeneous irradiance on the rear of a panel. The most remarkable feature is that the inhomogeneity decreases rapidly with elevation, due to the quadratic dependency of $VF_{rear-shade}$ on the distance between the panel and its shade on the ground. Smaller distances not only lead to a larger$VF_{rear-shade}$, but also to larger variations of the value over the panel. [3]. We also found that the RSD of portrait-orientated panels is smaller than for landscape-orientated ones that we consider in this study, since portrait -orientated panels have more solar cells at larger distance from a shade on the ground.. Other system lay-out parameters that affect the inhomogeneity are the tilt angle, i.e. at lower tilt angle the relative difference in distances to the shade are larger, and the position of the panel in the system. On panels that are not located near the edges of the sheds the rear irradiance has a regular pattern, which can be used when grouping cells in strings (Fig. 1, bottom). The second factor determining the inhomogeneity is the irradiance. As will be shown in more detail below, the inhomogeneity on the rear will increase when the ground reflected contribution increases and the diffuse contribution decreases.

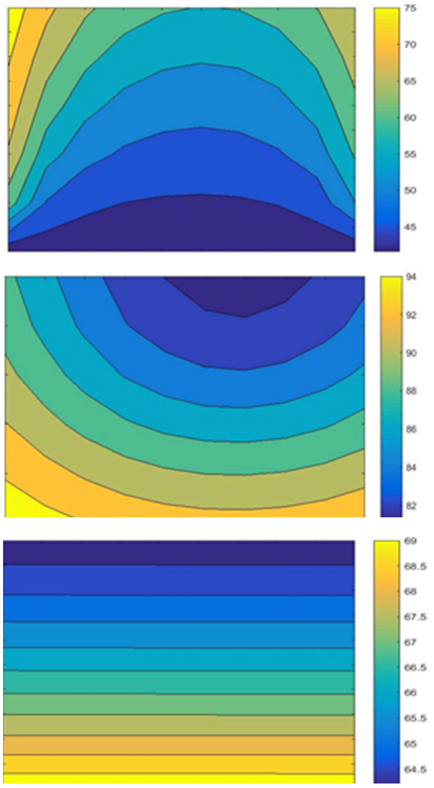

Figure 1: Examples of inhomogeneous irradiance at the rear of a 10x6 cell landscape-oriented, south-facing panel in Amsterdam, with tilt angle 38° and albedo 0.2.The scale is rear irradiance inWm^{-2}. The top and center graph are free-standing modules with elevation 0 and 0.5 m, respectively. The bottom panel is in the center of a 19 panel-wide shed, at 2 m elevation. The RSD of the rear irradiance was 17.9% (top) 4.6% (center), and 2.6% (bottom).

The RSD of the rear irradiance of the south-facing, free-standing panel with 38° tilt at 0.5 m elevation can be as large as 13%, depending on the albedo. The RSD increases with the total irradiance G_{tot} incident on the panel (see Fig. 2). Conditions of high total irradiance imply a large contribution of the beam component (see Fig. 3) and therefore a more pronounced self–shading effect. However, it must be noted that also the position and size of shade affects these variations, the highest RSD is often obtained at times when the sun is just before or after its most southern position.

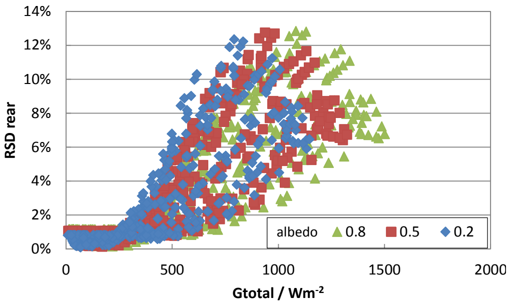

Figure 2: The calculated RSD of the rear irradiance of a free standing, south-facing panel in Amsterdam during the month of April.

The dependency of the rear RSD on the albedo is small. This is because the irradiance on the rear is dominated by the albedo, i.e. the numerator and denominator in eq. 2 both essentially scale with the albedo. The calculated RSD values shift to higher values of G_{tot} because G_{tot} increases with albedo.

Although RSDs in the order of 13% of the rear irradiance may seem quite significant, the impact on the module or string output is determined by the variations occurring in the total generated current in each cell, i.e. variations in the total incident irradiance. In the cases under consideration the RSD of the total irradiance is much smaller, ranging from 1.5% at albedo 0.2 to 4% at albedo 0.8, as Fig. 4 shows.

The ratio G_{rear}/G_{front} determines what the contribution of the rear RSD will be on the RSD of the total irradiance. This ratio depends on the irradiance conditions and, as Fig. 5 shows, decreases with the total irradiance. When the *diffuse* component dominates, as is often the case at low G_{tot}, the ratio is given by:

$$\frac{G_{rear}}{G_{front}} = \frac{(1-\cos\beta)+\gamma(1+\cos\beta)}{(1+\cos\beta)+\gamma(1-\cos\beta)} \qquad (3)$$

This means that at tilt angle β=0° (and high enough elevation) G_{rear}/G_{front} is equal to the albedo γ; at 90° tilt angle the ratio is equal to one. At 38° tilt angle the ratio is 0.31, 0.58 and 0.83 at albedo 0.2, 0.5 and 0.8, respectively. This is in good agreement with the data at low G_{tot} shown in Fig. 5.

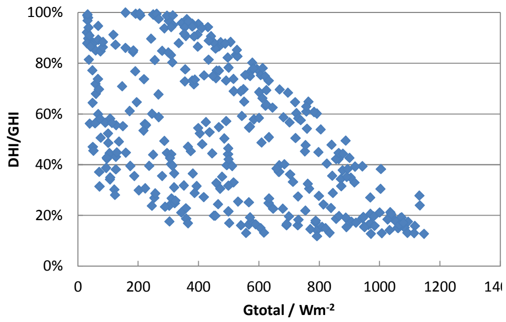

Figure 3: The ratio DHI/GHI in Amsterdam during the month of April plotted versus the total irradiance on a free standing, south-facing panel in Amsterdam.

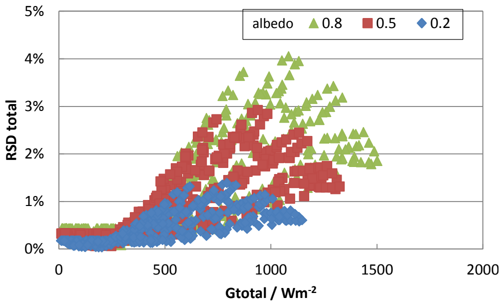

Figure 4: The calculated RSD of the total irradiance of a free standing, south-facing panel in Amsterdam during the month of April.

At high G_{tot} the *beam* component is dominant and G_{rear}/G_{front} is determined by (neglecting the self-shade):

$$\frac{G_{rear}}{G_{front}} = \frac{\gamma(1+\cos\beta)/2}{\cos\theta/\cos\theta_z+\gamma(1-\cos\beta)/2} \qquad (4)$$

Now G_{rear}/G_{front} depends on the position of the sun with respect to the panel. At Amsterdam conditions in April, the ratio for a panel with 38° tilt angle decreases to values of half the albedo (Fig. 5).

Comparison of Fig. 2 and 5 shows that when the irradiance on the rear is most inhomogeneous, the fraction of rear irradiance is small. In most south-facing configurations the G_{rear}/G_{front} will be lowest at high irradiance conditions, and this leads to RSD values of the total irradiance that are considerably lower than the RSD of the rear irradiance, even at high albedo.

The module tilt angle is usually such that maximum use is made of the beam component, i.e. that the annual sum of $(GHI - DHI)\cos\theta/\cos\theta_z$ is highest. However, bifacial panels can also be advantageously used in an east-west configuration. In this case the tilt angle is 90°, i.e., the modules are placed vertically, to make best use of beam components coming from either the east or the west. Although this would lead to lower $\cos\theta/\cos\theta_z$ values and thus higher G_{rear}/G_{front} compared to the south-facing configuration, the self-shade of the panel is usually further away from the rear (in this case the rear is the side not receiving direct light) and the RSD of the G_{rear} is smaller. Fig. 6 (top) shows the RSD of the west side. The

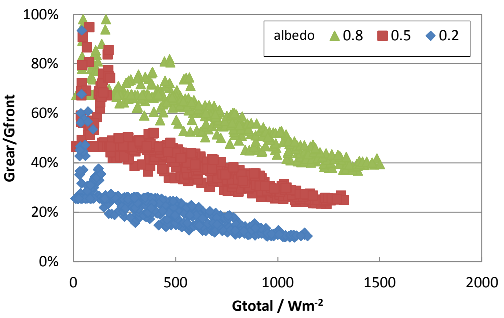

Figure 5: The ratio G_{rear}/G_{front} for a free standing, south-facing panel in Amsterdam during the month of April.

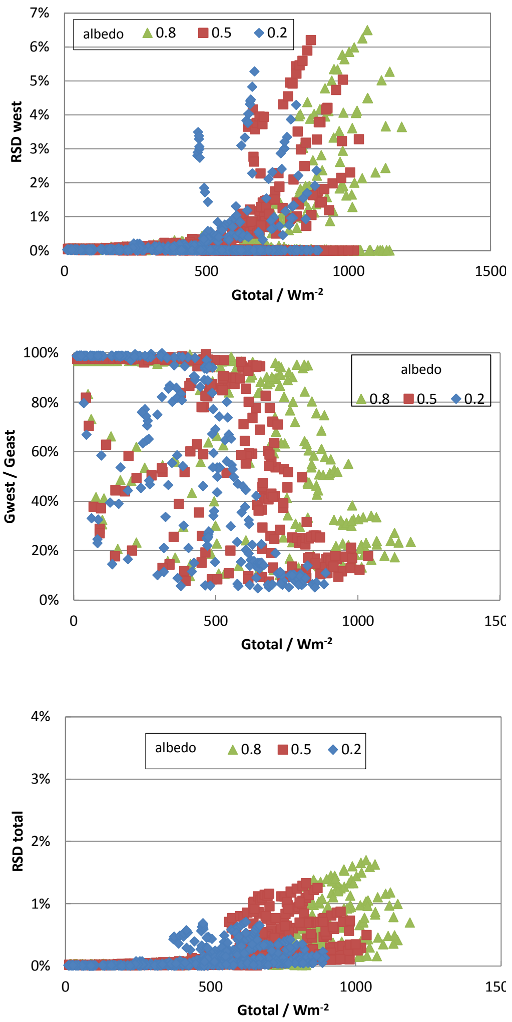

Figure 6: The calculated RSD of the irradiance on the west side (top), the ratio G_{west}/G_{east} (center) and the RSD of the total irradiance (bottom) on a free standing, vertical, east-west facing panel in Amsterdam during the month of April.

inhomogeneity is either very small, i.e., when the direct light is from the west, or up to values of about 7%. The G_{west}/G_{east} is now 100% when diffuse light prevails, and reduces to values much lower than the albedo at high G_{tot} values (Fig. 6, center). A similar picture applies for the east side of the panel and in the resulting RSD values for the total irradiance are < 2% even at high albedo (Fig. 6, bottom).

3.2 Near-field shading

Shading by objects such as junction boxes at the rear can easily lead to the situation where several cells receive only a fraction of the rear irradiance [4]. Using Eq. 2 it can be calculated that if the irradiance on the rear of one or two cells is zero and homogeneous and non-zero on all other cells, the RSD for the rear irradiance of a 60-cell module will be 13%, respectively 19%. In the case that these two cells receive half the irradiance the other cells receive, the RSD will be 9%. In practice, there will also be differences in self-shading as discussed in 3.1, but these will yield a smaller increase in RSD. Moreover, it will not matter much which cells are completely shaded.

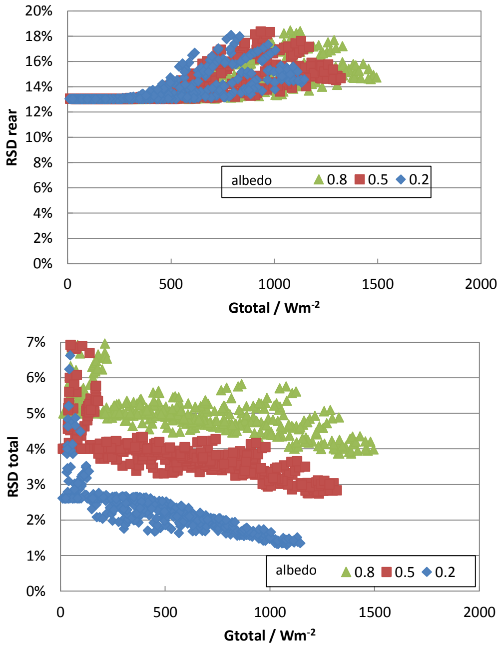

Figure 7: The calculated RSD of the rear irradiance (top) and of the total irradiance (bottom) on a free standing, south-facing panel in Amsterdam during the month of April. In the calculation it was assumed that one of the cells does not receive any rear irradiance.

Note, that in the experimental, outdoor study at ECN, which included near-field shading but where no cell was completely blocked, the rear irradiance of a portrait-oriented module had an RSD of 13.8%

Fig. 7 shows the calculated RSD of the rear and total irradiance, under identical conditions as Fig. 2 and Fig. 4, with the addition that one cell receives no rear irradiance. Because of the fairly constant RSD of the rear irradiance, the RSD of the total irradiance now decreases with the total irradiance, in agreement with the decreasing ratio of G_{rear}/G_{front} (Fig. 5). At Amsterdam conditions, the RSD of the total irradiance of a 60 cell module with one cell completely shaded at the rear will then be 2-4% at moderate albedo and about 5% at high albedo (Fig. 7).

3.3 Impact of current mismatch on electrical output.

The inhomogeneous irradiance on the rear leads to variation in the photocurrents of the solar cells, which are connected in series. LTspice was used to calculate the power output of modules with inhomogeneous irradiance distributions, characterized by combinations of G_{mean} and RSD, as explained in section 2.2. The power loss due to the current mismatch can be quantified by the parameter *f*:

$$f = 1 - \frac{P_{inhom}}{P_{hom}}, \qquad (5)$$

where P_{hom} is the sum of the power at MPP of 60 cells with a homogeneous irradiance G_{mean}; P_{inhom} is the output of a string of 60 cells, which have an irradiance distribution with average irradiance G_{mean} and an RSD > 0.

Fig. 8a shows the mismatch fraction f calculated with each distribution as a function of the mean irradiation G_{mean}. The mismatch fraction f is not strongly dependent on G_{mean}. However, as Fig 8b shows there is a clear correlation with the RSD of the distribution, especially for RSD < 10%.

For RSD < 10% the relative power loss f depends only on RSD and not on the total irradiance. In the majority of realistic irradiance-view factor-albedo conditions the RSD is significantly smaller than 10%; even with one cell fully blocked for rear irradiance and at albedo 0.8, the RSD of the total irradiance is < 6% (see Fig. 7 bottom).

At RSD > 10% the loss factor f increases more rapidly with RSD and exhibits a large variation, in the order of ±5%, for very similar RSD values. In these cases the RSD alone is not sufficient to accurately predict the loss.

4 DISCUSSION

The results for the free-standing panel in Amsterdam show that the inhomogeneity of the total irradiance due to self-shading effects will be limited to < 5%, even at high albedo (Fig. 4). The main cause is that the homogeneous front side irradiance will dominate, especially at high irradiance conditions where the ratio between front and rear irradiance will approach half the ground-reflection coefficient.

Such small variations in irradiance, or equivalently in current, will not lead to hot-spots, as simulations by LTspice showed. This result is in agreement with observations in the literature that inhomogeneities in cell power up to 15% over a string can still be tolerated without large mismatch losses [10].

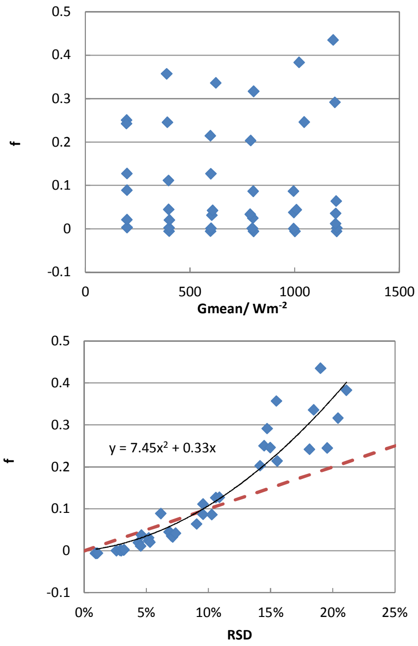

Figure 8: The calculated power mismatch fraction f as a function of the mean irradiance (top) and as a function of the relative standard deviation RSD (bottom). In the bottom figure the dashed, red line indicates f=RSD, the black line is the best fit through all data points with the quadratic equation given.

Near-field shading, as long as it is not shading the direct light, will in most cases not give rise to a large inhomogeneity in the overall irradiance, except when the front and rear irradiance are similar. This can only happen in the absence of a direct beam component and thus at low total irradiance; but in that case, hot-spots will not occur because the energy dissipation is too low.

Consider a possible “worst-case scenario” where the front side is covered by snow and sun light is reflected of fresh snow below the bifacial modules. In this case the RSD of the overall irradiance will be identical to that of the rear. However, in this case the module’s rear side must face down. Due to the sun’s position in the sky in the winter, i.e. low and in the Southern hemisphere, the total (rear) irradiance due to diffuse and ground-reflected light will not be high. Thus the dissipated energy will usually be limited.

The calculations here were done for Amsterdam at 52° north. At locations closer to the equator lower tilt angles are used and more inhomogeneity in the rear irradiance is expected. But at these locations the beam component will be (much) stronger, which will limit the effect of the inhomogeneous rear irradiance on the total irradiation.

For energy yield predictions the power losses due to current inhomogeneity that is not caused by direct beam shading can be approximated by a linear dependence when the RSD does not exceed 10%. For higher RSD values, a quadratic expression as found for the 60-cell case in section 3.3 can be used. Note, that these relationships were obtained for a 6o-cell circuit that is a single module under MPP tracking. Larger module strings are not within the scope of this paper, but we expect a similar relationship to be valid as long as the variations in the irradiance are in the same range.

5 CONCLUSIONS

- Due to self-shading the rear irradiance of a PV-panel in Amsterdam shows relative standard deviations up to the order of 13% at an elevation of 0.5 m. Larger RSD values for the rear irradiance are obtained for higher beam component, but the maximum values are not sensitive to the albedo value. The RSD decreases with elevation and tilt angle.
- The effect of the inhomogeneous rear irradiance on the variation of the total radiance depends on the ratio of the front and rear irradiance. The presence of a strong beam component on the front, and thus a low G_{rear}/G_{front} ratio, reduces the RSD of the total irradiance to < 2% at albedo 0.2, and < 5% at albedo 0.8. For vertical east-west facing vertical panels even smaller values were found.
- A near-field shade that fully blocks reflected and diffuse light on the rear can cause an inhomogeneity in the rear irradiance exceeding 13%. But the occurrence of hotspots is not very likely. At low light intensity, the induced reverse voltage in the shaded cell is not accompanied by a significant power dissipation, whereas at high light intensity the inhomogeneity in the total irradiance is much reduced by the dominating, homogeneous front irradiance.
- Because the inhomogeneity in the total irradiance rarely exceeds 10%, the relative power loss will be about the same as the RSD of the total irradiance.

ACKNOWLEDGEMENTS

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