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Energy Rating of Solar Modules

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Abstract

Up to now, the quality of solar modules has been judged by means of the STC-value. But it's known from experience that modules with the same STC-value can show significant differences in their yearly energy yield, even if they are mounted at the same location. An approach to this problem is to prognose the yearly energy yield of a module at a certain location with the so called "Performance Matrix". The Performance Matrix forecasts the performance of a solar module against solar irradiance and ambient temperature. To determine the performance matrix of a solar module, first its power is measured at different irradiances and temperatures; then a mathematical model is used to fit a plane through the power data. In this project the suitability of different measurement methods and mathematical models to create a Performance Matrix was analysed. For this purpose 3 modules BP580 and 3 Kyocera modules were measured indoor and outdoor. These measurement data were used to create Performance Matrices of the modules with different mathematical models.

It revealed that the measurement points must cover the whole irradiance spectrum and at least a part of the temperature spectrum to create a reliable Performance Matrix. To obtain measurement data, Indoor measurements with a sun simulator are suitable. Outdoor measurements can also be used, but under certain circumstances (changing weather conditions, changing angle of incidence etc.) a high scatter of the data can occur which makes necessary a filtering of the measurement points before creating the performance matrix. At least two of the investigated mathematical models were suitable to create a reliable performance matrix with relatively few measurement points. Using these models, yearly brut energy yields of 1100 kWh/kWp to 1200 kWh/kWp were predicted for Zurich, which is reasonable. The differences between the yearly energy yields calculated with the different Performance Matrixes were small: all energy yields were within 4% of the average energy yield, for Kyocera as well as for BP580 modules. The small standard deviation showed the high consistency between the different sets of measurement data and between the mathematical models.

The mathematical models and the measurement methods are continuously improved. In the next steps it should be verified, how close the predicted energy yields are to practice and if the Performance Matrix depends on geographical location of the module or on the inclination angle.

1. Introduction

Swiss experts in solar energy expect up to 10 % difference in specific energy production between different c-Si modules. Considering that even a 1 % difference of energy production can be worth € 4 to € 6 per kW_p per year for a typical European climate, it stands to reason that the choice of the most applicable solar module is of high financial consequences.

In this project, a new approach for predicting the yearly energy yield of a module at a certain location was investigated: the Performance Matrix. This matrix presents the power of a module in dependancy of the irradiance and the temperature (see figure 1). If the meteorological data of the location for a new PV system is known (e.g. from METEONORM [i]), the yearly energy yield of the module then can be calculated. To create the Performance Matrix, the power of the module has to be measured at different irradiances and temperatures. These measurement data are fitted with a mathematical model to the final Performance Matrix.

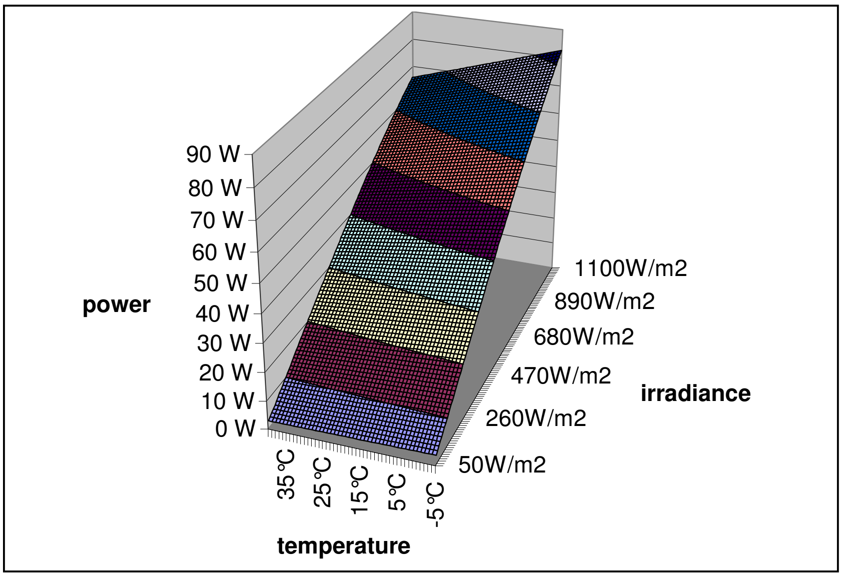


Figure 1: Performance Matrix of a module BP580

2. Goals

In the energy rating project, different measurement procedures and mathematical models to create the Performance Matrix were compared with the goal to verify the applicability of the Performance Matrix for energy predictions. The main criteria for the applicability of a Performance Matrix is their reliability: the difference between the prognosticated and the effective specific energy production should be less than 5 % to allow a ranking of different modules (the average difference in specific energy production between different types of solar modules are estimated to be 5 %). Other criteria are the necessary expenses for the measurements and the complexity of the mathematical model.

To decide about the applicability of the Performance Matrix, the Performance Matrix for two module types (polycristalline Kyocera and monocristalline BP580) was created with different measurement methods and mathematical models. The Performance Matrixes were used to predict the yearly energy yield at Zurich and at different standard days. These results were compared to determine if the different measurement methods and mathematical models give similar results and to find out, if differences between the two module types (poly- and monocristalline) are visible. Furthermore, the accuracy of the energy yields predicted with the Performance Matrix was calculated with a statistical error analysis.

3. Participants

Measurements of the modules were performed at PSI, JRC ISPRA and LEEE-TISO. Sensors were provided by ISET Kassel and the modules by Edisun Power AG. Enecolo AG was responsible for the creation of the Performance Matrixes and analysis of the data, in correspondence with LEEE TISO. The project was funded by Gesellschaft Mont Soleil and the Swiss Federal Office of Energy.

4. Materials and methods

MODULES

Six modules were measured in a round robin at all three institutes: three monocristalline modules BP 580 (called BP580 20S, BP580 22S and BP580 90S) and three polycristalline modules Kyocera (called Kyo03, Kyo04 and Kyo05). The characteristics of these modules are described in table 1. Additionally, a module was measured at ISET.

Table 1: Characteristics and indoor measured STC values of the modules BP580 and Kyocera. The module BP580 90S was not degraded yet when measured at JRC ISPRA. In this project the average of the measured STC values was used to calculate the specific yield of the modules.

	Module	**number**	**STC measured at LEEE-TISO**	**STC measured at JRC ISPRA**	**STC Project Energy Rating**
BP580 20S	BP580 (monocristalline)	683520S	79.21 W	78.23 W	78.72 W
BP580 22S	BP580 (monocristalline)	683522S	78.58 W	78.18 W	78.38 W
BP580 90S	BP580 (monocristalline)	680790S	77.31 W	80.16 W	77.31 W
Kyo03	Kyocera (polycristalline)	94308103	47.01 W	45.98 W	46.49 W
Kyo04	Kyocera (polycristalline)	94308104	46.68 W	46.90 W	46.79 W
Kyo05	Kyocera (polycristalline)	94308105	46.48 W	45.49 W	45.99 W

MEASUREMENT METHODS

Every module was measured with three different measurement methods:

- **Indoor:** Indoor measurements of current/voltage characteristics with sun simulator at JRC ISPRA [ii]
- **I/U suntracker:** manual outdoor measurements of current/voltage characteristics with sun-tracker at PSI [iii]
- **MPPT fixed rack:** Outdoor measurements of power at MPPT in 1 minute intervals on a fixed open rack at LEEE TISO [iv]
- **I/U fixed rack:** Outdoor measurements of current/voltage characteristics on a fixed open rack in 5 minute intervals at JRC ISPRA. The module is maintained at MPPT between the measurements [v]

Measurement points at an irradiance of less than 50 W/m^2 were excluded from the analysis.

MATHEMATICAL MODELS

For every measurement data set, the following mathematical models were used to create Performance Matrixes:

- **Linear:** first linear regressions Pmax = f(Tamb) at constant irradiances, then regression Pmax = f(G) at constant temperatures [vi, Appendix A]
- **Power:** Regression of Pmax = f(Tamb, G) with 6 empirical parameters [vii, Appendix B]
- **Efficiency:** Regression of Efficiency = f(Tcell, G) with 6 empirical parameters [viii, Appendix C]
- **ImUm:** Indoor measurement of Im,STC and Um,STC. Regression of Impp = f(G, Tamb) and of Umpp = f(G, Tamb) with 7 parameters [vi, ix, x]
- **IscUocFF:** Regression of Isc = f(G, Tamb), Uoc = f(G, Tamb) and FF = f(G, Tamb) with totally 12 empirical parameters [xi , Appendix D]

To calculate the ambient temperature from cell temperature values, the formula Tcell = h*G + Tamb was used. For all BP580 modules an average value of h = 0.0344 was determined with linear regression, for all Kyocera modules a value of h = 0.0277.

METEOROLOGICAL DATA

To predict the yearly energy yield of the modules at Zurich, irradiance for a 20° inclined module and ambient temperature were determined with the software METEONORM [i]. Additionally, the daily energy yields for five different IEEE standard days (Hot-Sunny, Cold-Sunny, Hot-Cloudy, Cold-Cloudy and Cool-Sunny) were determined [xii]. These standard days represent the US american climate.

STATISTICAL ERROR ANALYSIS

To determine the reliability of the Performance Matrixes, the 95% prognosis interval of the power for every irradiance and temperature of the Performance Matrix was determined with the following formula [Appendix E]:

$$\Delta P = t_{97.5\%,n-number\ of\ parameters} \cdot \hat{\sigma} \cdot \sqrt{1+\mathbf{x_0^t}\left(\mathbf{X^t X}\right)^{-1}\mathbf{x_0}}$$

This interval indicates the range in which a future value will be measured with a probability of 95%. The value of $t_{97.5\%,n-number\ of\ parameters}$ is 1.98 if the Performance Matrix bases on more than 100 measurement points. $\hat{\sigma}$ is the standard deviation between the measured data and the corresponding powers in the Performance Matrix. The matrixes $\mathbf{x}_0^t$ and $\mathbf{x}_0$ depend on the irradiance and temperature values for which the uncertainty is calculated. The matrixes $\mathbf{X}^t$ and $\mathbf{X}$ depend on the irradiance and temperature values of the measurement data.

The 95% prognosis interval can be calculated for those regions of the Performance Matrix that are covered with measurement data. For regions of the Performance Matrix that don't contain any measurement data, the 95% prognosis interval is not valid. The reliability of the predicted energy yields depends mainly on the systematic and the stochastic part of this 95 % prognosis interval but also on the uncertainty of the meteorological data. The systematic percentage of the 95% prognosis interval could not be determined and even the 95 % prognosis interval could only be calculated for those regions of the Performance Matrix that were covered with measurement data. Therefore the uncertainty of the predicted energy yields could not be calculated.

5. Results

MEASUREMENTS

Every module was measured with every measurement method except for the method I/U fixed rack. With this method, only the module BP580 20S was measured. The measurements of the BP580 modules with the method MPPT fixed rack could not be used for the analysis because it revealed that the electronic of the measurement stand was defect and produced too low values.

A comparison of the measurement data in a three dimensional matrix shows clear differences in the distribution of the data (see figures 2 to 5): Indoor measurements allow a uniform distribution of the data over the whole range of irradiances and temperatures, while outdoor measurements are restricted to the prevailing irradiance conditions during the measurement phase. If measurements are done automatically during the whole day (e.g. data MPPT fixed rack and I/U fixed rack), the whole irradiance spectrum can be covered within a time of several days to weeks, while the temperature range depends on the season. If measurements are done manually and only in the afternoon (e.g. data suntracker), not even the temperature range is covered sparely but also the irradiance spectrum.

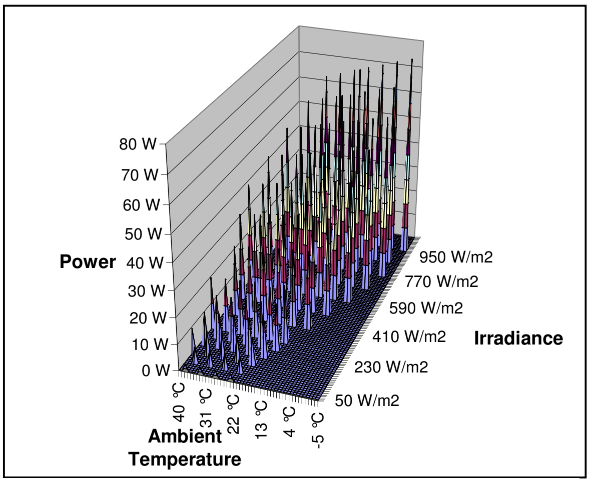


Figure 2: Measurement data Indoor for the module BP580 20S, measured in 2003

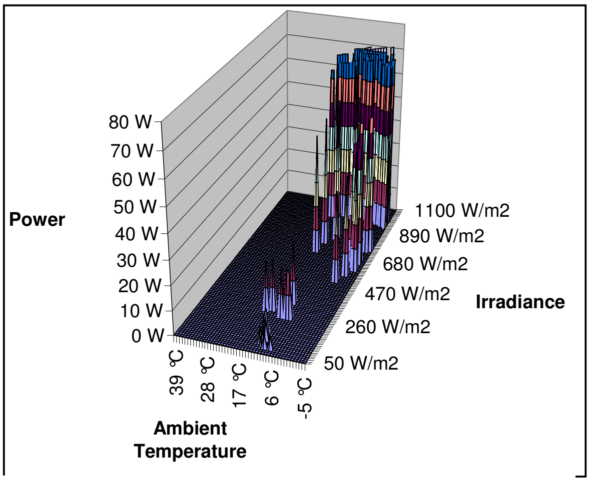


Figure 3: Measurement data suntracker for the module BP580 20S, measured in 2003

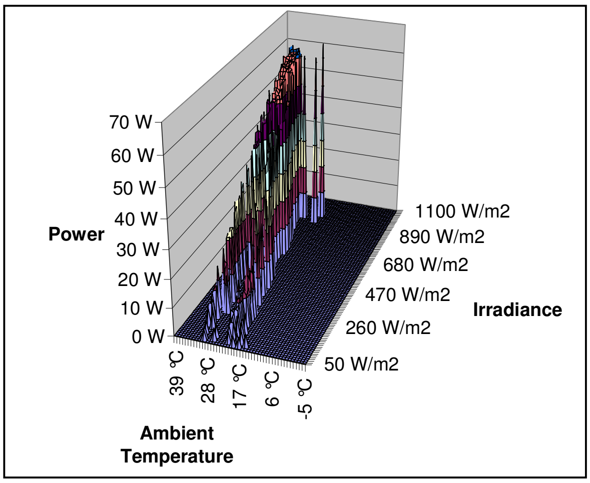


Figure 4: Measurement data I/U fixed rack for the module BP580 20S, measured in 2003

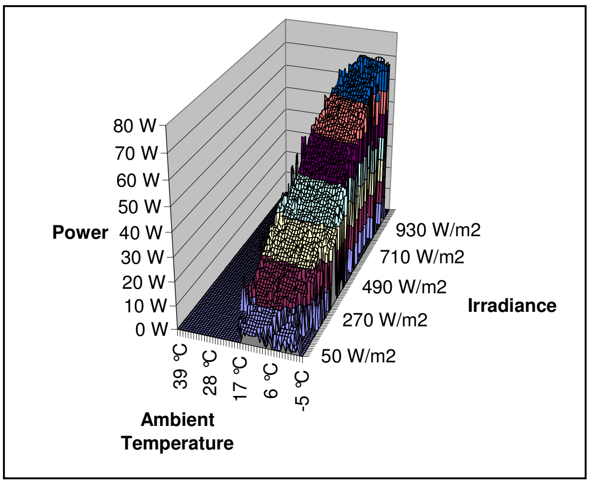


Figure 5: Measurement data MPPT fixed rack for the module BP580 20S, measured in 2003

A comparison of the measurement data in a two dimensional graph presenting the power in dependence of the irradiance shows clear differences in the scatter of the data, depending on the measurement method (see figures 6 to 7): Indoor measurements are not influenced by other meteorological parameters than irradiance and temperature and therefore the scatter at a defined irradiance is only due to temperature effects. For outdoor measurements, the method suntracker shows the smallest scatter, because there is no influence of changing angles of incidence. Additionally, measurements were only done at stable weather conditions. Measurement data I/U fixed rack shows similar scatter as suntracker measurements whereas measurement data MPPT fixed rack has clearly higher scatter. This is not only due to the changing angle of incidence but also due to problems of the MPPT tracker at changing weather conditions during the 1 minute measurement interval.

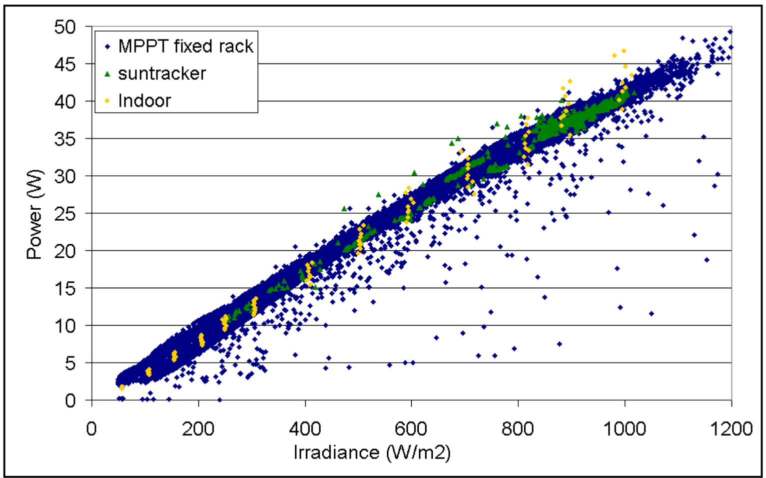


Figure 6: Measurement data of the module Kyo04, measured in 2003

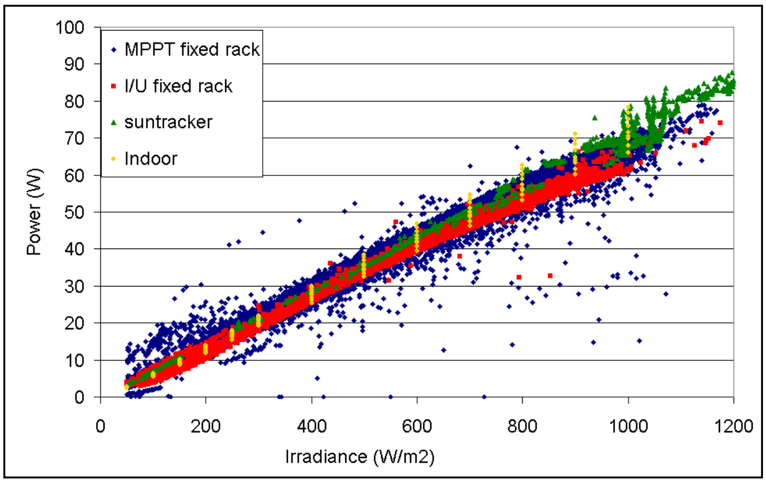


Figure 7: Mesaurement data of the module BP580 20S, measured in 2003

PERFORMANCE MATRIXES

Not all combinations of measurement data and mathematical models were usable to create a Performance Matrix. For the BP580 modules no reliable measurement data MPPT fixed rack could be measured because of a defect in the electronic. With the measurement method suntracker only very few performance data was measured and therefore the data basis for some modules was insufficient to create a Performance Matrix[1]. For single mathematical models also the data sets achieved with the other measurement methods didn't contain enough data points to create sufficient Performance Matrixes.

[1] A Performance Matrix was considered sufficient, if the power was increasing with increasing irradiance and decreasing temperature.

Two of the five mathematical models showed to be insufficient for the creation of a reliable Performance Matrix: The model Linear only produced complete Performance Matrixes if the whole range of irradiances and temperatures was covered with measurement data. For restricted data sets, either no Performance Matrix could be calculated or the 95% prognosis interval was very high (sometimes exceeding 100%). The model IscUocFF lead to high 95 % prognosis intervals too, especially at low irradiances. For Indoor Measurements, the deviation between the Performance Matrix and the measured data was up to 50% (see figure 8). Furthermore, the Performance Matrix showed systematically higher powers than measured for low irradiances. This trend of a systematic deviation could also be observed for outdoor data, but not always in the same direction. The models Power and Efficiency showed lower deviations between the Performance Matrix and the measured data and no obvious systematic trend (see figures 9 to 11).

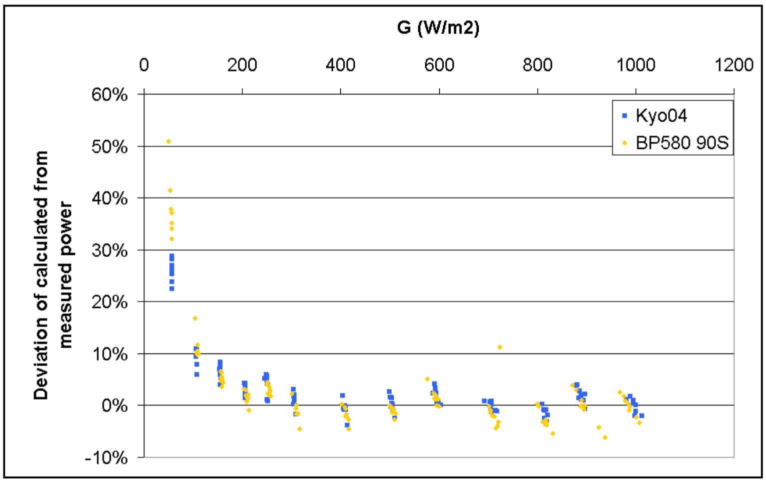


Figure 8: Deviation of the Performance Matrix model IscUocFF from the measurement data Indoor

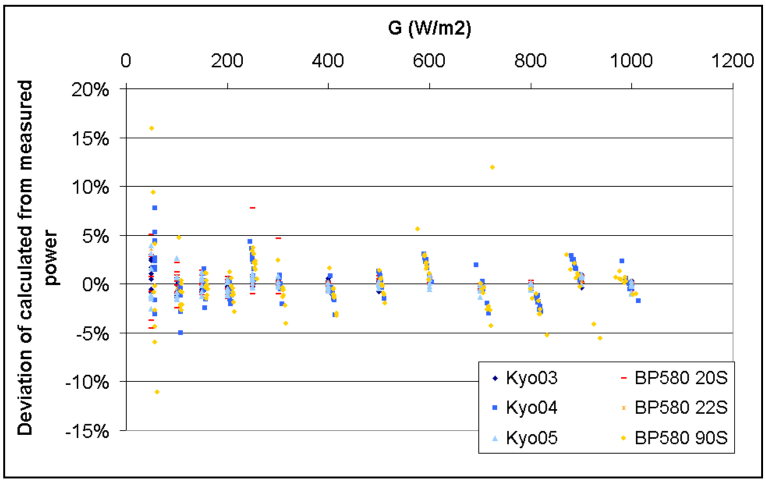


Figure 9: Deviation of the Performance Matrix model Power from the measurement data Indoor

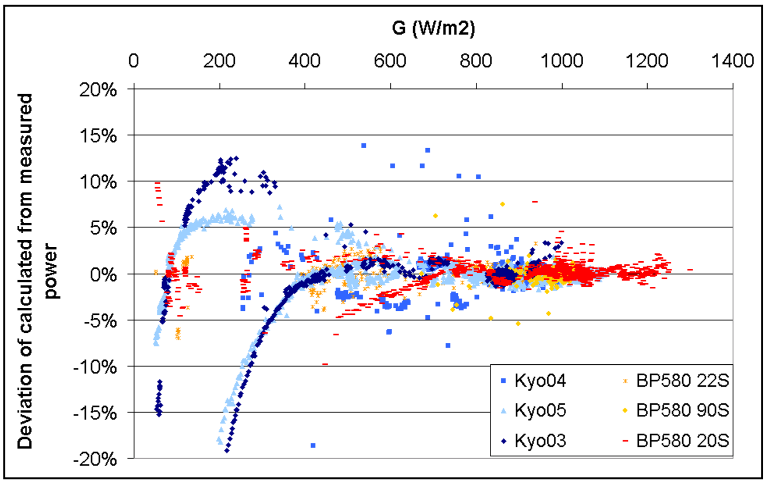


Figure 10: Deviation of the Performance Matrix model Power from the measurement data suntracker

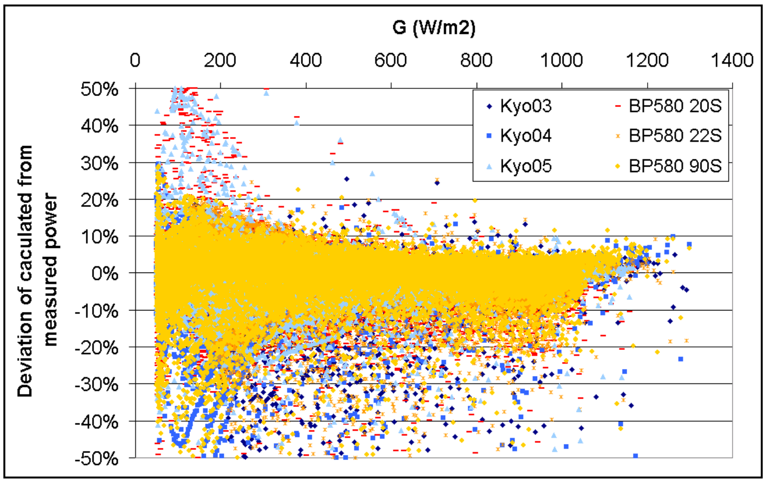


Figure 11: Deviation of the Performance Matrix model Power from the measurement data MPPT fixed rack

The 95 % prognosis interval and consequently also the percentage deviation between the Performance Matrix and the measurement data increased with decreasing irradiance (see figure 12). For the model ImUm, the 95 % prognosis interval and the deviation between the Performance Matrix and the measurement data was not calculated because of time reasons.

For the investigated modules, the measurement data Indoor produced uncertainties of less than 1% at high irradiances and uncertainties of up to 8% at an irradiance of 100 W/m^2 (method Power, see figure 12). Measurement data MPPT fixed rack produced uncertainties of 2 – 3% at high irradiances and uncertainties of up to 20% at an irradiance of 100 W/m^2 (see figure 13).

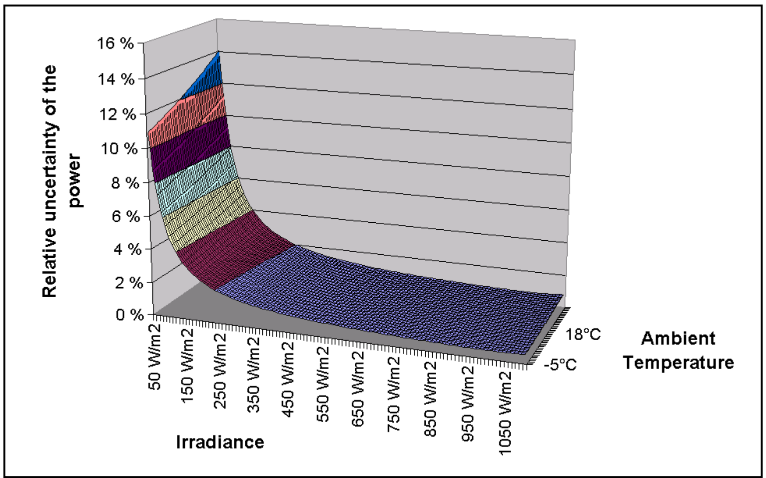


Figure 12: relative uncertainty of the performance matrix model Power with measurement data Indoor of the module Kyo03

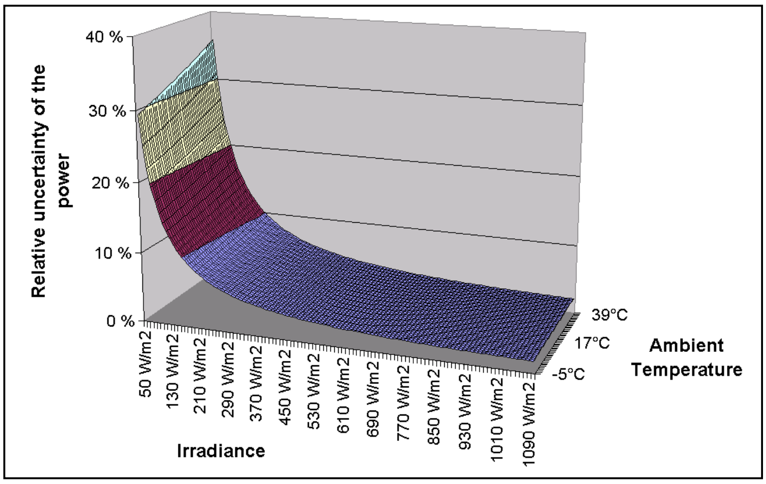


Figure 13: relative uncertainty of the performance matrix model Power with measurement data MPPT fixed rack of the module Kyo03

As explained above, not all measurement data and mathematical models revealed to be suitable to create a Performance Matrix. Table 2 gives an overview which combinations of the different possible measurement data and mathematical models produced reliable Performance Matrixes and which combinations could not be used because of different reasons.

Table 2: possible combinations of Measurement Data and Mathematical Models and their usability to create a Performance Matrix

	Kyo03	Kyo04	Kyo05	BP20	BP22	BP90
MPPT fixed rack - Linear	not reliable (model)	not reliable (model)	not reliable (model)	data not reliable (defect)	data not reliable (defect)	data not reliable (defect)
MPPT fixed rack - Power	reliable	reliable	reliable	data not reliable (defect)	data not reliable (defect)	data not reliable (defect)
MPPT fixed rack - Efficiency	reliable	reliable	reliable	data not reliable (defect)	data not reliable (defect)	data not reliable (defect)
MPPT fixed rack - ImUm	reliable	reliable	reliable	data not reliable (defect)	data not reliable (defect)	data not reliable (defect)
MPPT fixed rack - IscUocFF	Isc/Uoc n.a.	Isc/Uoc n.a.	Isc/Uoc n.a.	Isc/Uoc n.a.	Isc/Uoc n.a.	Isc/Uoc n.a.
suntracker - Linear	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)
suntracker - Power	reliable	no reliable fit	reliable	reliable	no reliable fit	no reliable fit
suntracker - Efficiency	reliable	no reliable fit	reliable	reliable	no reliable fit	no reliable fit
suntracker - ImUm	reliable	reliable	reliable	reliable	reliable	no reliable fit
suntracker - IscUocFF	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)
Indoor - Linear	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)	not reliable (model)	not calculated
Indoor - Power	reliable	reliable	reliable	reliable	reliable	not calculated
Indoor - Efficiency	reliable	reliable	reliable	reliable	reliable	not calculated
Indoor - ImUm	reliable	reliable	reliable	reliable	reliable	not calculated
Indoor - IscUocFF	Isc/Uoc n.a.	not reliable (model)	Isc/Uoc n.a.	Isc/Uoc n.a.	Isc/Uoc n.a.	not reliable (model)
I/U fixed rack - Linear	not measured	not measured	not measured	not reliable (model)	not measured	not measured
I/U fixed rack - Power	not measured	not measured	not measured	reliable	not measured	not measured
I/U fixed rack - Efficiency	not measured	not measured	not measured	reliable	not measured	not measured
I/U fixed rack - ImUm	not measured	not measured	not measured	reliable	not measured	not measured
I/U fixed rack - IscUocFF	not measured	not measured	not measured	not reliable (model)	not measured	not measured

legend:

- reliable Performance Matrix
- not measured
- measurement data not reliable because of a defect in the electronic
- not reliable Performance Matrix because of unsufficient mathematical model
- Isc and Uoc not available
- not calculated because the module was not yet degraded
- no reliable fit possible because of too less measurement data

ENERGY YIELDS

Using hourly meteorological data (Tamb, Irradiance) of METEONORM for Zurich, the yearly energy yield of a module could be predicted (see figure 14). The predicted yearly energy yield was in average 1161 kWh/kWp for the Kyocera modules with a standard deviation of 2.0 % between the different measurement methods, modules and mathematical models. For the BP580 modules, the predicted yearly energy yield was in average 1099 kWh/kWp with a standard deviation of 1.9 % . The maximum deviation from the average calculated energy yield was 3.7 % for Kyocera as well as for BP580 modules.

Additionally to the yearly energy yield, the daily energy yield for several standard days was predicted with the Performance Matrixes (see figures 15 to 19). Similar to the results for the yearly energy yield, Kyocera modules showed in tendency higher predicted yields than BP580 modules at all standard days. Especially for sunny days and suntracker data, the predicted energy yields for the BP580 modules were lower than for the Kyocera modules.

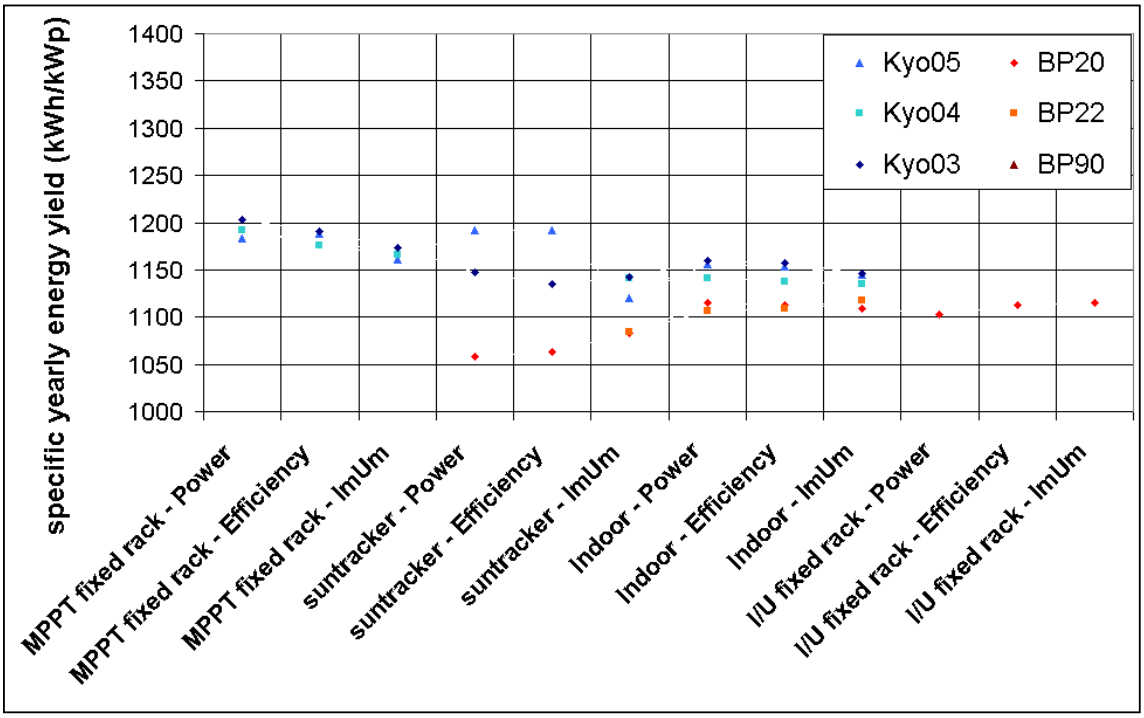


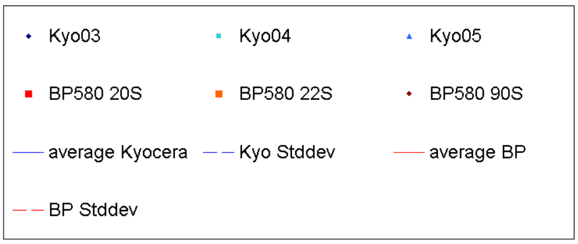
Figure 14: specific yearly energy yields for Zurich, calculated with different Performance Matrixes for 3 modules Kyocera and 3 modules BP580

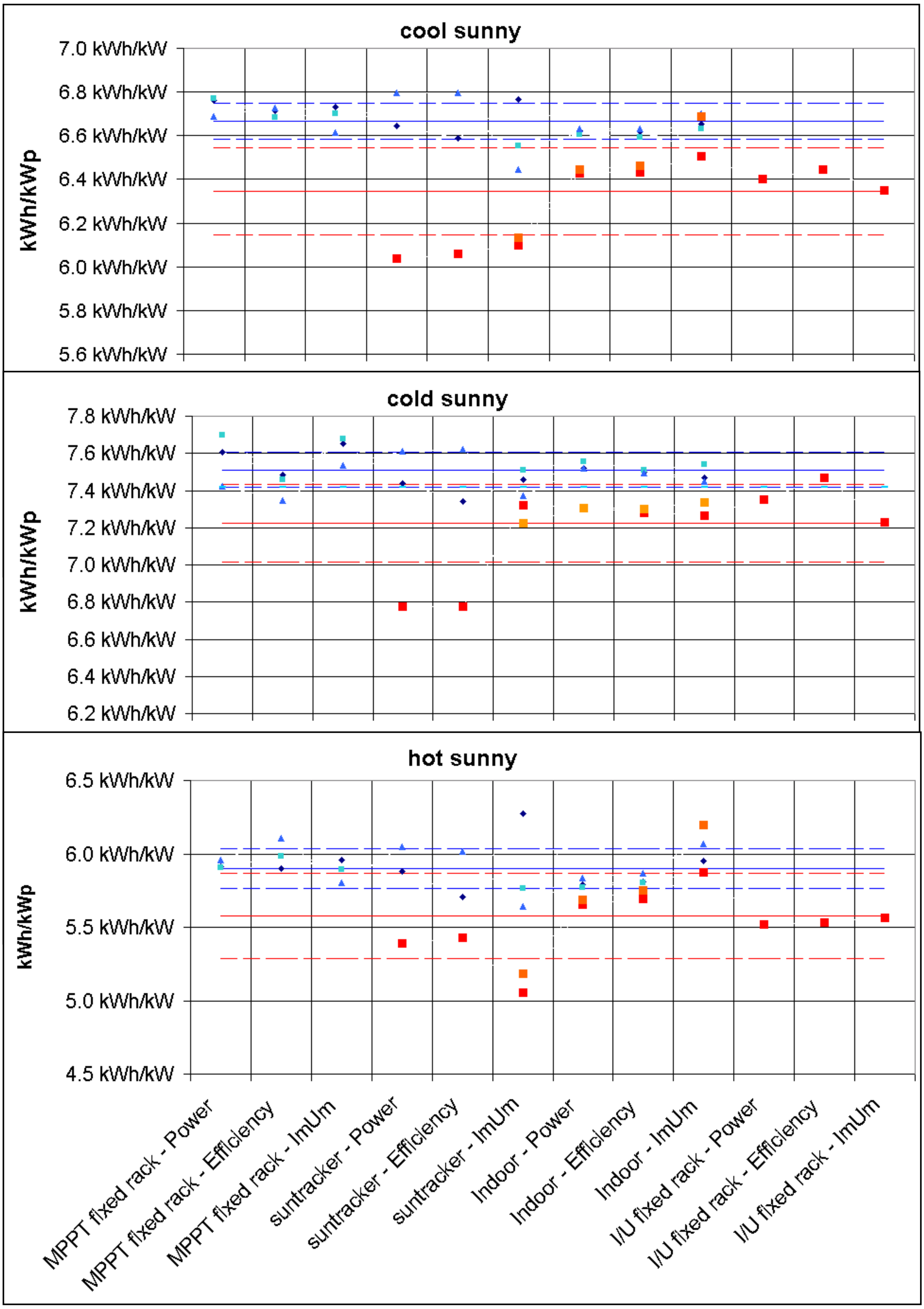
The calculated energy yields for standard days showed standard deviations of 1.2 % to 5.2 % from the average. For BP580 modules, the standard deviation between the energy yield of the different Performance Matrixes was similar at sunny days as at cloudy days (2.9 to 5.2 %). At sunny days, the standard deviation was mainly caused by the Performance Matrixes with suntracker data which produced clearly lower energy yields than the other Performance Matrixes (i.e. Indoor and I/U fixed rack data).

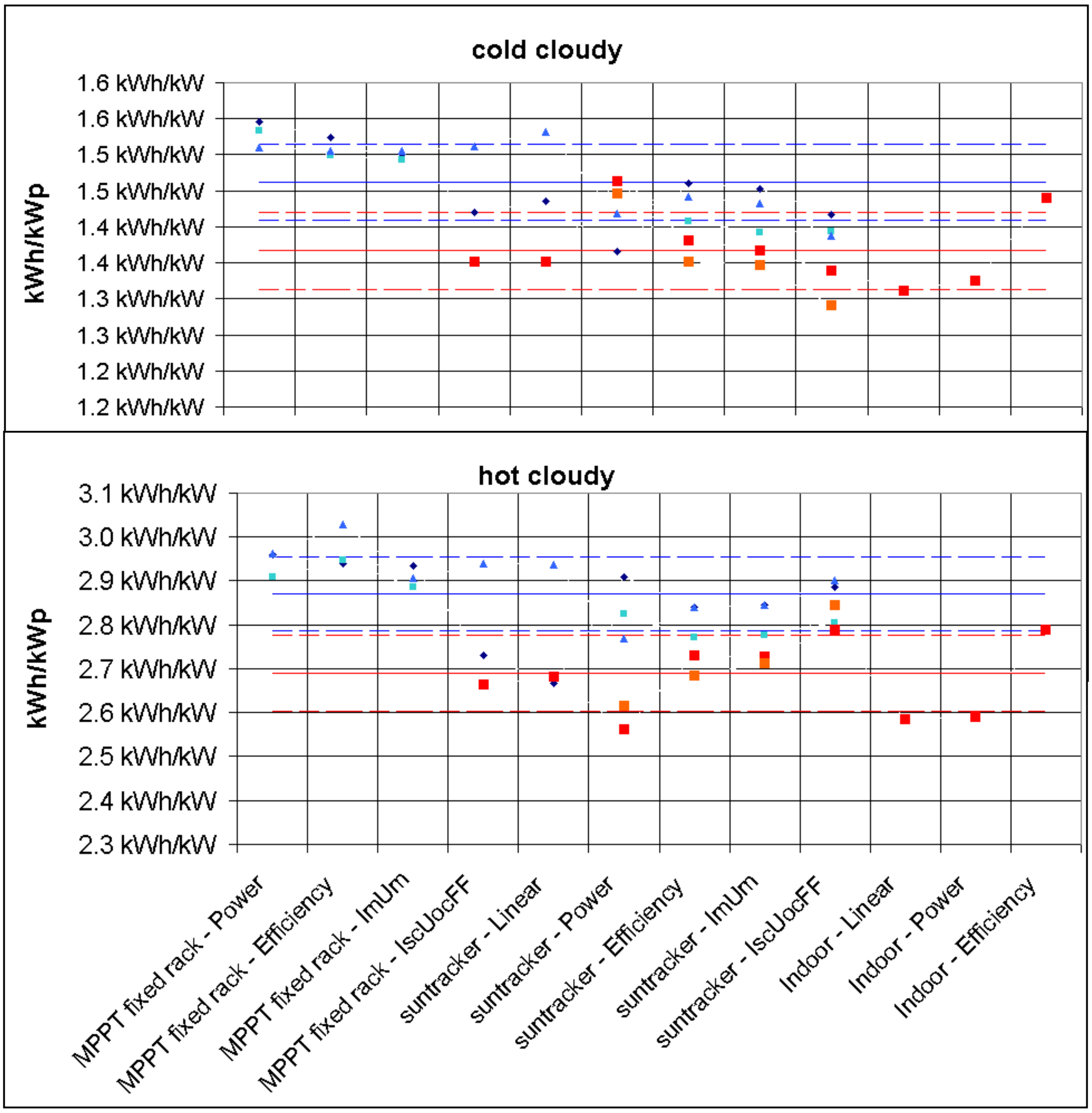
For Kyocera modules the standard deviation was very small: 1.2 % to 2.3 % for sunny days and 2.9 to 3.7% for cloudy days. Standard deviations were higher at cloudy days due to higher differences between the results of MPPT fixed rack and Indoor Measurements: at cloudy days the energy yields calculated with MPPT fixed rack Performance Matrixes were clearly higher than the energy yields calculated with Indoor Performance Matrixes.

Figures 15 - 19: specific daily energy yields for the standard days hot cloudy, cold cloudy, cold sunny, cool sunny and hot sunny calculated with different Performance Matrixes for 3 modules Kyocera and 3 modules BP580

Legend:




cool sunny
7.0 kWh/kW
6.8 kWh/kW
6.6 kWh/kW
6.4 kWh/kW
6.2 kWh/kW
6.0 kWh/kW
5.8 kWh/kW
5.6 kWh/kW
kWh/kWp
cold sunny
7.8 kWh/kW
7.6 kWh/kW
7.4 kWh/kW
7.2 kWh/kW
7.0 kWh/kW
6.8 kWh/kW
6.6 kWh/kW
6.4 kWh/kW
6.2 kWh/kW
kWh/kWp
hot sunny
6.5 kWh/kW
6.0 kWh/kW
5.5 kWh/kW
5.0 kWh/kW
4.5 kWh/kW
kWh/kWp
MPPT fixed rack - Power
MPPT fixed rack - Efficiency
MPPT fixed rack - ImUm
suntracker - Power
suntracker - Efficiency
suntracker - ImUm
Indoor - Power
Indoor - Efficiency
Indoor - ImUm
I/U fixed rack - Power
I/U fixed rack - Efficiency
I/U fixed rack - ImUm



6. Conclusions

The results showed that it's possible to create a Performance Matrix based on measured power or current/voltage characteristics at different cell temperatures and irradiances. To get a reliable Performance Matrix, the measurement points must cover the whole irradiance spectrum and at least a part of the temperature spectrum of the Performance Matrix. To obtain measurement data, Indoor measurements with a sun simulator are suitable. Outdoor measurements can also be used, but under certain circumstances (changing weather conditions, changing angle of incidence etc.) a high scatter of the data can occur which makes necessary a filtering of the measurement points before creating the performance matrix.

At least two of the investigated mathematical models were suitable to create a reliable performance matrix with relatively few measurement points. One of these models (Power) consists of one equation with 6 empirical parameters which are fitted in a regression. The other model (ImUm) consists of two equations with totally 7 parameters. 5 of these parameters are physical and thus could be measured instead of fitting them in a regression. In this project 2 parameters (Im, STC and Um, STC) were measured indoor, the other five parameters were fitted in the regression.

An important goal of this project was to verify, if the uncertainty of the predicted energy yields is lower than 5%. It turned out that it's impossible to fully answer this question within this project. It developed that the uncertainty depends on the number of measurement points and on their distribution over the performance matrix. For regions in the performance matrix outside the range of measurement data the uncertainty can't be determined reliably. But independent of the data set, the relative uncertainty of the Performance Matrix always increased with decreasing irradiance.

Using the reliable Performance Matrixes of the measured modules, yearly energy yields of 1100 kWh/kWp to 1200 kWh/kWp were predicted (see figure 14). PV plants in Zurich usually have yearly energy yields of approximately 900 kWh/kWp. Taking into account a loss of about 20% due to the inverter and the cables, the predicted brut yield of 1100 kWh/kWp is very reasonable. The differences between the yearly energy yields calculated with the different Performance Matrixes were very small: all energy yields were within 4% of the average energy yield, for Kyocera as well as for BP580 modules. The small standard deviation shows the high consistency between the different sets of measurement data and between the mathematical models. Thus it can be concluded that the three models Power, Efficiency and UmIm give very similar results. Because the „real“ energy yield of these modules in Zurich is not known it can't be determined, how close these calculated energy yields come to the real energy yield.

Another goal of this project was to determine whether the different measurement methods and locations (Indoor, suntracker, MPPT fixed rack and I/U fixedrack) lead to the same results. With Indoor data, the differences in the predicted energy yields between Kyocera and BP580 modules seemed to be smaller than with outdoor measurement data. Because the measurement procedures Indoor and MPPT fixed rack were different, it was not possible to decide if this difference was due to the measurement method or due to other influence factors at outdoor measurements. Between I/U fixed rack and Indoor data, no significant differences could be detected.

The data base was too small to decide, if the difference in the energy yields calculated with MPPT fixed rack, I/U fixed rack, Indoor and suntracker measurements were significant.

The main reason for the project energy rating was the hope of being able to rank modules according to their energy yield at a certain location and thus to be able to find the best module for a planned PV system. In this project therefore two different module types (polycristalline Kyocera modules and monocristalline BP580 modules) were investigated. The results indicate a lower energy yield in Zurich for the BP580 modules than for the Kyocera modules. Also for standard days, Kyocera modules seem to produce higher energy yields than BP580 modules. But the differences are very small (4 to 6.5%) and depend on the measurement method. With Indoor measurements the predicted differences in energy yields are only 3 %. With outdoor measurements, the differences are higher, but there doesn't exist a reliable data set of all 6 modules measured outdoor with the same measurement method. Differences in the energy yield therefore might be due to differences in the measurement methods instead of differences between the module types.

7. Outlook

The models and measurement methods investigated in this project are consequently improved. At PSI already a new version of the model Efficiency exists [xiii] and also the model ImUm is further developed at TISO. Outdoor measurements are improved, too. The measurement stand at PSI has been automated which will allow to measure suntracker data all over the day in 2 minute intervals in future. Performance Matrixes based on suntracker data therefore won't suffer from too small data bases any more. At TISO the electronic will be modernised thus preventing corrupt data sets as occurred in this project for the modules BP580. The MPPT tracking and the measurement interval probably will be changed too, which might reduce the amount of scatter.

Due to the improved hardware, some additional measurements in the course of this project could give important additional information to the following questions:

1. Are the observed differences in predicted energy yields of up to 4% between measurement data Indoor, suntracker, MPPT fixed rack and I/U fixed rack due to the different measurement methods, due to the different locations (climate) or random?
2. What is the influence of the angle of incidence on the Performance Matrix?

To answer the first question, measurement data of one module at different climates should be acquired with the same measurement method. This would allow to decide, if the differences depend on the measurement method. The easiest way to gather measurement data of different locations with the same measurement equipment would be to install a transportable measurement stand on a truck. In order to be able to detect possible climatic influence factors, in addition to the irradiance and temperature also other parameters as cell temperature, direct irradiance and air mass should be measured.

To answer the second question, measurements with suntracker and fixed rack should be done simultaneously and at the same location. Thus, measurement data and the resulting Performance Matrixes could directly be compared.

The results of this project show, that the Performance Matrix allows to predict energy yields and that the results are very reasonable. Nevertheless, in the course of this project it couldn't be verified how close these predicted energy yields come to the „real" energy yields of the modules. To answer this, the real energy yield of a module should be measured and then compared with the predicted energy yields. This could easily be done with the method MPPT fixed rack: this method allows to measure the "real" energy yield of a module and at the same time to acquire measurement data for producing the Performance Matrix. Such measurement data for a whole year already exist for different modules. Therefore it would be easy to create the Performance Matrixes with different mathematical models and to predict the yearly energy yield using METEONORM data of irradiance and temperature for Lugano.

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Appendix A: Mathematical Model "Linear"

NEEDED INPUT DATA

- Electricity yield Pmax
- Incident global irradiation Gglobal
- Ambient temperature T_{amb}

ELIMINATION OF OUTLIERS

1. Creation of a temperature – irradiation grid. The length of one grid cell corresponds to 1°C, the width to 10 W/m^2
2. For each single grid cell calculate the average Pav by taking the average of all Pmax-values belonging to that grid cell. Use all measurement data. (Example: all Pmax-values with a belonging ambient temperature between 10.5°C and 11.5°C and with a belonging global irradiation between 355 W/m^2 and 365 W/m^2 are averaged and filled in the grid cell 11°C, 360W/m^2.)
3. Eliminate all grid cells with a low event number (less than 10 belonging Pmax-values)
4. Eliminate all grid cells whose Pav has a standard deviation > 20% of Pav.
5. The standard deviation is calculated with the formula Standard deviation = $\sqrt{\frac{\sum_i \left(P_{\max,i} - P_{av}\right)^2}{n-1}}$

   $P_{max,I}$ are the P_{max}-values that were used to build P_{av}. n is the number of P_{max}-values that were used to build $P_{av.}$

CREATION OF THE PERFORMANCE MATRIX

1. Perform a linear regression (formula: Pav = a + b*T_{amb}) for every row of your grid that contains more than 6 Pav-values. Then calculate the Pav-values for all temperatures and fill them in the row.
2. Perform a multiple regression (formula: Pav = a*Gi + b*Gi^2) for every column of your grid that contains more than 6 Pav-values. Then calculate the Pav-values for all irradiations and fill them in the column.

Appendix B: Mathematical Model "Power"

NEEDED INPUT DATA

- Energy yield at maximum power point Pmax
- Global irradiance G
- Ambient temperature Tamb

ELIMINATION OF OUTLIERS

1. Fit the power P = P1·G2 + P2·G3/2 + P3·G4/3 + P4·G5/4 + P5·G6/5 + P6·Tamb·G (with P1, P2, P3, P4, P5, P6 = parameters). Use all measurement data.
2. Calculate σ_P: $\sigma p^2 = \dfrac{\sum_{i=1}^{n} \left(P_i - \hat{P}_i\right)^2}{n - number\ of\ \ parameters}$
3. Eliminate all data with $\left(\left|P_i - \hat{P}_i\right| > \sigma_P\right)$

CREATION OF THE PERFORMANCE MATRIX

1. Fit the power $P = P_1 \cdot G^2 + P_2 \cdot G^{3/2} + P_3 \cdot G^{4/3} + P_4 \cdot G^{5/4} + P_5 \cdot G^{6/5} + P_6 \cdot Tamb \cdot G$ (with P_1, P_2, P_3, P_4, P_5, P_6 = parameters). Don't use the outliers.
2. Calculate P from the power formula for many different global irradiances and temperatures
3. Plot the performance matrix (P against G and Tamb)

Appendix C: Mathematical Model “Efficiency”

NEEDED INPUT DATA

- Efficiency η
- Global irradiance G
- Ambient temperature Tamb
- Cell area

ELIMINATION OF OUTLIERS

1. Fit the efficiency $\eta = a\cdot\left(\frac{G}{G0}\right) + b\cdot\left(\frac{G}{G0}\right)^{1/2} + c\cdot\left(\frac{G}{G0}\right)^{1/3} + d\cdot\left(\frac{G}{G0}\right)^{1/4} + e\cdot\left(\frac{G}{G0}\right)^{1/5} + f\cdot\left(\frac{Tcell}{T0 - 1}\right)$

   with a, b, c, d, e, f = parameters. Use all measurement data.

2. Calculate the appropriate σeff: $\sigma_{eff}^2 = \frac{\sum (eff_i - \hat{eff}_i)^2}{n - number\ of\ \ parameters}$

3. Eliminate all data with ($|effi - \hat{e}ffi| > \sigma eff$)

CREATION OF THE PERFORMANCE MATRIX

1. Fit the efficiency $\eta = a\cdot\left(\frac{G}{G0}\right) + b\cdot\left(\frac{G}{G0}\right)^{1/2} + c\cdot\left(\frac{G}{G0}\right)^{1/3} + d\cdot\left(\frac{G}{G0}\right)^{1/4} + e\cdot\left(\frac{G}{G0}\right)^{1/5} + f\cdot$ with a,

   b, c, d, e, f = parameters. Don’t use the outliers.
2. Calculate Tcell for many different ambient temperatures with the formula: Tcell = Tamb + h·G
3. Calculate η from the efficiency formula for many different global irradiances and the cell temperatures computed before
4. Calculate Pmax from every η value: Pmax = η ·cell area·global irradiance
5. Plot the performance matrix (Pmax against G and Tamb)

Appendix D: Mathematical Model "IscUocFF"

NEEDED INPUT DATA

- Current at short circuit Isc
- Voltage at open circuit Uoc
- Fill factor FF
- Incident global irradiation Gglobal
- Cell temperature Tcell

ELIMINATION OF OUTLIERS

1. Fit the current: Isc = a1 + a2 · G + a3 · Tcell. Use all measurement data.
2. Calculate σ_{Isc}: $\sigma_{Isc}^2 = \frac{\sum_{i=1}^{n}\left(Isc_i - \hat{I}sc_i\right)^2}{n-3}$
3. Fit the Voltage: Uoc = b1+ (b2 + b3·Tcell)·LN(G) – b4·Tcell. Use all measurement data.
4. Calculate σUoc: σUoc2 = $\frac{\sum_{i=1}^{n}\left(Uoc_i - \hat{U}oc_i\right)^2}{n-4}$
5. Fit FF: FF = c1 – (c2·G + c3)/LN(G) – Tcell · (c4 ·G + c5). Use all measurement data.
6. Calculate σFF: σFF2 = $\frac{\sum_{i=1}^{n}\left(FF_i - \hat{F}\hat{F}_i\right)^2}{n-5}$
7. Eliminate all data with $\left(\left|Isc_i - \hat{I}sc_i\right| > \sigma_{Isc}\right)$, $\left(\left|Uoc_i - \hat{U}oc_i\right| > \sigma_{Uoc}\right)$ or $\left(\left|FF_i - \hat{F}\hat{F}_i\right| > \sigma_{FF}\right)$

CREATION OF THE PERFORMANCE MATRIX

1. Fit the current: Isc = a1 + a2 · G + a3 · Tcell. Don't use the outliers.
2. Fit the Voltage: Uoc = b1+ (b2 + b3·Tcell) · LN(G) – b4·Tcell. Don't use the outliers.
3. Fit FF: FF = c1 – (c2·G + c3)/LN(G) – Tcell · (c4 ·G + c5). Don't use the outliers.
4. Calculate Isc from the formula for many different global irradiances and ambient temperatures:
5. Isc = a1 + a2 · G + a3 ·(h*G + Tamb – 2)
6. Calculate Uoc from the formula for many different global irradiances and ambient temperatures:
7. Uoc = b1+ b2· LN(G) + (b3 · LN(G) – b4) ·(h*G + Tamb – 2)

8. Calculate FF from the formula for many different global irradiances and ambient temperatures:
9. $FF = c1 – (c2 \cdot G + c3)/LN(G) – (h \cdot G + Tamb – 2) \cdot (c4 \cdot G + c5)$
10. Fit Pmax: $Pmax = FF \cdot Isc \cdot Uoc$
11. Calculate Pmax from the formula for many different global irradiances and ambient temperatures
12. Plot the performance matrix (Pmax against G and Tamb)

Appendix E: Statistical Error Analysis

PROGNOSIS INTERVAL

The 95% prognosis interval of a multiple linear regression is defined as

$$\Delta y = t_{97.5\%,n-number\ of\ parameters} \cdot \hat{\sigma} \cdot \sqrt{1+\mathbf{x_0^t}\left(\mathbf{X^t X}\right)^{-1}\mathbf{x_0}}$$

This interval indicates the range in which a future value will be measured with a probability of 95%.

t- value

The value of $t_{97.5\%,n-number\ of\ parameters}$ is 1.98 if the Performance Matrix bases on more than 100 measurement points.

Sigma

For a formula of the form y = a1·x1+a2·x2+ … +ap·xp $\hat{\sigma}$ can be calculated with the formula:

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - (a_1 \cdot x_1 + a_2 \cdot x_2 + ... + a_p \cdot x_p)_i\right)^2}{n-p}}$$

yi: measured y-values

$\hat{y}_i$: calculated y-values that correspond to yi

n: number of measurements

p: number of parameters in the formula

Matrixes

For a formula of the form Yi = a1·x1i+a2·x2i+ … +ap·xpi the matrixes are:

$$\mathbf{x}_0^t = \begin{bmatrix} x_{01} & x_{02} & x_{03} & ... & x_{0p} \end{bmatrix}$$

$$\mathbf{x}_0 = \begin{bmatrix} x_{01} \\ x_{02} \\ ... \\ x_{0p} \end{bmatrix}$$

with xoi: dependent variables for which you want to forecast y

$$\mathbf{X}^t = \begin{bmatrix} x_{11} & x_{12} & ... & x_{1n} \\ x_{21} & x_{22} & ... & x_{2n} \\ ... & ... & ... & ... \\ x_{p1} & x_{p2} & ... & x_{pn} \end{bmatrix}$$

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{21} & \dots & x_{p1} \\ x_{12} & x_{22} & \dots & x_{p2} \\ \dots & \dots & \dots & \dots \\ x_{1n} & x_{2n} & \dots & x_{pn} \end{bmatrix}$$

with xai: measurement values of the dependent variables

LAW OF ERROR PROPAGATION

For any dependent variable y that is defined by the equation y = f(x1, x2, …,xn) with the independent variables x1, x2, … xn the 95% prognosis interval is:

$$\Delta y = \sqrt{\left(\frac{\partial y}{\partial x_1} \cdot \Delta x_1\right)^2 + \left(\frac{\partial y}{\partial x_2} \cdot \Delta x_2\right)^2 + \dots + \left(\frac{\partial y}{\partial x_n} \cdot \Delta x_n\right)^2}$$

where ∆x1, ∆x2,… , ∆xn are the 95% prognosis intervals of the independent variables x1, x2, … xn