ANNUAL ENERGY HARVEST OF PV SYSTEMS – ADVANTAGES AND DRAWBACKS OF DIFFERENT PV TECHNOLOGIES

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ABSTRACT: The increasing share of various thin film technologies on the global PV market has intensified the discussion if there is a best technology for a specific application and location to achieve a maximum annual energy yield. A key point for comparison of energy yields for different technologies is the determination of the installed power, which is not a trivial task for thin film technologies. In addition, reversible changes of the output power (annealing, light soaking) and a possible long term variation of module parameters have to be taken into account.
The paper discusses the influence of material and module specific parameters on the operational behaviour and the annual energy yield. The energy harvest of thin film solar plants is essentially determined by the temperature behaviour and (especially in Central Europe) by the sensitivity for low light levels, which can be characterised by the dependence of fill factor vs. irradiance. In general, CdTe and a-Si modules are less temperature sensitive than CIS and crystalline silicon. CdTe modules especially of the early production years show an excessive efficiency under low light levels.
Keywords: Energy Performance, PV Module, PV System, System Performance, Thin Film

1 INTRODUCTION

Actually many different PV technologies are on the market with an increasing share of various thin film technologies. Apart from a cost advantage many thin film manufacturers promise a superior annual energy production normalized by peak power (kWh/kWp) for their product compared to crystalline Si modules.
There is an ongoing discussion if there is an optimum module technology for a specific application and many projects and papers deal with a performance comparison of different PV modules and systems [1] – [6]. Among the most relevant thin film technologies a-Si/µc-Si is most advanced in the production technology, CIS has achieved the highest module efficiencies and CdTe has reached the lowest production costs.

However, since the large scale production of thin film PV is fairly recent and improvements are still going on, most results about thin film long term performance come from studies of small populations of pilot production products.

The key point for a sound determination of energy yields is the reference to the peak power. An investor will prefer to use the "paid" PV power i.e. the nameplate rated power; however, this figure depends on tolerances of the rating and on the manufacturers' rating policy. For a technical assessment it is more adapted to use the "real" installed power, either determined by simulator measurements or determined by on-site outdoor measurements translated to STC.

Up to now many aspects of a correct power rating are not yet solved for thin film technologies and recent results of the European research project PERFORMANCE have demonstrated a spread of reported Pmax values up to ±6 % between different institutes [7]. This is mainly explained by the use of crystalline silicon reference devices, current mismatch for multi-junction modules and non-optimal pre-conditioning procedures.

A new standard (draft IEC 61853: PV module performance testing and energy rating) is actually under development.

2 REAL OPERATION CONDITIONS

The actual module power is mainly determined by the irradiance in the module plane, the module temperature (influence of temperature coefficient) as well as the spectral and angular distribution (optical losses at high incidence angles) of the radiation. Commonly, all these conditions deviate from standard test conditions (1000 W/m², 25 °C, AM1.5 spectrum, normal incidence).

In many cases experimental data are available for the irradiance in the module plane and for module temperature (commonly module back temperature). The incidence angle of the direct irradiance can easily be calculated from the sun position. In contrast, measurements of the solar spectrum are on-hand rather seldom.

In the next figures typical basic environmental characteristics are given for the ZSW PV test site Widderstall, Southern Germany (year 2004, minute averages, 40° tilt angle, pyranometer CM11 in module plane). The total irradiation of 1300 kWh/m² corresponds to 100 %.

Figure 1 illustrates the distribution of the relative annual irradiation in different classes of the in-plane irradiance.

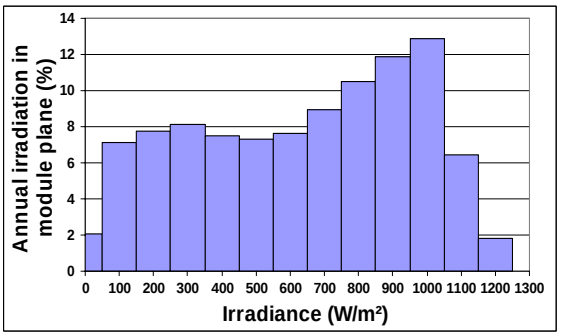

Figure 1: Percental distribution of annual irradiation in the module plane versus irradiance.

It is evident that about 50 % of the annual radiation is below 650 W/m² with nearly constant distribution. Therefore it is important to have a good performance at low irradiance levels in order to achieve a high energy yield under Central European climatic conditions.

The distribution of annual irradiation with respect to classes of module temperature of a naturally ventilated CIS module is outlined in Figure 2.

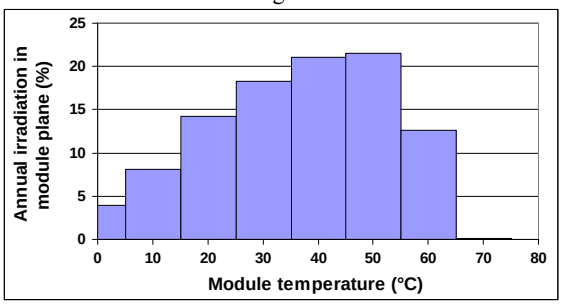

Figure 2: Percental distribution of annual irradiation in the module plane versus module temperature.

About 27 % of the annual irradiation is received at module temperatures below the reference temperature of 25 °C. Module temperatures above 65 °C are hardly ever observed.

The distribution of annual irradiation with respect to the incidence angle of the direct irradiance (see Figure 3) demonstrates that about 88 % of the irradiance is received under incidence angles below 60°. Portions above 90° are related to diffuse irradiance with the sun position in the back of the module.

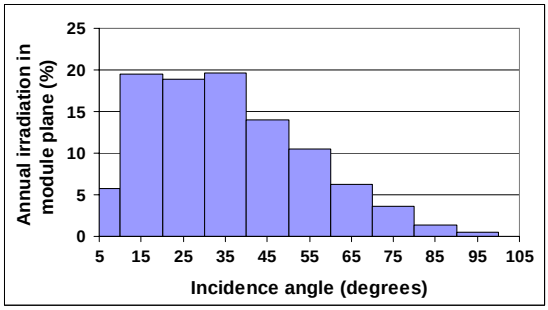

Figure 3: Percental distribution of annual irradiation in the module plane versus incidence angle.

3 OPERATIONAL PERFORMANCE

3.1 Temperature effects

Module performance varies with operating temperature, the rate is determined by the module's temperature coefficients. With increasing temperature typically voltage decreases and current increases, with the larger influence on voltage. According to standard, the module efficiency is rated at the reference temperature of 25 °C. Therefore, the module efficiency is lower than the rated efficiency during operating conditions where the module temperature is above 25 °C.

The operating temperature is influenced by the module design, mounting technique (open rack, roof mounted, building integrated), irradiance level, ambient temperature, wind velocity, and to a minor degree wind direction.

A useful parameter to compare the performance of different module designs is the nominal operating cell temperature (NOCT). NOCT is defined as the equilibrium mean solar cell junction temperature within an open-rack mounted module under 800 W/m² total irradiance, 20 °C ambient temperature, 1 m/s wind velocity under open circuit operation (no load). Commonly, NOCT is given in the module data sheet.

The range of typical temperature coefficients for various technologies from manufacturer data sheets is given in Table I.

Table I: Temperature coefficients

Temp. coeff in %/K	c-Si	a-Si	CdTe	CIS	CSG
P_{MPP}	-0,37 to -0,52	-0,1 to -0,29	-0,18 to -0,36	-0,35 to -0,6	-0,58
U_{OC}	-0,25 to -0,55	-0,19 to -0,5	-0,22 to -0,43	-0,26 to -0,5	-0,47
I_{SC}	0,02 to 0,08	0,01 to 0,1	0,02 to 0,08	0,01 to 0,1	0,14

In general, the output power of CdTe and a-Si modules is less temperature sensitive than CIS and crystalline silicon. Crystalline silicon on glass (CSG) shows a pronounced dependence on temperature.

As the MPP power can be written as the product of short circuit current, open circuit voltage and fill factor, the temperature coefficient for power is in good approximation the sum of temperature coefficients for Voc, Isc and FF.

The translation of measured parameters into standard test conditions (STC) is simplified for irradiance levels around 1000 W/m². Under these conditions apart from the irradiance level also incidence angle and spectral distribution are close to reference conditions and the temperature coefficients can be determined from experimental data by plotting the respective parameter versus module temperature.

As an example the temperature coefficient for the power of a c-Si module is determined from measurements of power for irradiation levels between 950 W/m² and 1050 W/m² in the period from March to October 2006 at Widderstall (Figure 4).

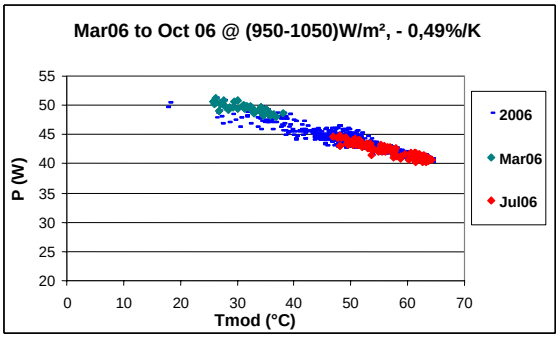

Figure 4: Variation of c-Si module power as a function of module temperature.

It is evident that all data represent a linear dependence and the temperature coefficient can be determined from the slope of the best fit straight line for all data.

This method is not applicable if the module

characteristics vary with time. Figure 5 gives an example for a-Si with a pronounced annealing effect between March and July. In this case only a restricted time interval can be used to determine the temperature coefficient.

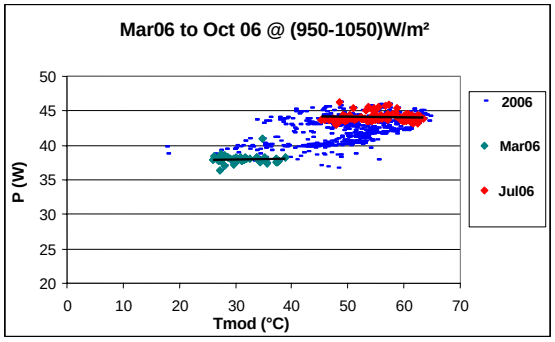

Figure 5: Variation of a-Si module power as a function of module temperature.

With known temperature coefficient for power and known module temperature the STC module power and any variations can easily be determined from the experimental data. Figure 6 shows the long term performance of a CIS module.

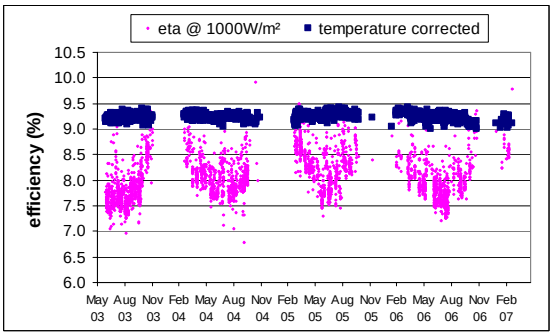

Figure 6: Measured and temperature corrected efficiency (power temperature coefficient -0.48 %/K) of a CIS module from Würth Solar, production year 2003.

The module demonstrates an excellent long term stability, but there is a remarkable efficiency reduction in summer months. It must be noted that actual CIS modules from Würth Solar have a power temperature coefficient -0.36 %/K.

Corresponding data for a CdTe module are outlined in Figure 7.

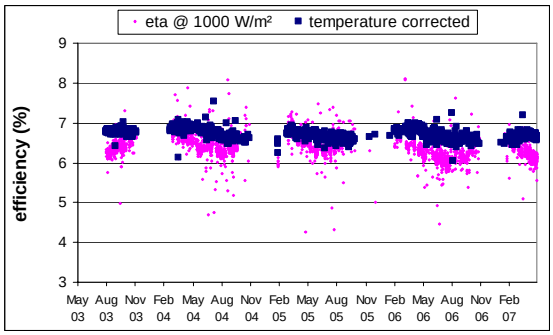

Figure 7: Measured and temperature corrected efficiency (power temperature coefficient -0.25 %/K) of a CdTe module from First Solar, production year 2003.

Due to the small temperature sensitivity the effect of efficiency reduction during summer is less pronounced (a power temperature coefficient of -0.25 %/K is still valid for actual First Solar modules). The degradation rate is less than 0.4 % per year.

3.2 Low irradiance level effects

Figure 8 illustrates typical variations of efficiency with irradiance for the most important module technologies measured during one month (June 2005). Additionally indicated are a single overcast day (17.6.) and a single clear day (20.6.).

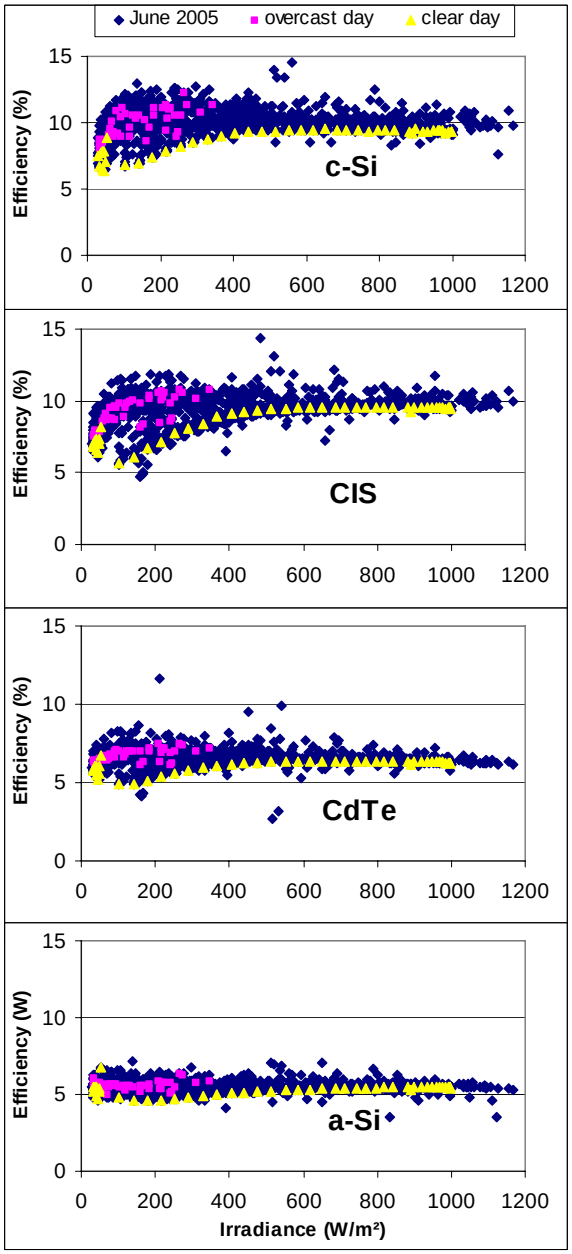

Figure 8: Efficiency versus irradiance without temperature correction for different technologies (c-Si Atersa A60, CIS Würth Solar WS11007, CdTe First Solar FS-50, a-Si Unisolar US32).

All technologies show a decrease of efficiency with decreasing irradiance level, increasing again at very low

irradiance for the clear day. The efficiency values at low irradiance levels for the overcast day are generally above the clear day data. This is due to the fact that on clear days low irradiance levels correspond to high incidence angles, which lead to a reduction of the usable energy caused by increased optical losses and spectral variations.

This effect can be taken into account by defining an effective irradiance, which describes the usable radiation energy for the module. The effective irradiance E_{eff} at a certain spectral and angular distribution is equivalent to an irradiance at AM1.5 spectrum and normal incidence and is characterized by the actual short circuit current related to Isc at 1000 W/m², AM1.5 spectrum, normal incidence and actual module temperature. The module itself is used as irradiance sensor (self referencing) instead of a pyranometer:

Eeff = Isc (E, Tmod, S(λ), θ)/ Isc (Eref, Tmod, AM1.5, θ=0°) * Eref.

With this concept the difference between clear and overcast days disappears (compare Figure 9 and Figure 10).

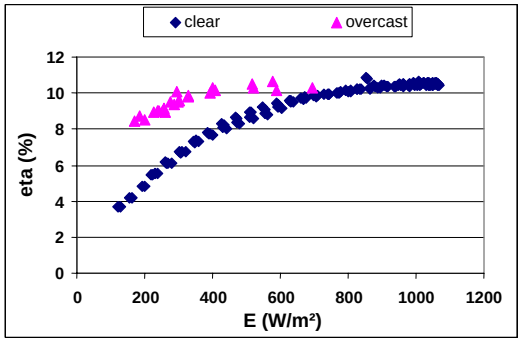

Figure 9: Temperature corrected efficiency of CIS module related to irradiance (pyranometer).

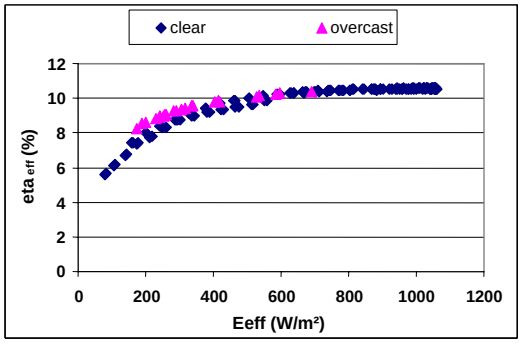

Figure 10: Temperature corrected efficiency of CIS module related to effective irradiance (self referencing).

The data from Figure 10 correspond to simulator measurements with a variation of irradiance.

The performance of modules at low irradiance levels is described by the fill factor. Figure 11 compares the temperature corrected fill factors of the modules from Figure 8. The fill factor is calculated by division of power by the product of Voc and Isc and therefore relates to the effective irradiance inherently.

Typically c-Si and CIS fill factors are similar and are characterized by a nearly constant plateau for irradiance levels above 200 W/m² and a reduction for low irradiances. In contrast, CdTe shows a significant increase with decreasing irradiance which leads to an excellent performance for medium irradiance levels. This effect is predominant for CdTe modules from early production years and is connected to a relatively high series resistance. With improvements in module efficiency the shape approaches the characteristics for c-Si and CIS.

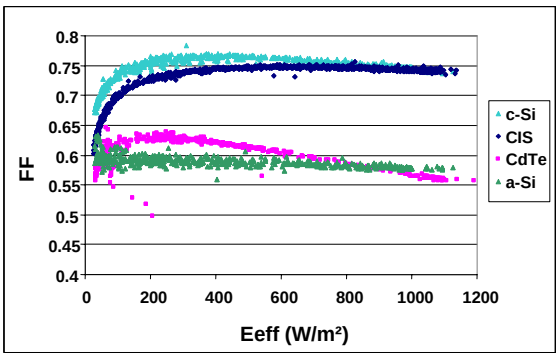

Figure 11: Temperature corrected fill factor versus effective irradiance.

Typical a-Si fill factors are nearly constant over the entire range even below 200 W/m². The modules show a superior performance for sites with a high percentage of diffuse light.

It must be noted that within the single technologies considerable differences are observed as well for the low light level sensitivity as for the temperature coefficients. Moreover, with progress in thin film quality in parallel to an increasing efficiency a general improvement of fill factors can be expected.

3.3 Angular effects

On clear days the module efficiency of fixed installations is reduced in the morning and in the evening due to high incidence angles of the direct irradiance. The loss is associated with higher reflectance losses from the front surface so that less sunlight reaches the cells inside the module. In addition, for low sun elevations the spectrum shifts to higher air mass values.

Figure 12 illustrates the measured response of the short circuit current with the variation of the incidence angle for different thin film technologies.

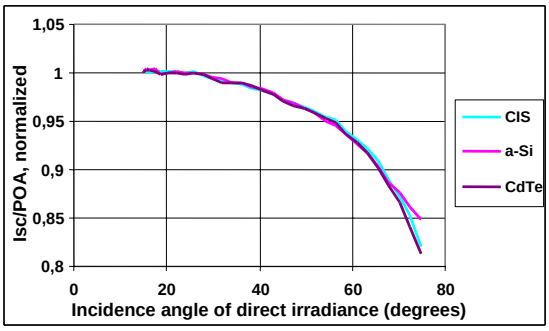

Figure 12: Normalized ratio of short circuit current to irradiance in the module plane (fix, 40° tilt).

With respect to the influence of reflection losses and spectral variations, there is no significant distinction between the thin film technologies. Regarding that about.

88 % of the annual irradiance is received under incidence angles below 60°, any differences in the annual energy production between different technologies related to angular effects and associated spectral effects can be regarded as of second order.

4 CONCLUSION

The energy harvest of thin film solar plants is essentially determined by the temperature behaviour and (particularly for sites with a high percentage of overcast sky conditions) by the sensitivity for low light levels, which can be characterised by the dependence of fill factor vs. irradiance. Angular effects and associated spectral effects can be regarded as of second order.

Within the single thin film cell technologies there are significant differences with respect to the characteristic parameters. In general, CdTe and a-Si modules are less temperature sensitive than CIS and crystalline silicon. CdTe modules especially of the early production years show an excessive efficiency under low light levels. CIS and CdTe show a stable long time performance, for a-Si seasonal variations have to be taken into account.

The key point for a sound determination of energy yields is the reference to the peak power. Up to now many aspects of a correct power rating are not yet solved for all thin film technologies.

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