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PV YIELD PREDICTION FOR THIN FILM TECHNOLOGIES AND THE EFFECT OF INPUT PARAMETERS INACCURACIES

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ABSTRACT: Accuracy of the PV yield prediction process, including meteorological data (direct and diffuse irradiance including its actual spectral composition and spatial distribution), material properties of encapsulation (refractive indices, absorption coefficients, and thermal properties), parameters relevant for heat transfer and heat dissipation, PV conversion parameters of the cells (spectral response, weak light performance, temperature coefficients, degradation) considerably depends on the quality of the input data applied (derived from literature, data sheets, norms, software tools, or own measurements). The contribution gives an overview of the processes involved, the relevant parameters, the accuracy achievable and the impact on yield prediction.

1 INTRODUCTION

1.1 Background

Due to elevated prices of solar grade silicon, the PV industry introduced several different cell technologies based on different materials and thin film technologies. The existing PV yield prediction tools have been created for single and multi-crystalline silicon cells. They are quite accurate and are backed by extensive monitoring. The recently introduced thin-film materials show significant different properties in terms of spectral response, weak light performance, temperature coefficients, flat incidence absorption, degradation and regeneration effects. This leads to a considerable error in electrical yield prediction by those established tools. Preliminary screening shows that the deviation effects may reach the vicinity of 20%, depending on cell technologies, installation site and operating conditions. To overcome this unsatisfying fact, an extensive program accounting for all sun rays incidending on the module (direct or scattered) with their actual angles of incidence, spectra and polarization condition for every minute of PV operation has been developed [1–3, 5–7]. The model calculates the reflected part and matches the cell-reaching spectrum with the actual quantum efficiency of the cell a achieve I_{SC}. The absorbed irradiance that is not transformed into electricity defines the input heat-flow for the consecutive thermal model (see Fig.1, lower part).

The model computes the cell temperature with an accuracy of ±1.5 K via a heat transfer balance considering dissipation via natural or forced convection, thermal emission and storage, thus allowing determining actual voltage, form factor and power output of the module. Computed results have been verified via outdoor data [6].

1.2 Approach

During tests run of that PV yield prediction software the following particulars have been found:

Accuracy of the entire yield prediction process, including meteorological data (direct and diffuse irradiance with its actual spectral composition and spatial distribution), material properties of encapsulation (refractive indices, absorption coefficients, thermal properties), PV conversion parameters of the cell (temperature coefficients, spectral response, weak light performance, degradation) considerably depends on the quality of the input data applied (derived from literature, data sheets, norms, software tools, or own measurements).

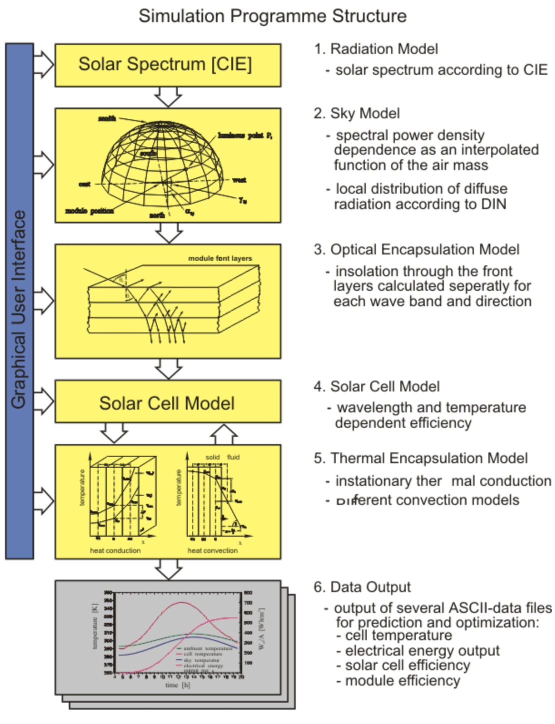

Figure 1: Structure of the PV yield prediction software.

2 PARAMETERS

- Irradiance could be measured quite precisely (within an accuracy range of 2%) using state-of-the-art pyranometers.
- Usually irradiance measurements are carried out on a horizontal plane and irradiance on tilted surfaces (e.g. the plane of the PV module installation) is extrapolated, causing an inaccuracy of 3% to 5%, depending on the local conditions.
- Irradiance has an almost linear impact on PV yield: while I_{SC} is very linear, V_{oc} and FF are increasing for

higher irradiance levels.

- Information on the actual incoming spectrum is quite vague and more based on estimation rather than on measurements.
- Spectral response of the PV modules depends considerably on the cell technology (see Fig. 2) to a lesser extend on irradiance level (see Fig. 3, 4) and on temperature (see Fig. 5).

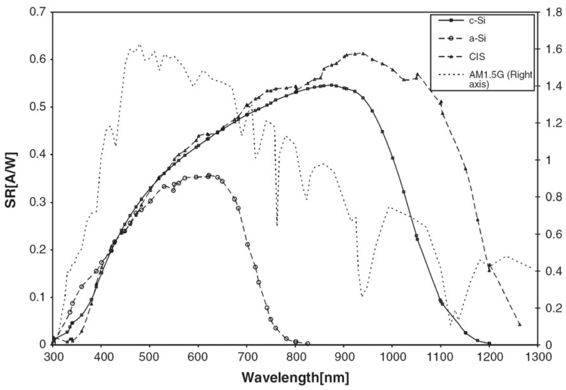

Figure 2: Comparison of absolute spectral responses for different solar cell materials, together with an AM 1.5$_G$ spectrum (according to [9]).

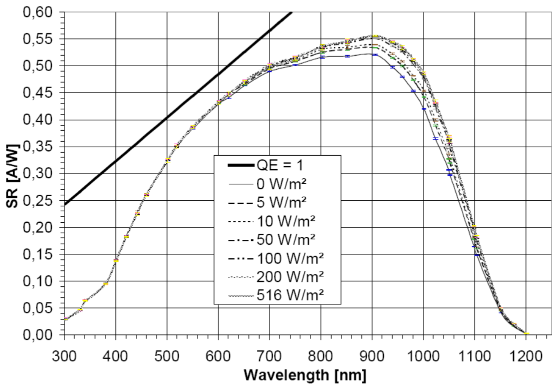

Figure 3: Expansion of spectral response at increasing bias irradiance levels (c-Si at 25°C, according to [10]).

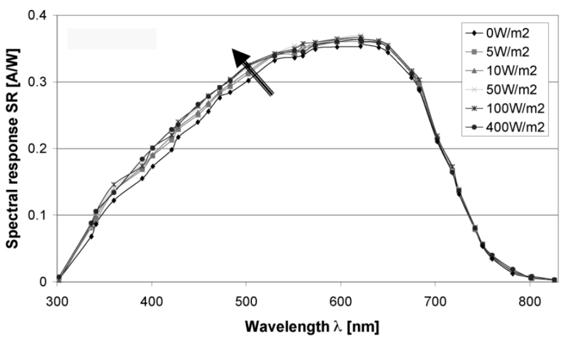

Figure 4: Expansion of spectral response at lower wavelengths for increasing bias irradiance (for a-Si at 25°C, according to [11]).

- Increasing temperature reduces V_{OC}, but also enables slightly higher wavelengths to generate an electron-hole pair, thus expanding the usable wavelength and increasing slightly I_{SC} (see Fig. 5).

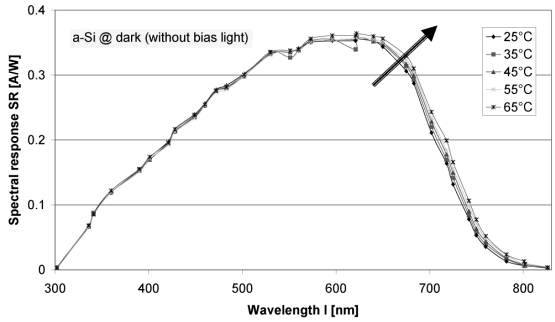

Figure 5: Expansion of spectral response at increasing temperatures (for a-Si, according to [11]).

- Polarization of diffuse irradiance occurs commonly but is rarely taken into account. Not considering polarization leads to an overestimation of PV yield in the vicinity of 0.4–0.7% (see [7] and [8]).
- Albedo depends very much on micro-siting of the PV power plant, reflectivity of ground surface may vary significantly and could even change for different weather conditions (e.g., wet vs. dry, see [6]). Usually the effect of Albedo plays a greater role for locations more distant from the equator, where module elevation angle is more elevated, esp. at PV façade installations. In the tropics the PV module surface is facing towards the sky, thus reducing considerably possible Albedo.
- Shadowing from fixed objects can be determined quite accurately via different tools, however shadowing from living vegetation or smoke (or vapor) from chimneys is hard to determine exactly.
- Outdoor temperature can be measured quite precisely and does not pose a relevant problem for the determination of PV yield.
- Wind speed and wind direction is most often measured at a certain height above ground (typically at 5 m or at 10 m) and extrapolation of this data to the module front and back surface causes significant errors. Even at a distance of 1 m only from the module installation site the deviation of wind speeds is considerable (see Fig. 6), however the impact of that inaccuracy on PV power output remains below 3%.

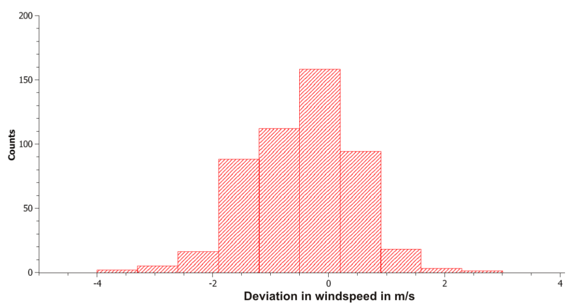

Figure 6: Frequency of deviation of measured wind speed on the module surface compared to measurements at a distance of 1 m from the module installation site.

- Optical and thermal parameters of the materials of encapsulation such as the refractive index, the absorption and the heat conductivity of glass, EVA, and antireflective coating (cell or module) can be determined accurately in the case of glass, less accurate for EVA and antireflective coatings, leading summarized to an uncertainty in yield of about 2.7% to 3.7% (see also [2]).

- Thermal parameters at module surface and the ambient cannot be found very precise, their impact on yield is intermediate (ca. 3.7%). Instead of using a theoretical approach [2, 6], convective heat transfer can be measured also [4].

- Data for temperature coefficients (*tc*) is often inaccurate (esp. for I_{SC}) and may even change during lifetime (e.g., reduction of *tc* at a-Si modules after degradation, see [13]).

- Cell temperature: Typically, measurements of the module surface temperature are taken as cell temperatures. The error of that method is at least 2 K for backside measurements at modules equipped with conventional backsheets (Tedlar-Polyester-Tedlar). Also a temperature distribution over the area of the module can be observed (see Fig. 7), therefore positioning of the temperature sensor is important, while the range of measured temperatures can deviate by 5 K. Front surface temperature can be considerably lower than temperature on the back surface (see Fig. 7), especially for thick glass-glass modules and for high wind speeds.

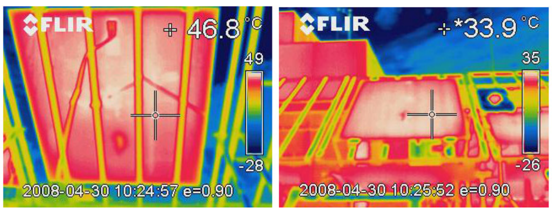

Figure 7: To the left: temperatures on the back surface of a glass-glass a-Si module. To the right: temperatures on the front surface of the same module. Maximum temperature is displayed.

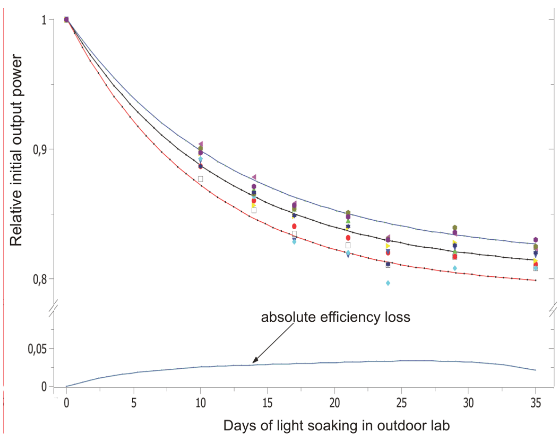

Figure 8: Degradation observed at several a-Si modules from the same manufacturer at PI's outdoor lab during 40 days of light soaking.

- Degradation: Even for the same PV technology degradation may vary: As shown in Fig. 8, the final loss by degradation can be 16.5% or reach 19.5% (for some cases even 24.9%) – even for the same PV technology (a-Si) from the same manufacturer, thus causing large errors for the prediction of PV yield.

- Weak light performance & degradation: the general characteristics for weak light performance at different irradiance levels seems to remain similar for different levels of degradation, as shown in Figure 9 for a single-junction a-Si module. However, there is a very slight tendency that the degradation is less pronounced for weak light levels.

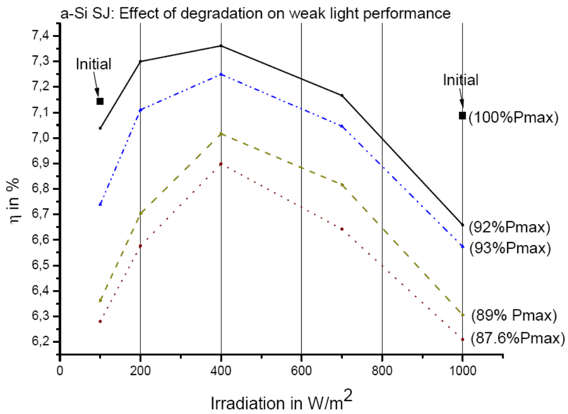

Figure 9: Weak light performance (100 to 1000 W/m²) at different degradation levels for a single junction a-Si module (a totally degraded module of this type would show 75% of the initial power P_{max}).

- MPPT-Tracking (see [12]) and final power measurement can be performed within an accuracy of 0.5–1% each, leading to the same value in deviation for the determination of PV yield (summarized 1–2%).

3 SIMULATION

The simulation was used as a tool to carry out the prediction on electrical energy yield and to observe the impact on the results from variations of the different parameters. As described above it is based on an extensive model (as shown in Figure 1) that uses the incoming spectra from each direction on the sky sphere, traces the rays through the encapsulation and into the cell, matches the outcome with the actual spectral response of the cell, and computes the power output along with the heat flow, heat dissipation and operating cell temperature.

4 RESULTS

A large dissimilarity of input data was observed with at times less relevant, but occasionally with significant effects on the accuracy of PV yield prediction. Consequently, a preliminary screening of inaccuracies has been carried out. The results of that screening are presented in Table I (preliminary data).

Table I: Overview on the parameters that influence PV yield prediction, incl. qualified guess of values.

Parameter	Variation of data (±)	Effect on PV-yield (±)
Irradiance:		
Horizontal global irradiance	2–4%	2–4%
Tilted global irradiance	3–5%	3–5%
Actual spectral information	10–70%	5–20%*
Polarization - diffuse irradiance	10–20%	0.5–1%
Albedo	9–50%	4–19%
Shadowing	0–20%	0–85%
Meteorological parameters:		
Outdoor temperature	2%	0.5%
Wind speed (at module)	50%	1.5%
Wind direction (at module)	10%	1%
Encapsulation parameters:		
refractive indices	2%	0.5–1%
absorption coefficients	2–10%	0.5 %
heat conductivity of module materials	3-10%	0.5-1%
Thermal parameters at module surface relevant for heat exchange with ambient:		
emissivity of module surfaces	2–5%	ca. 0.7%
emissivity of ground surfaces	10–15%	ca. 0.5%
equivalent sky temperature	15–20%	ca. 0.5%
convective heat transfer coeff.	10–30%	ca. 2%
Cell Parameters:		
spectral response	5–10%	5–10%*
temperature coefficients	5–20%	0.5–2%
weak light performance	1–20%	1–10%
degradation (for thin film)	3–20%	3–20%
Electrical yield:		
MPP tracking accuracy	0.5–1%	0.5–1%
Measurement of electrical power output and yield	0.5–1%	0.5–1%

* depending on cell technology and materials

5 CONCLUSION

The effects on PV yield range from 0.5% to 20%; consequently, further effort should focus on the improvement of the data precision for those parameters that are responsible for most relevant PV yield inaccuracies:

a. The degradation effect (in particular at a-Si): Its complete understanding and the set-up of a time-variant model considering the history of the modules including recovery effects due to daily and seasonal changes in temperature and irradiation, possibly a model that is used to describe the lifetime performance of an electrical accumulator can be used. Some technologies such as CdTe and CIGS do not degrade; they even may improve after light soaking.

b. Accuracy of spectral metrological data: considering the range of exiting and frequently used models differences in yield prediction may reach up to 20%. While precise instruments within an accuracy range of 2-5% are available, a significant improvement should be obtainable via an extensive measurement program, focusing the special needs for the calculation of PV yield. As an ideal result, an accurate database offering all spectra from every direction of the sky sphere for every moment in time would be obtainable.

c. Albedo & Shadowing: Those parameters depend very much on the actual location of the PV power plant and its installation. An accurate mirco-siting has to be carried out in order to take Albedo and shadowing into account. In general, those effects are less momentous for locations close to the equator while the modules are facing more towards the zenith, so obstacles close to the ground surface have a reduced impact on PV performance and PV yield.

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