

# WEAK LIGHT PERFORMANCE AND ANNUAL YIELDS OF PV MODULES AND SYSTEMS AS A RESULT OF THE BASIC PARAMETER SET OF INDUSTRIAL SOLAR CELLS

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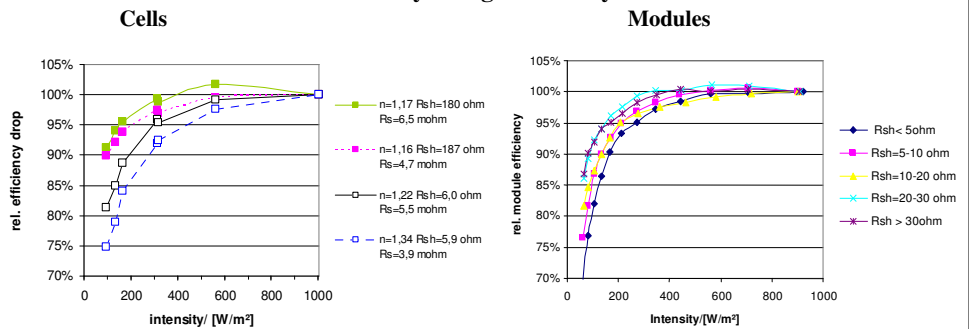
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## Motivation

The energy output of PV systems strongly depends on the irradiation conditions over the entire year. In Europe, the larger part of the total irradiation is below 1000W/m<sup>2</sup> as used for standard testing conditions (STC). The cell and module performance under weak light conditions becomes a crucial quality issue. This work studies the influence of the shunt resistance R<sub>sh</sub> of multicrystalline solar cells on the weak light performance of cells and modules.

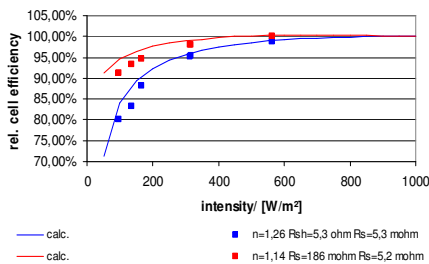
## Relative efficiency vs. light intensity



Measured relative efficiencies vs. intensity for 150mm multicrystalline cells with different parasitic resistances R<sub>s</sub> but same efficiency at 1000W/m<sup>2</sup>

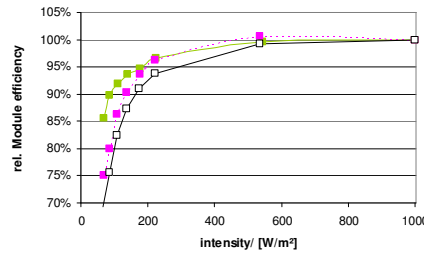
Relative efficiencies vs. intensity for modules with cells grouped by R<sub>sh</sub>

## Measurement and calculation for cells

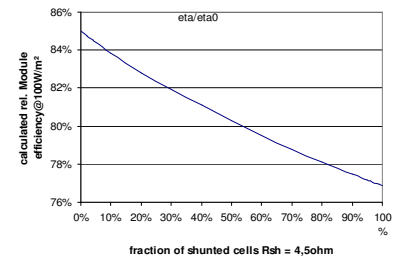


Calculated relative efficiencies from the basic parameter set

## Mixing of different R<sub>sh</sub> classes in the module



Relative efficiencies vs. intensity for modules based on cells out of two R<sub>sh</sub> classes and one mixed cell strings in a ratio of 1:1

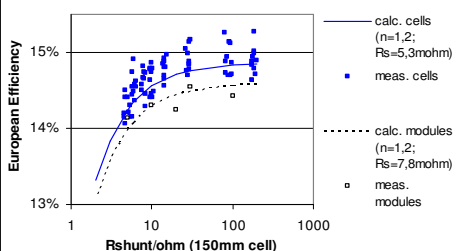


The relative module efficiency at 100W/m<sup>2</sup> for variation of the cell mix from 0% content to 100% of cells with R<sub>sh</sub>=4,5ohm

## European efficiency

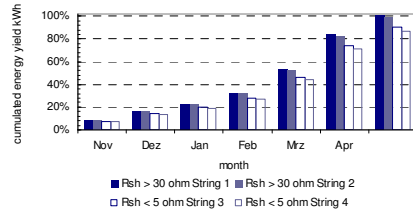
Rsh/ohm	weighting factors						Europ. Eff.
	3%	6%	13%	10%	48%	20%	
200	13,6%	14,1%	14,5%	14,7%	14,8%	14,5%	14,6%
100	13,5%	14,1%	14,5%	14,7%	14,7%	14,5%	14,6%
30	13,1%	13,9%	14,4%	14,6%	14,7%	14,5%	14,5%
20	12,9%	13,7%	14,3%	14,5%	14,7%	14,5%	14,5%
10	12,0%	13,3%	14,1%	14,4%	14,6%	14,4%	14,3%
6	10,9%	12,7%	13,8%	14,2%	14,4%	14,4%	14,1%
5	10,4%	12,4%	13,6%	14,1%	14,4%	14,3%	14,0%
3	8,2%	11,2%	13,0%	13,6%	14,1%	14,2%	13,6%
2	5,5%	9,8%	12,2%	13,1%	13,8%	14,0%	13,1%

Calculation of the European module efficiency by averaging over the relative module efficiencies between 50 and 1000W/m<sup>2</sup>; R<sub>s</sub>=7,8 mohm, n=1,2

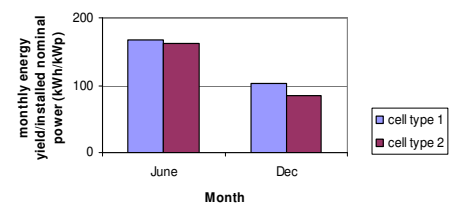


European efficiencies from the intensity depended efficiencies measured on 80 cells and 5 modules and calculated with known R<sub>shunt</sub>

## Energy yield of photovoltaic systems



Energy yields for cells from same power class but different values for R<sub>sh</sub> (0,7kW/string, Thalheim); average R<sub>sh</sub>=80 ohm (1&2) and 2 ohm (3&4)



Energy yields for different cell types with different average values for R<sub>sh</sub> (Berlin, 1,7kW and 1,9kW)

## Conclusions

- The shunt resistance R<sub>sh</sub> of cells is the key parameter for the weak light performance of modules and systems
- Differences in the shunt resistance can lead to 10% difference in annual energy yields of photovoltaic systems
- The energy yield starts to drop for shunt resistances below 20-30 Ohm (150mm x 150mm cells)
- European module efficiencies are calculated from R<sub>sh</sub> and fit to measured energy yields
- Performance reduction of modules with mixed R<sub>sh</sub> classes are governed by the lower R<sub>sh</sub>
- Control of R<sub>sh</sub> is essential for enhanced module performance
- With increased market volumes in photovoltaics, standardized testing procedures for energy yields will become more and more necessary

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**ABSTRACT:** The weak light performance of multi- and mono-crystalline PV modules are known to be dependent on the used cell type, but also vary from cell supplier to cell supplier using even the same cell type. It is shown, that this is a result from the characteristic distribution of the parasitic resistances. This paper shows that these differences can lead to 10% difference in annual energy yields of photovoltaic systems. This itself provides a major optimisation opportunity. The corresponding energy yields of identical designed reference PV systems are differing in a range, which is roughly of the same order as the efficiency variation for actual crystalline silicon modules found on the market. This underlines the on-going need for an extension of the STC parameters to characterize the potential energy yield of PV modules. For practical use, state-of-the-art industrial cell and module testing equipment provides reliable values for the parasitic resistances and currents by extracting the basic parameter set from the measured IV curves at different intensity levels as well as in the dark, i.e. values for the shunt resistances, 2<sup>nd</sup> diode contributions and series resistances in the cells and the European module efficiency for the modules.

**Keywords:** Multi-Crystalline, Performance, Shunts

### 1 INTRODUCTION

The cost per kWh is the key parameter of every commercial power plant. Photovoltaic modules are sold with respect to their nominal power at Standard Testing Conditions STC. This is generally agreed, because the energy yield or performance ratio of the complete system is depending on a number of factors, which can not only be attributed directly to the module. The energy yield of a specific system is usually estimated using commercially available simulation software tools, which calculate annual energy yields on the basis of the local irradiation and the system's performance ratio given by its electrical lay-out as well as its mounting conditions. This is based on the nominal power rating of modules under STC. The module performance in the field is also influenced by the following factors:

1. Degradation
2. Temperature dependence
3. Spectral response
4. Module efficiency at low illumination intensities

The initial  $I_{sc}$  drop of crystalline cells in the range of 1-5% [1] is considered to be a result of the immediate degradation of the used silicon wafer material under illumination. Alternative doping and reduction of the oxygen content are efforts currently undertaken by the wafer manufacturers. There is a drop of 0.5-1% per year due to degradation of the standard glass/EVA encapsulation system [1].

The temperature coefficients on  $P_{max}$  are not differing significantly for modules based on crystalline silicon pn-junction cells [2]. The temperature coefficients themselves are independent of the illumination level as shown in [3].

Differences of the cells can be important at diffuse irradiation and low latitudes of the sun. But in difference to thin film technologies, the variations in the spectral

response are not significant enough to have a major contribution on the total energy yield for crystalline silicon cell technologies [4].

This paper focuses on the efficiency drop of crystalline silicon cells and modules under weak light conditions.

The IV curves of cells and modules are measured at 25°C and AM 1.5 on single pulse sun simulators from Berger Lichttechnik. Energy yields are logged for two photovoltaic systems in Berlin and Thalheim, Germany, using different solar cells types and classes, but equal module sizes and identical system configuration.

### 2 WEAK LIGHT PERFORMANCE OF INDUSTRIAL SOLAR CELLS

#### 2.1 Measurement

The IV curves of multi-crystalline solar cells are measured for different light intensities using metal grids in the light path of the sun simulator. The IV curves can be simulated with the basic parameter set of single cells using either the two diode model or the empirical expressions for the fill factor as given in [5].

The extraction of the basic parameter on an industrial stage is performed similarly to the method described in [6]. Additionally to the standard parameter set  $U_{oc}$ ,  $I_{sc}$  and FF, the shunt resistance  $R_{sh}$  is determined by the linear slope of the reverse dark current on every cell. The series resistance  $R_s$  is calculated from two IV curves measured at 1000 W/m<sup>2</sup> and 500 W/m<sup>2</sup>, respectively, according to IEC 891. The whole basic cell parameter set including the measured values for  $I_{sc2}$  and  $U_{oc2}$  at 500 W/m<sup>2</sup> are fed into a data base and serves usually for the on site process control in modern cell productions.

The weak light performance of the cell efficiency was studied on 80 multicrystalline cells with a format of 300µm x 150 mm x 150mm.

The cells were selected from only one power class and were sorted into 8 classes of 10 cells in a range of

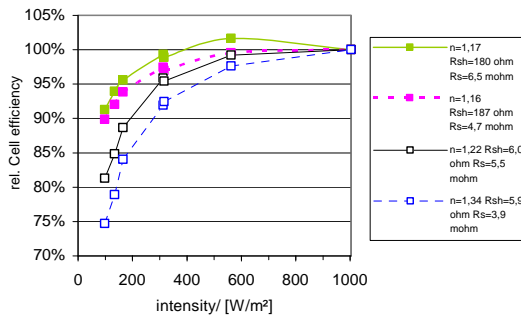
Rsh with a tolerance of +/- 10%. They were then re-measured at various light intensities from 1000W/m<sup>2</sup> down to 100W/m<sup>2</sup> using the automatic data acquisition described above. The ideality factor reflects the 2<sup>nd</sup> diode contribution in the used 1-diode-model and was additionally calculated for benefit of this work from Isc and Voc at 1000W/m<sup>2</sup> and Isc2 and Voc2 at 500W/m<sup>2</sup> as described in chapter 5.3 in [6].

$$n = \frac{U_{OC(1000W/m^2)} - U_{OC(500W/m^2)}}{\ln\left(\frac{I_{SC(1000W/m^2)}}{I_{SC(500W/m^2)}}\right)} \frac{q}{kT} \quad (1)$$

### 2.2 Cell results

The short circuit current Isc decreases linearly with intensity and Voc decreases with the well known logarithmic slope for all cells of the chosen power class without significant differences (not shown). The variation of the fill factor on light intensity is highly dependant on Rsh and Rs. They dominate the different intensity dependence of the relative cell efficiencies via the fill factor in Fig. 1.

For high series resistances one observes a slight initial increase of the efficiency to lower intensities, what results in a local maximum of the efficiency at around 500 W/m<sup>2</sup>. This local maximum vanishes, when going to cells with lower Rs and/or lower Rsh.



**Figure 1:** Measured relative efficiencies vs. intensity for 150 mm multicrystalline cells with different parasitic resistances but same efficiency at STC 1000W/m<sup>2</sup>

The relative weak light performance for a solar cell is maximized for higher series resistances, while its absolute efficiency at STC is decreased by it. Decreasing shunt resistances reduces the weak light performance and the STC efficiency as well.

### 2.3 Calculation of low light IV curves for the cells

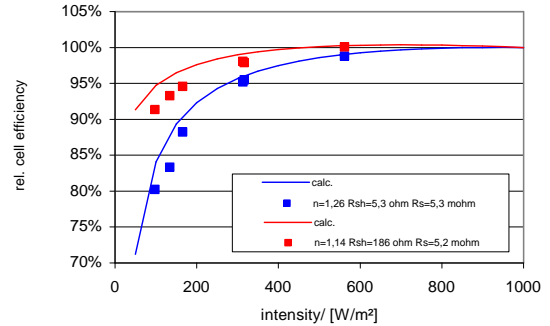
With this measured data set Voc, Isc, Rsh, Rs and n the relative cell efficiencies at lower light intensities can be calculated using the empirical expressions in [5] for the fill factors FF<sub>0</sub> (eq. 5.15), FF (eq. 5.17) as a function of Rs and FF (5.18) as a function of Rsh:

$$FF_0 = \frac{u_{OC} - \ln(u_{OC} + 0.72)}{u_{OC} + 1} \quad \text{with } u_{OC} = U_{OC} / (nkT/q) \quad (2)$$

$$FF_{R_s} = FF_0 (1 - R_s / (U_{OC} / I_{SC})) \quad (3)$$

$$FF_{R_{sh}} = FF_{R_s} \left( 1 - \frac{(u_{OC} + 0.7)}{u_{OC}} \frac{FF_{R_s}}{R_{SH} / (U_{OC} / I_{SC})} \right) \quad (4)$$

It was found, that the measured and the calculated curves are in good correlation only for the case of cells with lowest shunt resistances, i.e. Rsh=5 ohm. For 150 mm cells a shunt resistance of 4.5 ohm, i.e. 1000 ohmcm<sup>2</sup>, is generally considered as the lower limit for successful edge isolation. Shunt resistances below this value are attributed to either bad raw material or bad processing [7]. For higher shunt resistances, the calculated curves tend to show an improved weak light performance, see Fig. 2, as if the shunt resistance Rsh is lower or the ideality factor n is higher in the experimental curves.



**Figure 2:** calculated relative cell efficiencies from the basic parameter set

The deviations are considered as a result of the inhomogeneous structure of large area industrial multicrystalline cells with respect to their shunt resistance and/or to their series resistance.

Despite these limitations, the general trend of the weak light dependence can be simulation using simply the basic parameter set of a given cell.

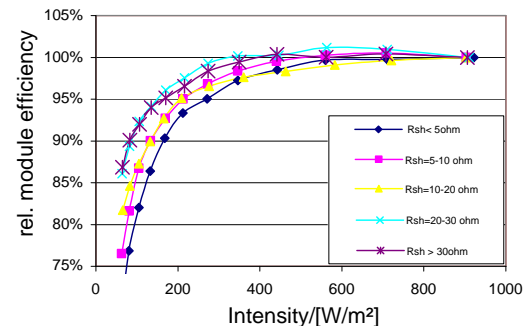
The weak light performance is primarily determined by Rsh, while Rs and n have minor importance.

In section 3.2 the calculations are applied to the weak light performance of modules including the additional effect of the series resistance from the copper ribbons.

## 3 WEAK LIGHT PERFORMANCE OF INDUSTRIAL SOLAR MODULES

### 3.1 Measurement

The modules were produced from cells with the same power classes and are again grouped regarding their shunt resistance. The cells were not sorted with respect to their series resistance. For the Berger module tester metal grids in the light path were used for the measurements below 1000 W/m<sup>2</sup>.

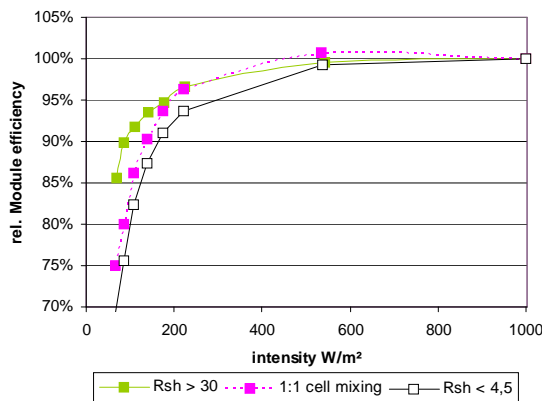


**Figure 3:** Relative efficiencies vs. intensity for modules with cells with equal Rsh classes

As can be seen in Fig. 3 the weak light dependence of the module efficiencies for different shunt resistances are very similarly to the tendencies for the cells in Fig. 1.

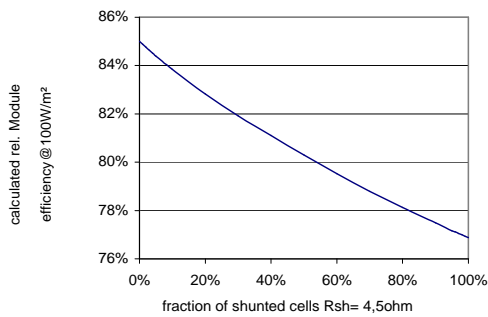
It can be seen, that a Rsh between 20 and 30 ohm represents a saturation value (150mmx150mm format). Higher values do not improve the weak light performance further.

In industrial practice cells are only sorted by power classes, i.e. they are sorted by the current measured at a fixed voltage near the maximum power point, and not by their shunt resistances. In real modules one will have an uncertain mixing of different shunt resistances and therefore unclear weak light performances. Fig.4 shows the effect of mixing cells with different shunt resistances, i.e. with 50% of the cells having Rsh < 4.5 ohm and 50% with Rsh > 30 ohm in one module.



**Figure 4:** Relative efficiencies vs. intensity for modules out of two Rsh classes and one with a 1:1 mixing ratio

The resulting weak light performance of the 1:1 cell mixed module is given by an intermediate behaviour with respect to the modules with defined Rsh. There is a somehow stronger influence from the string with the lower Rsh < 4.5ohm.



**Figure 5:** The relative module efficiency at 100W/m² for variation of the cell mix from 0% shunted cells to 100% with Rsh= 4.5ohm vs. Rsh= 30ohm

The mixed module can be described theoretically with an effective shunt resistance between 4,5 and 30 ohm, but again closer to 4,5 ohm. Fig. 5 is showing the effect of the variation of the content of shunted cells with Rsh < 4,5ohm to the disadvantage of non-shunted cells with Rsh > 30ohm. This is simply calculated by adding the cells' IV-curves.

The deviation from the linear dependence on the fraction of shunted cells stresses out, that the lower shunt values contribute more to the weak light performance of

the module.

This confirms the approach to sort out cells below a lower shunt resistance limit. Their influence can not be compensated by cells with Rsh far above the saturation limit of 20 to 30 ohm. The average Rsh of a cell type or class is therefore only a rough indication for the weak light performance of the resulting modules. It should be tested independently by the module manufacturer.

3.2 European module efficiency

The interconnection of the cells via solder ribbons adds an extra series resistance per cell in the module. Its value is depends on the cross section of the used tinned copper ribbons, the area of the soldered contact and to certain extend on the soldering process itself. Typically it adds 2.5 mohm per cell.

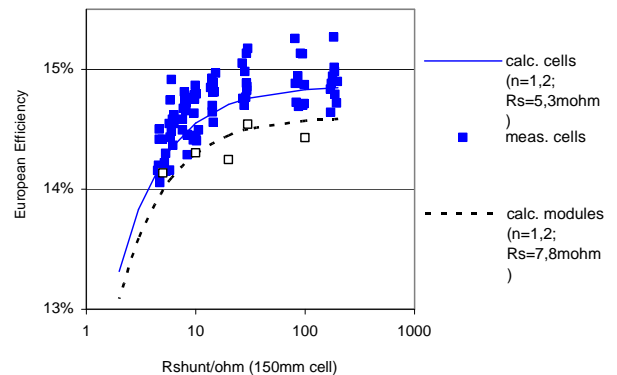
In Fig. 6 the intensity dependence of the efficiency of the measured modules and cells are linearly combined to one single value, called the European efficiency as used in the inverter technology, e.g. [7]:

$$\eta_{EUR} = 0.03\eta_5 + 0.06\eta_{10} + 0.13\eta_{20} + 0.1\eta_{30} + 0.48\eta_{50} + 0.2\eta_{100} \quad (5)$$

Rsh/ohm	weighting factors						sum = 100%
	3%	6%	13%	10%	48%	20%	
200	13,6%	14,1%	14,5%	14,7%	14,8%	14,5%	14,6%
100	13,5%	14,1%	14,5%	14,7%	14,7%	14,5%	14,6%
30	13,1%	13,9%	14,4%	14,6%	14,7%	14,5%	14,5%
20	12,9%	13,7%	14,3%	14,5%	14,7%	14,5%	14,5%
10	12,0%	13,3%	14,1%	14,4%	14,6%	14,4%	14,3%
6	10,9%	12,7%	13,8%	14,2%	14,4%	14,4%	14,1%
5	10,4%	12,4%	13,6%	14,1%	14,4%	14,3%	14,0%
3	8,2%	11,2%	13,0%	13,6%	14,1%	14,2%	13,6%
2	5,5%	9,8%	12,2%	13,1%	13,8%	14,0%	13,1%

**Table I:** Calculation of the European module efficiency by weighted averaging over the relative module efficiencies from 50 to 1000W/m² according to equation (5) for Rs=7.8 mohm per cell and n=1.2 from eq. (2)-(4)

As a parameter, the European efficiency is designed to estimate the potential energy yield of an inverter or another photovoltaic system component, as e.g. the module, under European weather conditions.



**Figure 6:** European efficiencies from the intensity depended efficiencies measured on 80 cells and 5 modules and calculated with known Rsh, see text.

For systems in Europe, it has therefore more commercially relevance than the currently used module efficiency at STC.

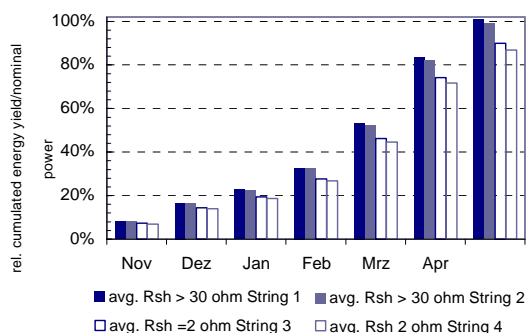
For the encapsulated module efficiency, the  $I_{sc}$  values and  $U_{oc}$  values are taken from the cells used and only the fill factors are from the original module measurements neglecting changes in  $I_{sc}$  or  $U_{oc}$  during encapsulation. The calculated curves for the modules are based on the basic parameter set of the cells after adding 2,5 mohm on the  $R_s$  of the cells.

This finding confirms, that the shunt resistance can be considered as the key parameter for the intensity dependence of both the investigated cells and modules. In Table 1 the relative difference in European efficiency between  $R_{sh}=30$  ohm and  $R_{sh}= 2$  ohm is at -9,7%, what matches exactly to the measured energy yields below.

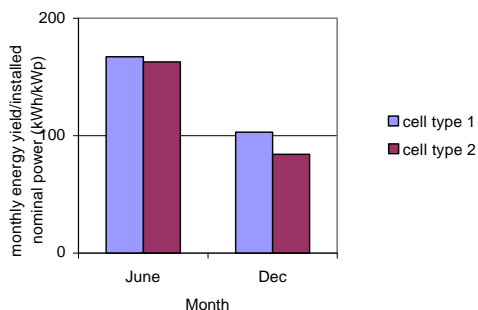
#### 4 ENERGY YIELDS OF ACTUAL PV SYSTEMS

##### 4.1 Energy yields

Fig. 7 is compares the monthly energy yields for a flat roof PV system in Thalheim consisting of four 0,7kW strings built with multicrystalline cells at  $R_{sh}> 30$ ohm (string 1&2) and  $R_{sh} = 2$  ohm (string 3&4). The energy yield differs by -10% for the strings with  $R_{sh}=2$ ohm against the strings with  $R_{sh}> 30$ ohm for the period November to April. This is in very good accordance with the calculated differences in the European efficiency in Fig. 6 and Table 1.



**Figure 7:** cumulated energy yields for average cell  $R_{sh}= 80$  ohm (string 1&2) and  $R_{sh}= 2$  ohm (string 3&4)



**Figure 8:** energy yields for different cell types with different average values for  $R_{sh}$

In a second installed flat roof system in Berlin two different cell types were compared (Fig. 8): Cell type 1 is a multicrystalline silicon solar cell with moderate texturisation, but an average shunt resistance  $R_{sh}>30$ ohm and a cut-off limit for lowest shunt values. Cell type 2 is a texturized monocrystalline silicon cell

with a shunt resistance level at 10 ohm and no limit for lower  $R_{sh}$ . Cell type 2 shows a 4% lower annual yield. It generated 18% less energy in December and 3% less in June, respectively. This confirms that the value of the shunt resistance is also relevant when comparing different cell types.

#### 5 CONCLUSIONS

Differences in the shunt resistance can lead to 10% difference in annual energy yields of photovoltaic systems. Optimization strategies should focus on improving the shunt resistance as a key parameter for good weak light performance on mono- and multicrystalline cells. Beside its negative effect on the efficiency at STC when going below 1000 ohmcm<sup>2</sup>, the weak light performance expressed by the European efficiency is already reduced when going below 20-30 ohm. This paper highlights this parameter as an optimization guide line for cell and module producers in order to provide enhanced module performance.

Testing equipment both for the cell manufacturer (already widely incorporated) and the module manufacturer to measure and sort by weak light performance characteristics is required. The market demand for higher energy yields gives increasing pressure on the manufacturers. The specification of potential energy yields will be an increasingly important but also more complex task than the power measurement at STC. With increased market volumes in photovoltaics, standardized testing procedures for energy yields will become more and more necessary.

#### ACKNOWLEDGEMENTS

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