EVALUATION OF PV SYSTEM PERFORMANCE OF FIVE DIFFERENT PV MODULE TECHNOLOGIES

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ABSTRACT: Based on the outdoor test PV power plant near Zürich the performance regarding single module and grid connected string of five different cell technologies has been analyzed and compared to indoor measurements. Good correlation between indoor and outdoor behavior has been shown for irradiance around 1000W/m^2. For multi c-Si, mono c-Si and a-Si/µc-Si the determined performance values agree within ±2% between indoor and outdoor measurement. Regarding the lowlight performance, evaluation depends on the irradiance reference sensor. While the performance is well determinable regarding self-reference to I_{SC} using c-Si based reference cells shows increasing instability towards lower irradiance due to spectral mismatch. Nevertheless the c-Si reference cell based model has proven to predict energetic output of single module well below measurement uncertainty within ±0.6% for all technologies for the analyzed timeframe and revealed problems in the inverter's maximum power point tracking.
Keywords: Energy Performance, Energy Rating, PV System, Modelling, Inverter

1 INTRODUCTION

Predicting the energetic output of a PV plant is a key requirement for choice of components of a specific site [1]-[4]. It is therefore a necessity to analyze the effects of temperature dependency, dependency of irradiance, degradation and other factors contributing to losses [1]. Within a joint project of a utility (EKZ Zürich), a university (ZHAW) and a thin film silicon technology provider (Oerlikon Solar) these effects are being studied to gain a broader understanding of their impacts on the system's output. This paper presents the results of outdoor STC values determination and its temperature coefficients for five relevant cell technologies at different levels of irradiance and other loss mechanisms of DC-AC grid connected systems. Furthermore anomalies between grid-connected string and single module measurements regarding inverter performance are shown.

2 APPROACH

In December 2009 a PV plant consisting of multi crystalline silicon (multi c-Si, Sunways), high efficiency crystalline silicon (mono c-Si HIT, Sanyo), and three thin film technologies (a-Si/µc-Si, Oerlikon Solar; CIS, Avancis and CdTe, First Solar) has been installed (see table I). For each technology a string of at least 1.8kW is feeding via standard inverter into the grid and is monitored and logged on the DC and AC side of the inverter. Most strings consist of one branch of serially connected modules, only the strings of technology D and F have several parallel branches of serially connected modules.

Table I: System definition of the test PV power plant and the single module monitoring setup

	A	B	C	D	E	F
Manufacturer	Sunways	Sunways	Sanyo	Oerlikon	Avancis	First Solar
Model	SM210 UA65	SM210 UA65	HIP-215 NKHE	micro-morph	PowerMax 110	FS275
Technology	multi c-Si	multi c-Si	mono c-Si HIT	a-Si/µc-Si TF	CIS TF	CdTe TF
Module efficency	14%	14%	17%	8%	10%	10%
Installation date	Sep 2009	Sep 2009	Sep 2009	Jun 2010	Sep 2009	Sep 2009
Module						
Total # modules	1	1	1	1	1	1
P_n Label [W]	230	230	215	110	110	75
String						
Total # modules	15	8	10	21	9	20
# serial modules	15	8	10	3	9	4
# parallel branches	1	1	1	7	1	5
Pn Label [W]	3450	1840	2150	2310	990	1500
Inclination	30°	30°	30°	30°	30°	30°
Mounting	fix	tracked	fix	fix	fix	fix
Inverter						
Manufacturer	Sunways	Sputnik	Sputnik	Sunways	Conergy	SMA
Model	NT4000	SolarMax 2000S	SolarMax 2000S	AT2700	IPG2000	SB1700
Phase	L1	L2	L2	L3	L3	L3
Euro-Efficency	97.1%	94.6%	95.4%	94.5%	93.6%	91.8%

Simultaneously the IV characteristic of one single module (reference module) of each technology is measured on a minute interval using four-terminal sensing. Between the scans it is tracked at U_{MP} [5]. In addition these non-grid connected modules are equipped with PT100 temperature sensors, mounted on the modules backside.

The horizontal and in module plain irradiance is recorded by pyranometers and non-filtered and filtered monocrystalline silicon reference cells. Meteorological conditions like ambient temperature, wind speed and direction are also logged.

Beside the minute-by-minute mean value for each sensor a second value is logged at the beginning of every minute to be synchronised with the IV scan.

All measured data is stored in a database for further analysis [5].

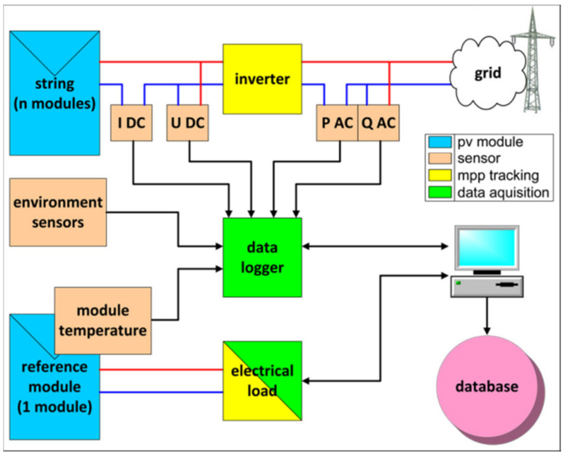

Figure 1: Block diagram of the single module and PV power plant monitoring setup at the EKZ roof in Dietikon near Zürich, Switzerland.

For every string current and voltage is monitored on the DC side and effective power and reactive power on the AC side of the inverter. All measured values are monitored for each of the five technologies by a data logger and stored into a database. One reference module of each technology is connected to an electrical load for IV characteristic measurements. The reference modules' temperature is also recorded trough the logger. Several environmental sensor measurements are stored in the database as well.

Multi c-Si is installed once on a fixed mounting and once on a one axis tracker following the daily sun azimuth.

All modules (string and reference modules) are measured at least on a yearly basis with a calibrated flasher to get actual STC values [6].

3 NOMINAL POWER MEASUREMENT

3.1 Flasher measurements

The flasher measurements are performed using the Swiss Solar Flasher Bus (SMFB) [6]. Comparison of the flasher measurement results show stable performance regarding the manufacturers flash within the measurement uncertainty (±3% for a level of confidence of 95%) for multi c-Si (A00 and B00) and mono c-Si HIT (C00). After completion of initial light induced degradation (LID) the reference module of the tandem technology a-Si/µc-Si (D00) has reached the predicted label value after the first winter of outdoor exposition in Switzerland.

Table II: Comparison of annual P_n flasher measurements of the reference modules performed in Jul 2009, Jun 2010 and Apr 2011.

P_n Flash	A00	B00	C00	D00	E00	F00	Unit
P_n Label	230.0	230.0	215.0	110.0	110.0	75.0	W
P_n Flash (Manufacturer)	231.5	231.8	216.0	130.1	107.1	na	W
Deviation to P_n Label	0.6%	0.8%	0.5%	18.2%	-2.6%	na	
P_n Flash (Jul 2009)	229.9	228.5	215.2	na*	102.3	72.1	W
Deviation to P_n Label	>-0.1%	-0.6%	0.1%	na*	-7.0%	-3.9%	
P_n Flash (Jun 2010)	225.1	223.8	214.9	129.1	94.3	62.7	W
Deviation to P_n Label	-2.1%	-2.7%	-0.1%	17.4%	-14.3%	-16.4%	
P_n Flash (Apr 2011)	226.2	224.5	213.0	109.9	97.4	63.2	W
Deviation to P_n Label	-1.7%	-2.4%	-0.9%	-0.1%	-11.4%	-15.7%	

* D installed in Jun 2010

The results for CIS technology (E00) show unstable results due to missing preconditioning (light soaking) prior to the measurement [7]. For further analysis this module will be compared to the manufacturer's flash results.

The CdTe (F00) reference module shows a drop in power of over 10% within the first year of operation. All installed modules of this technology are part of a malicious batch of Low-Power-Modules (LPM) produced between Jun 2008 and Jun 2009 by First Solar and thus not representative for the technology itself. While some modules degraded up to 20% of their initial power others remained steady. The manufacturer has granted replacement for all modules of the affected batch [8]. (see table II)

For each technology the tendencies of the reference module's measurements agree with the mean power at STC of the PV power plant's modules.

3.2 Nominal power based on outdoor data

Determination of nominal power based on outdoor measurements (P_n Outdoor) is achieved by selecting P_{MP} values normalized to 1000W/m^2 and the module's temperature for a narrow irradiance band around 1000W/m^2. The linear regression over those two parameters at 25°C describes STC conditions (disregarding AM) and determines P_n Outdoor. Furthermore the data are filtered to grant steady condition of irradiance within 0.5% and module temperature within 1°C from one minute to the following.

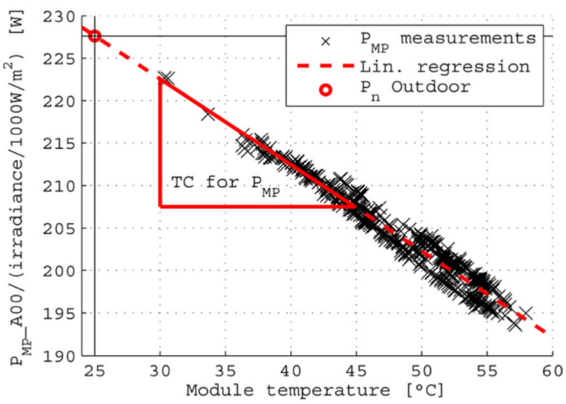

Figure 2: The linear regression method used to determine P_n and TC from outdoor measurements applied to the module A00 regarding an irradiance band of 1000±5W/m^2 measured by the use of a c-Si reference cell without optical filtering between 1.Mar 2011 and 5.Jun 2011 [9].

This method has shown to be highly dependent on the adhesive used for mounting of the temperature sensor. Mounting with duct tape has resulted in bad correlation for the interpolation. Since the rubber-based adhesive becomes brittle under the thermal influence over time direct contact between the sensor and the module's backplane can be lost and thus cause inaccurate measurement of the module's temperature [10]. So far kapton tape has proven to be more reliable. Using thermal conductance paste between sensor and module is advised. Nevertheless regular examination of the sensor mounting is a necessity.

Even more influential on the results is the choice of irradiance measurement used to select the data set. For the given test system three different irradiance measurements are used: Pyranometer, module dependent spectrally best matching filtered c-Si based reference cell and self-referencing through the module's temperature corrected I_{SC} relative to I_{SC} under STC [4], representing a perfectly matched reference cell.

For the time period from 1.Mar 2011 till 5.Jun 2011 P_n Outdoor (nominal power determined through outdoor data) has been determined for all three irradiance measurements using an irradiance band of 1000±5W/m^2 and compared to the flasher value measured within the selected timeframe. The results are shown in table III.

Generally the lowest values for P_n Outdoor are calculated using the pyranometer. While using reference cells to determine irradiance results in higher P_n Outdoor, the regression's coefficients of determination (R^2) of the two methods are similar. Self-referencing gives the best correlation and also the best match of P_n Outdoor to the flasher measurement, due to the absence of spectral mismatch.

For A00 (multi c-Si) and C00 (mono c-Si HIT) all methods are suitable. The determined P_n Outdoor values agree with the flasher measurement within ±2% and correlation is generally high.

Module B00 (see table II) cannot be analyzed through pyranometer or c-Si reference cell since the module is mounted on a tracker and no tracked sensor is available. To do so additional irradiance sensors, mounted on the tracker would be required. Self-referencing however renders similar deviations to the flasher measurements like for the module A00 being the identical multi c-Si model.

The micromorph module D00 (a-Si/µc-Si) does not correlate so well for sensor based irradiance measurement, showing more scattered data and therefor suggesting spectral mismatch between the sensors and the module. However the determined P_n Outdoor also agree within ±2% to the flasher value, better fitting for the c-Si reference sensor. The results will also depend on the type of matching of top and bottom cell of the tandem cell.

The module E00's (CIS) flasher measurements with the SMFB are unsatisfactory due to missing preconditioning. Thus the results are compared to the manufacturer's flasher values. Regarding irradiance measurement with pyranometer P_n Outdoor deviates 5% to the flasher value. Using the silicon reference cell gives a more accurate result matching the flasher value within 1%. Interestingly self-referencing the module to the I_{SC} measured by the manufacturer does not prove effective (-4%), while self-referencing the module to the label value of I_{SC} results in a value of 106.9W for P_n Outdoor matching the manufacturer's flasher value within less than 1%.

Although preconditioning requirements for flashing have been met for F00 (CdTe) due to longtime outdoor exposure and the flashing method has been confirmed by intercomparison with certified laboratories [11], the defective module presents unstable behavior. No interpretations are possible since the module is defective and thus not representative.

Equally the nominal power of the strings (P_n Outdoor String) based on outdoor data has been determined (see table IV). The results show the same tendencies as for the modules with an offset of about -1% to -2%. The offset is caused by additional losses of IV-imbalance and cable losses, since only the reference modules are measured by four-terminal sensing. The Coefficients of determination are generally lower for P_n Outdoor String than for P_n Outdoor of the reference module. Determination regarding the flasher measurement's short circuit current is not possible since the string's I_{SC} is not being measured in the grid connected plant.

Table III: Comparison of the reference modules' P_n calculated through outdoor data between 1.Mar 2011 and 5.Jun 2011 for an irradiance band of 1000±5W/m^2 determined by pyranometer, c-Si reference cell and I_{SC}. Also shown in the lower part of the table are the correlation coefficients and the number of measurements used for the approximation by linear regression.

P_n Outdoor	A00	C00	D00	E00	F00	Unit
P_n Flash (Apr 2011)	226.2	213.0	109.9	107.1*	63.2	W
P_n Outdoor Pyranometer (CMP21)	222.7	211.3	107.8	102.0	54.2	W
Deviation to P_n Flash (Apr 2011)	-2%	-1%	-2%	-5%**	-14%	
P_n Outdoor Ref. cell (c-Si)	227.6	217.1	111.5	105.9	58.1	W
Deviation to P_n Flash (Apr 2011)	1%	2%	2%	-1%**	-8%	
P_n Outdoor $I_{SC}/I_{SC_}$Flash	225.4	215.7	111.2	102.6	59.9	W
Deviation to P_n Flash (Apr 2011)	>-1%	1%	1%	-4%**	-5%	

* P_n Flash (Manufacturer), ** Deviation to P_n Flash (Manufacturer)

R^2 for P_n Outdoor		A00	C00	D00	E00	F00
using Pyranometer (CMP21)	# meas.	431	425	433	448	466
	R^2	0.97	0.89	0.49	0.93	0.55
using Ref. cell (c-Si)	# meas.	420	416	422	433	354
	R^2	0.96	0.92	0.47	0.95	0.88
using $I_{SC}/I_{SC_}$Flash	# meas.	205	489	483	573	110
	R^2	0.98	0.99	0.93	0.98	0.99

Table IV: Comparison of the strings' P_n calculated through outdoor data between 1.Mar 2011 till 5.Jun 2011 for an irradiance band of 1000±5W/m^2 determined by pyranometer and c-Si reference cell. P_n Outdoor String is affected by addition losses caused by cable losses and IV-imbalance.

P_n Outdoor String	A	C	D	E	F	Unit
P_n Flash (Apr 2011) String	3383	2103	2300	948*	1324	W
P_n Outdoor Pyranometer (CMP21)	3253	2055	2215	924	1149	W
Deviation to P_n Flash (Apr 2011) String	-4%	-2%	-4%	-3%**	-13%	
P_n Outdoor Ref. cell (c-Si)	3323	2133	2301	956	1225	W
Deviation to P_n Flash (Apr 2011) String	-2%	1%	<1%	1%**	-8%	

* Pn Flash (Manufacturer) String, ** Deviation to Pn Flash (Manufacturer) String

R^2 for P_n Outdoor String		A	C	D	E	F
using Pyranometer (CMP21)	# meas.	432	426	433	448	466
	R^2	0.94	0.78	0.50	0.91	0.66
using Ref. cell (c-Si)	# meas.	421	416	422	433	354
	R^2	0.93	0.85	0.53	0.91	0.90

4 TEMPERATURE COEFFICIENTS BASED ON OUTDOOR DATA

The slope of the regression line used to determine P_n Outdoor describes the temperature coefficient (TC Outdoor) of the module power (see figure 2). The coefficients of determination are thus the same as for P_n Outdoor (see table III).

The calculated TCs for P_{MP} are shown in table V. Overall c-Si reference sensors appear to be a valid source of irradiance determination to reproduce the label TC around 1000W/m^2.

Spectral mismatch between module and sensor as well as spectral dependency of the dominant subcell of the tandem module are limiting factors to determine the

Table V: Comparison of TC for P_{MP} calculated through outdoor data between 1.Mar 2011 till 5.Jun 2011 for an irradiance band of 1000±5W/m^2 determined by pyranometer, c-Si reference cell and I_{SC}.

TC for P_{MP} Outdoor	A00	C00	D00	E00	F00	Unit
TC P_{MP} Label	-0.43	-0.3	-0.35	-0.45	-0.25	%/°C
TC P_{MP} Outdoor Pyranometer (CMP21)	-0.45	-0.29	-0.19	-0.41	-0.22	%/°C
Deviation to TC P_{MP} Label	4%	-4%	-46%	-8%	-11%	
TC P_{MP} Outdoor Ref. cell (c-Si)	-0.45	-0.30	-0.23	-0.46	-0.35	%/°C
Deviation to TC P_{MP} Label	4%	1%	-34%	1%	40%	
TC P_{MP} Outdoor I_{SC}/I_{SC}_Flash	-0.46	-0.32	-0.35	-0.41	-0.37	%/°C
Deviation to TC P_{MP} Label	7%	7%	<1%	-9%	48%	

% of P_n Outdoor

TC of P_{MP} for technology D (a-Si/µc-Si). This can also be seen by the lower correlation coefficient indicating a lot of scattering of P_{MP} around the linear regression line, caused by the current. Self-referencing on the other hand results in TC Outdoor matching the label value very closely.

The defective CdTe module shows a lower TC Outdoor with increasing correlation.

Applying the same method to the measurements of U_{MP}, STC value and TC Outdoor for U_{MP} can also be calculated through outdoor data.

Since U_{OC} is logarithmically and U_{MP} nearly logarithmically dependent of irradiance and generally have a very stable temperature dependency it is not surprising that for technologies A, C, and D the determined U_{MP} STC value for every irradiance measurement method match the flasher results within ±1% with a coefficient of determination above 0.99. The determined TCs for U_{MP} of those modules are changing little based on the used irradiance measurement. The influence of the irradiance sensor is thus negligible. (see table VI)

The CIS module's U_{MP} Outdoor, again referenced to the manufacturer's flash, shows an offset of -3% suggesting, that the manufacturers preconditioning state (light soaking) might not be reached. Avancis is the only

Table VI: Comparison of U_{MP} and TC for U_{MP} calculated through outdoor data between 1.Mar 2011 till 5.Jun 2011 for an irradiance band of 1000±5W/m^2 determined by pyranometer and c-Si reference cell.

U_{MP} Outdoor	A00	C00	D00	E00	F00	Unit
U_{MP} Flash (Apr 2011)	29.2	42.1	96.4	39.9*	62.9	W
U_{MP} Outdoor Pyranometer (CMP21)	29.0	42.1	97.0	38.6	60.7	W
Deviation to U_{MP} Flash	-1%	>-1%	1%	-3%**	-3%	
U_{MP} Outdoor Ref. cell (c-Si)	29.0	42.3	97.5	38.9	60.4	W
Deviation to U_{MP} Flash	-1%	1%	1%	-2%**	-4%	
U_{MP} Outdoor I_{SC}/I_{SC}_Flash	29.0	42.3	97.2	38.6	60.5	W
Deviation to U_{MP} Flash	-1%	<1%	1%	-3%**	-4%	

* U_{MP} Flash (Manufacturer), ** Deviation to U_{MP} Flash (Manufacturer)

TC for U_{MP} Outdoor	A00	C00	D00	E00	F00	Unit
TC U_{MP} Outdoor Pyranometer (CMP21)	-0.44	-0.30	-0.44	-0.37	-0.35	%/°C
TC U_{MP} Outdoor Ref. cell (c-Si)	-0.44	-0.32	-0.45	-0.39	-0.34	%/°C
TC U_{MP} Outdoor I_{SC}/I_{SC}_Flash	-0.44	-0.32	-0.44	-0.37	-0.35	%/°C

% of U_{MP} Outdoor

R^2 for U_{MP} Outdoor		A00	C00	D00	E00	F00
using Pyranometer (CMP21)	# meas.	431	425	433	448	466
	R^2	>0.99	0.99	>0.99	0.97	0.97
using Ref. cell (c-Si)	# meas.	420	416	422	433	354
	R^2	>0.99	0.99	0.99	0.98	0.98
using I_{SC}/I_{SC}_Flash	# meas.	205	489	483	573	110
	R^2	>0.99	0.99	0.99	0.98	0.99

manufacturer of the analyzed technologies that names the TC for U_{MP} on its datasheet and calculates to -0.27%/°C according to the datasheet from May 2009, corresponding to the analyzed modules. Surprisingly this value could not be confirmed being determined to -0.37%/°C resp. -0.39%/°C. The newer datasheet from May 2010 however mentions a TC that calculates to -0.33%/°C and the one from Mar 2011 calculates to -0.48%/°C.

Calculating TCs for current based on outdoor data has shown to be impracticable for all technologies. Its effect is too little to evaluate, given the measurement uncertainty. Correlation coefficients above 0.5 are hardly found.

The flashers STC values for I_{MP} however can be confirmed within a close range of ±1% for all modules except F00 using c-Si reference cell as well as self-referencing. Regarding irradiance measurement by pyranometer D00 deviates by -3% and E00 -2% due to higher spectral mismatch.

5 IRRADIANCE DEPENDENCY OF P_{MP} OUTDOOR AND TC OUTDOOR

It is well known, that the efficiency is not constant at low irradiance [4].

Applying the method from above to lower irradiance should only be done using reference cells or self-referencing as irradiance reference. The use of pyranometer results in rapidly dropping correlation towards lower irradiance due to the increasing spectral mismatch between the modules and the irradiance measurement. Coefficients of determination bellow 600W/m^2 are less than 0.5 for all modules. And only for module A00 and E00 the lower limit of correlation coefficients above 0.5 reaches 800W/m^2.

Figure 3 shows the results of the method applied regarding c-Si reference cell and self-reference. The irradiance interval has been increased to ±50W/m^2 to avoid minuscule scattering. The performance values at 1000W/m^2 agree with the calculations for ±5W/m^2 within ±0.3% for P_n Outdoor regarding reference cell and within ±0.6% regarding self-reference. Coefficients of determination are generally even slightly higher for the wider irradiance band and the TCs are often determined closer to the flasher value.

Self-referencing gives the most accurate results as proven by the generally high regression coefficients. The use of c-Si reference cells presents dropping regression coefficients with decreasing irradiance. Again, spectral mismatch between reference and module presents less reliable evaluation and increases uncertainty.

Spectral mismatch shows its effect peak around 400W/m^2. All TC Outdoor of P_{MP} determined through reference cell are increasingly shifted towards zero (or even further for module D00) the closer the evaluation is to this peak offset and thus display a concavely curved shape. With self-reference on the other hand the calculated TCs for different irradiance values in the interval from 100 W/m^2 to 1050W/m^2 remain very stable (see figure 3) with a standard deviation for A00 of 0.009%/°C respectively 0.011%/°C for C00 and 0.024%/°C for D00. While the mean TC Outdoor of D00 is 0.05%/°C less than its label value the mean for modules A00 and C00 differs only by 0.01%/°C. Modules E00 and F00 show an irradiance dependent TC

Outdoor even regarding self-reference. While the TC Outdoor of E00 steady drops by 0.1% from 1000 to 100 W/m^2, being generally above its label value, the TC of the defective module F00 drops over 0.2%/°C starting at 1000W/m^2 already with an offset of -0.1%/°C to the label value. The standard deviation of a linear fit through the TCs from 100W/m^2 to 1050W/m^2 for module E00 is 0.002%/°C and for F00 0.008%/°C.

Regarding the enormous difference in shape of the TC Outdoor characteristic between c-Si reference cell and self-reference one can hardly believe the c-Si based characteristic to describe the physical behavior of the module. Much more is the concave shape the result of spectral mismatch between the reference cell and the module. Dropping coefficients of correlation underline this explanation. Due to the spectral dependency it must also be expected, that the shape differs at different sites.

The question remains: Why spectral mismatch causes the convex shape of irradiance dependent TC Outdoor regarding c-Si reference cell? And how can it be taken into account for modeling?

C-Si reference cells are often used as low cost reference devices for PV plant monitoring. Spectral characteristics are modified by filters to match the analyzed technology. Given the c-Si nature of the sensor the unfiltered cell is supposed to match the multi c-Si module A00 closely. This however could not be verified regarding the difference between its output and the measurement through the module's self-reference. Reference measurements of the unfiltered reference cell [12] and a spectrally certified indoor reference cell with equal filtering [13] have shown increasing deviation towards lower irradiance. This explains the rapidly decreasing coefficients of determination regarding c-Si reference cell as opposed to self-reference and shows that stability and spectral matching of irradiance sensors are crucial elements in the outdoor characterization of PV modules.

P_{MP} Outdoor values are also calculated for the different irradiance intervals representing the modules performance at 25°C for the given irradiance. Normalizing the P_{MP} Outdoor value to P_n Outdoor and irradiance, the lowlight behavior, describing the modules normalized efficiency can also be extracted by this method.

All technologies have a decreasing efficiency from 400W/m^2 downwards. Mayor differences can be found in the behavior from 1000W/m^2 to 400W/m^2. Regarding self-reference module A00 rises over 2% while C00 decreases by 1%. From the thin film (TF) technologies D00 shows a slightly decreasing behavior due to not fully optimized top and bottom cell balancing. E00 behaves like A00 and F00 increases nearly 5%. Although not consequentially this lowlight behavior of initially increasing efficiency towards lower irradiance seems to be accompanied by a greater temperature dependency of the module's performance. According to the label TC value F00 should prove otherwise: The efficiency

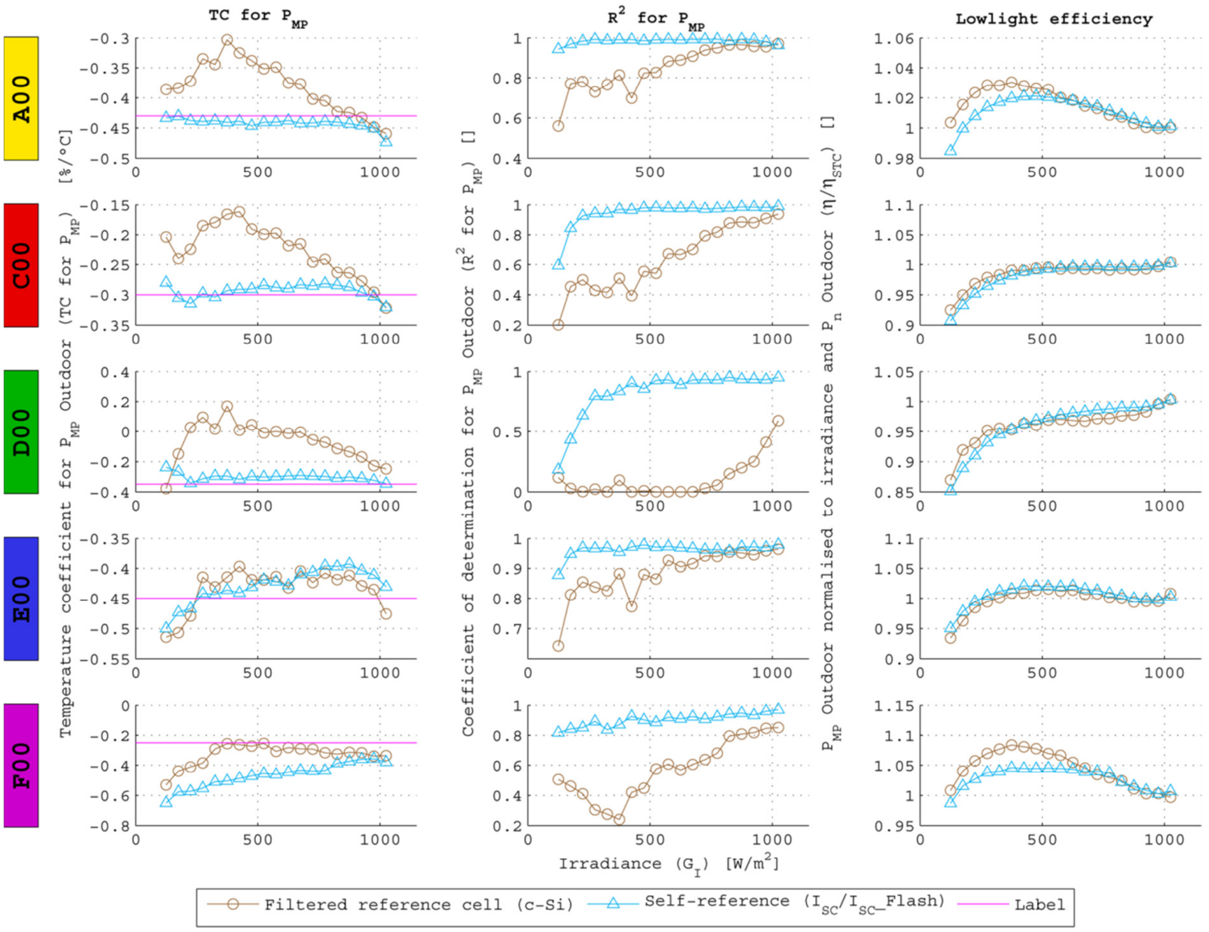

Figure 3: Irradiance dependency of TC and P_{MP} from outdoor data between 1.Mar 2011 till 5.Jun 2011 for irradiance intervals of 50W/m^2 between 100W/m^2 and 1050W/m^2 determined regarding c-Si reference cell and I_{SC}.

increases towards 400W/m^2 and the label TC value of -0.25%/°C is, compared to the other technologies, small. Unfortunately the small TC could not be confirmed for this defective module.

The same analysis has been done for U_{MP} and I_{MP}. As expected, due to the logarithmic dependence of voltage to irradiance the results for reference cell and self-reference based analysis are nearly identical. Coefficients of determination are generally above 0.9, with some exceptions below 200W/m^2. Even pyranometer based analysis is comparable, since spectral difference has little impact. While TC U_{MP} Outdoor does not show the concave shape TC I_{MP} again presents the increasing difference between the determinations through reference cell and self-reference towards 400W/m^2 accompanied by dropping regression coefficients, confirming its spectral dependency.

6 MODELLING AND YIELD PREDICTION

According to the TC results regarding the c-Si reference cell shown in figure 3 the yield of the different technologies has been attempted to model.

Given the current situation building a c-Si reference cell based model raises the necessity to approximate the concave TC Outdoor curve by a polynomial equation.

Given better spectral matching, linear interpolation might have been used to cope with linear irradiance dependent TCs as seen for E00 and F00 regarding self-reference.

Since the TC and lowlight behavior determined through c-Si reference cells is influenced by spectral mismatch (especially for technology D) the model will not be representing the physical reality. Furthermore it must be expected to work only for the given site due to its spectral pattern.

TCs determined bellow 100W/m^2 have extremely bad correlation and those above 1050W/m^2 lack satisfactory number of measurements and will thus not be taken into account for the approximation. Using a polynomial equation of 3rd degree has shown to describe the concave shape with acceptable correlation.

Due to scattering around 400W/m^2 the coefficient of determination for module D00 is less high. Using higher degree approximation would mainly improve the correlation for those points, rendering the approximated TC curve very unstable at this level of irradiance.

Using the calculated approximation for the TCs of P_{MP}, P_{MP} measurements can be corrected regarding the modules temperature and the c-Si reference cell's irradiance measurement. Normalized to P_n Outdoor and the corresponding irradiance these temperature corrected P_{MP} values plotted against the irradiance describe the module's lowlight behavior at 25°C by means of normalized module efficiency.

For modules A00, C00 and E00 these plots of the temperature corrected and normalized P_{MP} measurements (normalized efficiency) compare well with the lowlight behavior shown in figure 3. For modules D00 and F00 the spread of the corrected and normalized measurements around the previously determined lowlight behavior is generally greater and increases at irradiance levels below 500W/m^2. Correlation between the spread and the module's temperature could not be found. For the module D00 the spread can be explained through the module's tandem structure. Dependent of the spectral composition of the irradiance either the bottom or the top cell limits the maximal current going through the module and thus limiting its power [14]. Consequentially the measured irradiance with the c-Si reference cell and irradiance absorbed by the module do match only for certain spectra. The spread of F00's measurements towards low irradiance cannot be explained. At this point it is unknown whether it is due to its defection or a spectral mismatch between the module and the corresponding reference cell.

From the temperature corrected and normalized measurements the lowlight behavior used for the model is extracted by calculating the mean of bins of 50W/m^2.

Using the modeled description of TC, the lowlight behavior and P_n Outdoor, yield predictions can be rendered given the irradiation distribution and the module's mean temperature regarding irradiance.

The relative losses caused by increased module temperature are calculated by applying the temperature correction to the irradiation distribution and dividing it by the total irradiation.

$$L_{TC} = 1 - \frac{\int \left(1 + \Delta T(G_I) * TC(G_I)\right) * E_{in}(G_I) dG_I}{\int E_{in}(G_I) dG_I}$$

where:

L_{TC}: *Energy weighted, temperature affected losses relative to STC* []
$\Delta T = T_m - 25°C$ [°C]
T_m: *Module temperature* [°C]
G_I: *Irradiance* [Wm^{-2}]
E_{in}: *Irradiation* [$Wm^{-2}h^{-1}$]

Similarly the relative losses caused by the lowlight behavior can be calculated by weighting the incoming irradiation with the lowlight behavior and dividing the result by the total incoming energy.

$$L_{LL} = 1 - \frac{\int \eta(G_I) * E_{in}(G_I) dG_I}{\eta_{STC} \int E_{in}(G_I) dG_I}$$

where:

L_{LL}: *Energy weighted, lowlight behvior affected losses relative to STC* []
η: *module or string efficiency* []
η_{STC}: *module or string efficiency at* $1000W/m^2$ []

The combined losses of temperature and lowlight are calculated by combining both effects.

$$L_{TC\&LL} = 1 - \frac{\int \eta(G_I) * \left(1 + \Delta T(G_I) * TC(G_I)\right) * E_{in}(G_I) dG_I}{\eta_{STC} \int E_{in}(G_I) dG_I}$$

where:

$L_{TC\&LL}$: *Energy weighted, temperature and lowlight behavior affected losses relative to STC* []

$\eta(G_I)$ is acquired through binning and so are $\Delta T(G_I)$ and $E_{in}(G_I)$. The integrals thus are reduced to sums over all bins.

$$L_{TC\&LL} = 1 - \frac{\sum_{n=1}^{bins} \eta_n (1 + \Delta T_n \cdot TC_n) \cdot E_{in}}{\eta_{STC} \sum_{n=1}^{bins} E_{in}}$$

According to the previous equation losses in yield have been predicted and compared to the measured DC yields for the timeframe from 1.Mar 2011 till 5.Jun 2011 for the reference modules and the strings (see table VII). To avoid inconsistency in the comparison the dataset of the module and the string for each technology have been matched to describe exactly the same set of timestamps, by removing measurements where either the module's dataset or the string's dataset contained a data gap. The technologies however are not matched among each other.

Table VII: Comparison of the losses predicted by the model and the measurement results of the reference module and the string regarding P_n Outdoor for the timeframe from 1.Mar 2011 to 5.Jun 2011.

TC & Lowlight losses		A	C	D	E	F
Model	TC losses (L_{TC})	4.3%	2.9%	1.4%	6.4%	4.3%
	Lowlight losses (L_{LL})	-0.8%	1.6%	4.1%	0.8%	-3.0%
	Expected DC losses ($L_{TC\&LL}$)	3.5%	4.6%	5.5%	7.2%	1.5%
Module	Total DC losses	3.9%	4.4%	4.9%	7.6%	1.6%
	Deviation to Model	0.4%	-0.1%	0.6%	0.4%	0.1%
String	Total DC losses	3.7%	5.7%	5.5%	8.4%	3.6%
	Deviation to Model	0.2%	1.2%	>-0.1%	1.3%	2.2%
String-Module	Deviation between String and Module	0.3%	-1.3%	-0.5%	-0.9%	-2.1%

For every analyzed technology the predicted temperature affected losses lie within 1.4% and 6.4% for the given site and timeframe. The influence of the lowlight behavior on the other hand is predicted to have a positive impact of 0.8% for technology A and 3.0% for F. Technologies C, D and E are predicted to have losses between 0.8% and 4.1%. Except for technology D the temperature affected losses are dominant.

Since the model is based on data from the reference modules and the same timeframe, accurate predictions for the reference modules are anticipated, since no seasonal degradation effects are to be expected in that period of three months. Deviations between the model's prediction and the module's measurement are within ±0.6% for all technologies. Predictions are well met for module A00 and C00. Also the large impact of module E00's TC has proven to be predicted correctly like the compensating influence of the lowlight behavior for module F00. It is likely, that the negative value of lowlight losses of technology F is caused by its 10% lower power than the label value. (Serial resistance and fill factor behavior have to be checked in detail for further analysis.) For module D00 the prediction differs to the measurement by 0.6%. Regarding the coefficients of determination of D00's TCs used in creating the model (see figure 3) this is a satisfactory result, but may strongly depend on the local irradiation condition.

Energy output for the string has been normalized to P_n Outdoor for the strings, equally determined like for the modules, to calculate the string's yield. P_n Outdoor for the modules is determined without the cable losses by 4-wire sensing. Cable losses and losses caused by IV-imbalance within the string [1] are on the other hand included in the determination of P_n Outdoor of the strings.

Furthermore it must be said, that the predicted yield is based on the temperature measurements of the reference module. However, since the reference module is tracked at U_{MP} between the IV-measurements no excessive temperature of the reference module [2] is to be expected. And since the reference module is located between the modules of the string, similar temperature of the reference module and the string can be assumed.

Cause of deviation between the module's output and the string's output are to be searched in the inverter's tracking performance, since cable losses, IV-imbalance and temperature measurement can be excluded.

Technology A shows good correlation between module and string, so does technology D. Technologies E, C and F have increasing deviations between string and module, suggesting differences of the inverters' tracking approach.

7 MEASURED DC YIELD

Regarding P_n Outdoor a yield of 1200Wh/W and more has been measured for the reference modules from 18.Jun 2010 to 17.Jun 2011, with missing data due to flasher measurements and system maintenance. The datasets for all technologies have been matched to describe exactly the same set of timestamps, by removing measurements not available for every technology. (see figure 4)

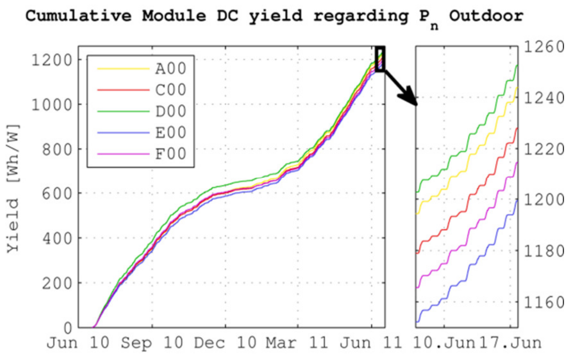

Figure 4: Cumulative DC yield of the reference modules regarding P_n Outdoor over the timeframe from 18.Jun 2010 to 17.Jun 2011.

Comparing the DC yield of the reference module and string over the timeframe of an entire year since all currently analyzed technologies have been installed shows the same tendencies in difference between string and module like for the previously analyzed timeframe (see table VII). Hardly any difference between string and module is detected for technology A. Differences for the other technologies also remain nearly unchanged. Technology F however shows an even greater deviation of the string to the reference module. (see table VIII)

Again the results suggest inverter tracking problems for technology F.

Table VIII: Comparison of annual DC yield between 18.Jun 2010 and 17.Jun 2011 regarding P_n Outdoor. All datasets describe the same set of timestamps.

DC Yield	A	C	D	E	F	Unit
Module	1244	1228	1252	1199	1215	Wh/W
String	1242	1208	1243	1184	1159	Wh/W
Deviation between String and Module	-0.2%	-1.6%	-0.7%	-1.3%	-4.6%	

8 INVERTER TRACKING AND LOSSES

Comparing the DC performance ratio (PR_{DC}) of the reference module and the corresponding string shows the losses caused by the inverter tracking (see figure 5).

On a bright day (10.Apr 2011) the module and the string behave equally, except for technology F. The string's PR_{DC} of technology A, C, D and E is within ±0.25% equal to the modules', both describing a very smooth characteristic. The typical U-shape of the PR_{DC} for irradiance levels above 200W/m^2 shows the dominant effect of the temperature coefficient of the voltage which is the most pronounced for technology E and the least for technology D. The PR_{DC} drops till midday and increases again as the module temperature drops towards the evening. The positive effect of the lowlight behavior (see table VII) for module A and F in combination with effects of spectral changes and angle of incidence (AOI) can be seen by the high PR_{DC} in the morning and evening. The most constant performance ratio is shown by technology C, where the model predicts losses caused by temperature and losses caused by lowlight behavior of similar magnitude.

Technology F shows a very large deviation between string and reference module in the morning at irradiance below 150W/m^2 and again in the evening starting and increasing as irradiance drops below 100W/m^2. Furthermore the string of technology F presents a very rough, jagged characteristic unlike the module.

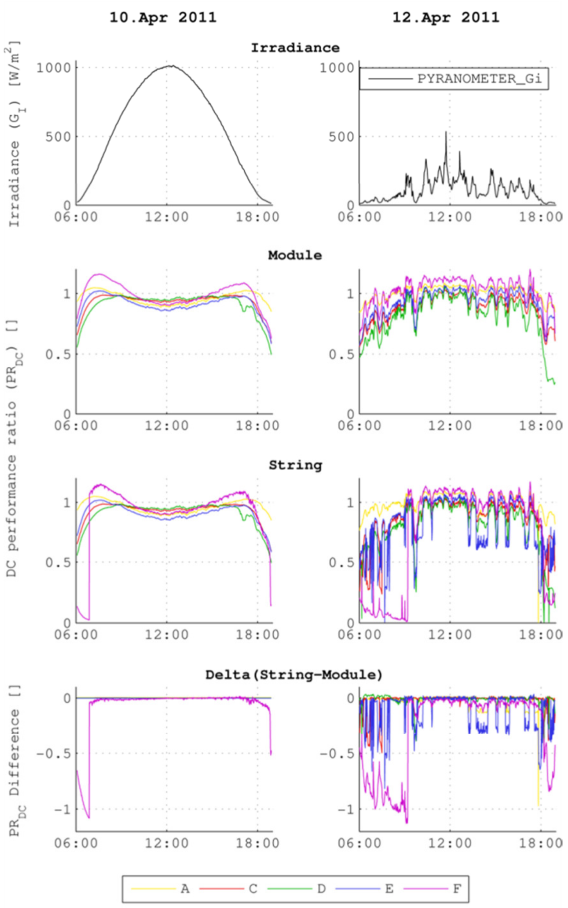

Figure 5: Comparison of DC performance ratio (PR_{DC}) regarding P_n Outdoor for reference module, string and their difference on a bright and a cloudy day.

On a cloudy day (12.Apr 2011) the difference between technology F's reference module and its string becomes even more severe. Up to 9:13 the inverter does not find a valid Maximum-Power-Point leaving all incoming energy unused. Once a working operating point is found it's not lost until irradiance drops below 30W/m^2 in the evening.

Analysis by a modified energy-voltage-plot (EVP) [15] (figure 6), where E_{in} instead of output energy E_A is plotted against the normalized voltage and power, clearly shows the result of the tracking problem of string F.

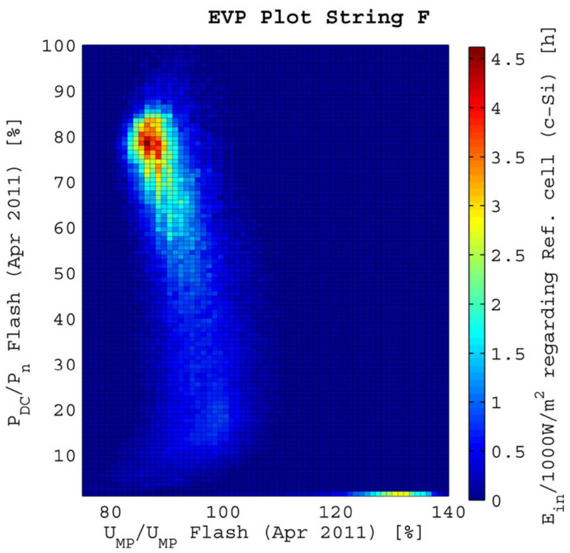

Figure 6: EVP, showing the incoming irradiation for normalized operating points of intervals of 1% within the timeframe from 6.Jun 2010 to 5.Jun 2011.

The sum of the bright band in the lower right corner indicates that the inverter is not tracking correctly for 31.7 nominal hours, equivalent to 1000W/m^2 irradiance. This accounts for 26.7Wh/W regarding the flasher measurement from Apr 2011 for the given timeframe of one year and represents 3% of the actually measured yield regarding P_n flash.

Even though the inverter is transformer based these effects should not appear and are even more surprising regarding the fact that the inverter appears on the list of compatible inverters of First Solar [16] for the given system design (see table I). Cause of the tracking problem is yet to be found and connectivity to the modules' defects cannot be excluded.

Also the inverter of technology E shows tracking problems as irradiance drops below 100W/m^2 accounting for some of the losses seen in table VII and VIII. Except some minor problems in the morning the inverter of string C does seem to operate properly. The cause of the losses for that string is yet to be found.

Losses caused by inverter tracking must and will be analyzed in more detail in the future within this project.

9 CONCLUSION

The combination of outdoor measurements with regularly executed indoor measurements sets excellent conditions for validation of performance analysis. By the method of linear regression the characteristic parameters of the reference modules have been determined through outdoor data regarding three different methods of determination of irradiance. At 1000W/m^2 little difference between the results based on the different irradiance determination methods could be found. The comparison of those parameters with the indoor measurement results are in agreement within the measurement uncertainty.

Equally, temperature coefficients for power and voltage have been determined and shown to be dependent at all levels of irradiance on the method used to determine irradiance. Spectral mismatch was determined as primary cause for irradiation dependent temperature coefficients.

A model has been built to predict losses caused by the module's efficiency temperature dependence and the losses caused by the module's efficiency irradiation dependence. Due to the spectral mismatch between the modules and the irradiance sensors (c-Si), used in building the model, the results are site specific and possibly seasonally dependent. The models' yield predictions agree well for the reference modules and revealed problems of inverter tracking for the grid connected strings.

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