INVERTER PERFORMANCE UNDER FIELD CONDITIONS

Nicolas Allet[1]*, Franz Baumgartner[2], Juergen Sutterlueti[1], Stefan Sellner[1], Manuel Pezzotti[3]

[1] Oerlikon Solar, PV Systems, Hauptstrasse 1a, 9477 Trübbach, Switzerland
*phone +41 (0) 81 784 8042; nicolas.allet@oerlikon.com
[2] ZHAW, Zurich University of Applied Sciences, School of Engineering
[3] EKZ, Utility of the Canton Zurich, Switzerland, www.ekz.ch/solarlab

ABSTRACT: Based on the outdoor test PV power plant near Zürich the inverter performance under field conditions has been analysed and compared to manufacturer data. Tracking and conversion efficiency is treated separately. Tracking performance depends on the generator's Maximum-Power-Point, which cannot be measured while the inverter's tracking is in operation. The generator's maximum output power is therefore deduced from a reference module. Tracking performance above 98% could be determined under stable environmental conditions, defined by low fluctuating irradiance and module temperature. Comparing conversion performance under the same steady conditions to the η_{EURO} generally showed lower measured efficiency as expected by the datasheet. By recalculating the weighting factors used for the calculation of η_{EURO}, site and system specific conversion performance expectancies (η_{EURO} adapted) have been determined to differ only by 0.3% to η_{EURO}. Direct comparison between measured and, according to the datasheet, expected conversion performance for different output power levels of the inverter have shown very different conversion characteristics under field than under laboratory conditions leading to losses of over 2% under steady conditions without considering measurement uncertainty of 1.1% (k=2).
Keywords: Inverter, Performance, PV Array, PV System

1 INTRODUCTION

Predicting the energetic output of a PV power plant is a key requirement for choice of components of a specific site [1]-[4]. Within a joint project of a utility (EKZ Zürich), a university (ZHAW) and a thin film silicon technology provider (Oerlikon Solar) the effects contributing to losses are being studied to gain a broader understanding of their impacts on the system's output. Previous publications within this project have presented detailed analysis of the module and generator behaviour under standard test condition (STC) and their temperature and irradiance dependency [5,6]. The focus of this paper lies in a more detailed analysis of inverter performance under field conditions. While antecedent publications heavily relied on irradiation measurements, relating to irradiation is deliberately avoided.

2 APPROACH

In December 2009 an outdoor PV power plant consisting of multi crystalline silicon modules by Sunways, high efficiency crystalline silicon HIT modules by Sanyo, and thin film modules by First Solar (CdTe), Avancis (CIS) and Oerlikon Solar (a-Si/µc-Si) has been installed. For each technology an array of several modules is feeding into the grid and is monitored and logged on both sides of the inverter, DC and AC. Simultaneously the IV characteristic of one single module (reference module) of each technology is measured once every minute and between the scans is tracked at V_{MPP} [6,7]. A detailed system definition is presented in table I.

This monitoring setup (figure 1) allows separate analysis of the inverters Maximum-Power-Point-Tracking efficiency (η_{MPPT}) and the actual DC-AC conversion efficiency (η_{DCAC}) [8] (figure 2). While the latter can be calculated solely from measurements of the generator power ($P_{DC\_generator}$ and $P_{AC\_generator}$) tracking efficiency can only be approximated. Due to the

Table I: System definition of the test PV power plant (not available data is marked grey)

Systems	A	B	C	D	E	F
Module						
Manufacturer	Sunways	Sunways	Sanyo	Oerlikon Solar	Avancis	First Solar
Model	SM210 UA65	SM210 UA65	HIP-215 NKHE	micro-morph	PowerMax 110	FS275
Technology	multi c-Si	multi c-Si	c-Si/a-Si HIT	a-Si/uc-Si TF	CIS TF	CdTe TF
η_{STC} Label	13.8%	13.8%	17.1%	7.7%	10.1%	10.4%
P_n Label [W]	230	230	215	110	110	75
P_n Flash (Apr 2011) [W]	226.2	224.5	213.0	109.9	107.1*	63.2
FF	0.75	0.75	0.74	0.62	0.60	0.53
V_{MPP} STC [V]	29.3	29.3	42.0	94.0	45.8	69.4
Generator						
# modules	15	8	10	21	9	20
# strings	1	1	1	7	1	5
P_n Label [W]	3450	1840	2150	2310	990	1500
P_n Flash (Apr 2011) [W]	3384	1807	2103	2300	948*	1324
V_{MPP} at STC [V]	440	234	420	282	412	278
Substructure						
Azimut	175°	175°	175°	175°	175°	175°
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
η_{EURO} Label	97.1%	94.6%	95.4%	94.5%	93.6%	91.8%
Transformerless	yes	yes	yes	yes	yes	no
P_{n_DC} Max [W]		2300	2300	3300	2000	1850
P_{n_DC} [W]	3800			2800	2000	
P_{n_AC} Max [W]	3700	1980	1980	2700	2000	1700
P_{n_AC} [W]	3700	1800	1800	2700	1800	1550
V_{MPP} Range [V]	350-750	100-500	100-500	150-600	200-800	147-320

* P_n Flash (Manufacturer)

inverter's input dependency of the Maximum-Power-Point-Tracking (MPPT) respectively V_{MPP} the actual power at the generator's Maximum-Power-Point ($P_{MPP\_generator}$) cannot be measured. In order to approximate the tracking efficiency, $P_{MPP\_generator}$ has to be retrieved from an appropriate model [6,10]. For this purpose the reference modules, who's minutely IV-scans and therefore P_{MPP_module} is known, can be used to approximate the generator's actual $P_{MPP\_generator}$.

In conclusion the total efficiency of the inverter is calculated by multiplication of η_{MPPT} and η_{DCAC}:

$$\eta_{tot} = \eta_{MPPT} \cdot \eta_{DCAC} = \frac{P_{DC}}{P_{MPP}} \cdot \frac{P_{AC}}{P_{DC}} = \frac{P_{AC}}{P_{MPP}} \qquad (1)$$

By weighting the performance factors by their respective input power (P_{input}; $P_{MPP\_generator}$ for η_{MPPT} and η_{tot} and $P_{DC\_generator}$ for η_{DCAC}), actual relevance of those values is calculated.

$$\eta_{weighted} = \frac{\sum \eta \cdot P_{input} \cdot \Delta t}{\sum P_{input} \cdot \Delta t} \qquad (2)$$

By additionally filtering the data for steady conditions [6] the energy weighted value for η_{DCAC} can be compared to the inverter's η_{EURO} Label [9] describing the inverter's weighted performance under steady conditions at different output power levels under defined voltage.

3 INVERTER EFFICIENCY

3.1 Maximum-Power-Point tracking efficiency

For correctly designed systems η_{MPPT} is supposed to be very high. If even noted, the manufacturer's datasheet claim efficiency above 99% for steady conditions.

One approach of modelling $P_{MPP\_generator}$ to determine η_{MPPT}, is by deriving it from a reference module's power (P_{MPP_module}) measured by an electrical load. The generator's power is thus expected to be linearly dependent on nominal power (P_n).

$$P_{MPP\_generator} = P_{MPP\_module} \cdot \frac{P_{n\_generator}}{P_{n\_module}} \qquad (3)$$

Using flasher measurements of each module and calculating the generator's nominal power as the sum of the module's nominal power (e.g. P_n Flash (Apr 2011) (see table 1)) can be used to improve accuracy. Obviously label values are less precise and nominal power values of a generator, deduced from outdoor performance are influenced by the inverter's MPPT [6].

Since the reference module is measured by a 4-wire system, consideration of cable losses from the generator to the inverter should be taken into account to avoid inaccuracy with rising generator current. By not including the cable resistance, higher generator power would be suggested by the model, thus causing lower η_{MPPT}. The expected generator power is lowered by $\Delta P_{MPP\_generator}$:

$$\Delta P_{MPP\_generator} = {I_{DC\_generator}}^2 \cdot R_{cable} \qquad (4)$$

where:
R_{cable}: cable resistance from and to the generator

This approach assumes equal soiling, temperature and irradiance/shading for each module. Also, the reference module is expected to have an identical temperature and lowlight dependency and same physical setup (substructure, location) as the generator. Also IV

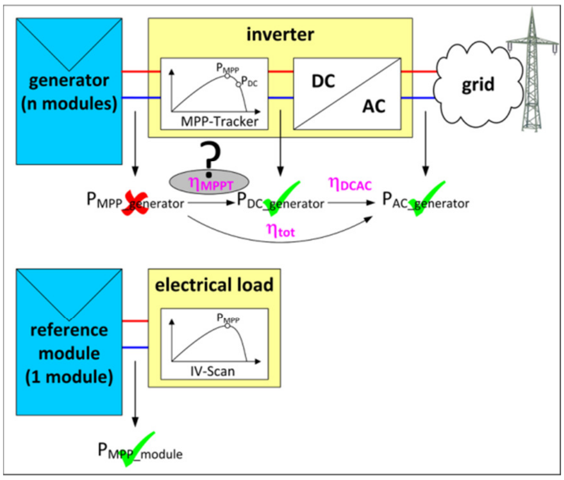

Figure 1: Block diagram, visualising η_{MPPT}, η_{DCAC}, η_{tot} [8]. Note: $P_{MPP\_generator}$ is not measurable since the inverter's MPP-tracking affects the inverter's input and thus the measurement of the generator's I_{MPP} and U_{MPP}. (adapted from [8])

imbalance of the generator's modules, limiting the maximum current in strings and voltage in parallel connected strings is not considered and the determination of P_{MPP_module} based on the IV-scan is expected to be exact. Differences may also be founded by different dynamic behaviour of the electrical load and the sensors used for the DC measurement.

Whether modelling all these idealisations, including or omitting consideration of a reference module's behaviour, renders better approximations for $P_{MPP\_generator}$ remains open at this point.

3.2 DC-AC conversion efficiency

The inverters η_{DCAC} is dependent on the system's output power (P_{AC}) and the DC-AC conversion unit's input voltage (V_{DC}) [11]. Additionally the DC-AC conversion is influenced by the stability of P_{AC} and by the unit's operating temperature.

The datasheets of the analysed inverters do not all contain data about the dependency of P_{AC} and V_{DC}. However all datasheets list η_{EURO} (η_{EURO} Label), a calculated efficiency value, representing expected operation efficiency, used for benchmarking purposes. Interestingly η_{EURO} is rarely given in dependence of V_{DC}, making the datasheet of the inverter model of systems B and C the exception. Only for two inverters enough data is presented in the datasheet to recalculate η_{EURO}, while other datasheets, containing only a graphic, illustrating the dependency of P_{AC} and V_{DC}, lack actual data.

From the measurements of P_{DC} and P_{AC}, η_{DCAC} can be calculated and weighted by the input power ($\eta_{DCAC\_weighted}$) to retrieve the overall conversion efficiency of energy.

The calculation of η_{EURO} Label is based on two characteristics, the DC-AC transfer characteristic of the inverter on one hand and a standardised irradiation distribution on the other. While the inverter's actual transfer characteristic is used, for the irradiation distribution, always the measurements of Hotopp [9], retrieved in the late 1980's, is used. From this irradiation distribution the percentage of six predefined irradiance bands (see table II), covering the entire range from

0W/m^2 upwards, have been calculated by Hotopp and are always used as weighting factors in the calculation for η_{EURO} given on current datasheets (η_{EURO} Label). Each of these values is then associated with a point of support defining the level of P_{AC} where the efficiency is to be read from the DC-AC transfer characteristic. By summing up the products of the efficiency at each point of support and its corresponding weighting factor, η_{EURO} Label is determined.

$$\eta_{Euro} = \sum_{ranges} x_i \cdot \eta_i \qquad (5)$$

where:
x_i: weighting factor for the i-th range
η_i: DC-AC efficiency at the point of support of for the i-th range

Table II: Definition of the ranges leading to the weighting factors used to calculate η_{EURO} using the inverters DC-AC conversion efficiencies at the points of support. [9]

η_{EURO}						
Range (% of 1000W/m^2)	0% .. 7.5%	7.5% .. 15%	15% .. 25%	25% .. 40%	40% .. 75%	75% .. ∞
Weighting factor	0.03	0.06	0.13	0.10	0.48	0.20
Point of support (% of P_{n_AC} Max)	5%	10%	20%	30%	50%	100%

Comparing $\eta_{DCAC\_weighted}$ to η_{EURO} Label suggests an optimal system design, where the sizing of the generator and the inverter are ideally matched and the system is supposed to be situated in central Europe, according to the input energy distribution used in the initial definition of η_{EURO} Label [9]. Regarding the analysed systems the first condition is not met since the inverters are generally (except system C) oversized in contrast to the generator's nominal power according to nameplate (P_n_Label) and all the more in contrast to the nominal power determined by flasher measurements from within the analysed timeframe (P_n Flash (Apr 2011)) (see table III). As shown in [12] also the second condition, concerning irradiation distribution, must be expected to differ from the assumptions. It must also be noted, that the generator's modules temperature, generally causing generator losses, is not considered by using the irradiation distribution as input for calculation of the weighting factors. Several propositions for redefining η_{EURO} Label have been made [10,12] without success so far, since the datasheets still display the value according to the definition by Hotopp.

To get an estimate of what energy-weighted efficiency is to be expected from the inverters, under consideration of the DC-AC unit's output power, the weighting factors of the calculation of η_{EURO} have to be adapted for the existing situation. Given more detailed manufacturer data about the inverter's efficiency at different output power (transfer characteristic), other points of support could be considered as well [12].

Given only the efficiency for the points of support for the η_{EURO} Label calculation, finding realistic weighting factors can be achieved by analysing the frequency the inverters are operating at the different input power level ranges used for the calculation of η_{EURO} Label (see table II) or by recalculating the weighting factors from the local irradiance distribution stretched by the nominal power proportion of the system ($P_{n\_generator}/P_{n\_AC}$ Max) (table III), disregarding temperature and lowlight dependency of the generator.

Table III: Proportions of the generators' nominal power and the inverters' maximum AC power.

Systems	A	B	C	D	E	F
Nominal power proportion						
P_n Label / P_{n_AC} Max	0.93	0.93	1.09	0.86	0.50	0.88
P_n Flash (Apr 2011) / P_{n_AC} Max	0.91	0.91	1.06	0.85	0.47*	0.78

* P_n Flash (Manufacturer)

4 RESULTS

4.1 Intraday analysis

Intraday inverter performance, as seen in figure 2, generally shows a stable behaviour on sunny days for all systems. Differences are primarily notable in the morning and evening hours when $P_{MPP\_generator}$ is low. Neither MPPT nor DC-AC conversion is operating optimally under low input power. Especially the inverters of systems E and F show MPPT problems at low input power, which might be related to the ratio between the generator's and the inverter's nominal power (see table III).

Since $P_{MPPT\_generator}$ is calculated from IV measurements of a reference module, cable losses are considered. The resistance of the two wires between generator and inverter (R_{cable}) is not known exactly and has therefore been estimated to be about 0.3 Ω for every system. Using IV-scans, representing the characteristic of the reference module at one moment, requires to use also instantaneous measurements on the the DC side for the calculation of η_{MPPT}, rather than minutely mean values also available. Regarding the evaluation of η_{tot}, equally recorded measurements are to be used for P_{DC} and P_{AC} used in the calculation of η_{DCAC}.

The smoothness of η_{MPPT} under steady conditions indicates different tracking algorithms of the analysed inverters. While the inverters of systems A and D show a smooth characteristic the other inverters present a jagged one.

The cloudy day (figure 2 right) contains a break-in at 9:45, where irradiance drops below 20W/m^2. The inverters that are connected to thin-film (TF) generators (D, E & F) are unable to keep tracking the MPP. Whether this is caused by different tracking algorithms or generator properties, like fill factor (FF), is unknown.

A problem caused by the determination of $P_{MPP\_generator}$ from P_{MPP_module} is pronounced for system B, residing on a one-axis tracker following the suns position during the day. During shading of the generator in the morning η_{MPPT} is calculated to be very low (<50%). The reversed situation can be observed in the evening, leading to unrealistic tracking performance above 100%. This however does not represent the facts since the generator obviously does not produce proportionally equal power to the reference module. A similar situation must be assumed for system D, although less pronounced.

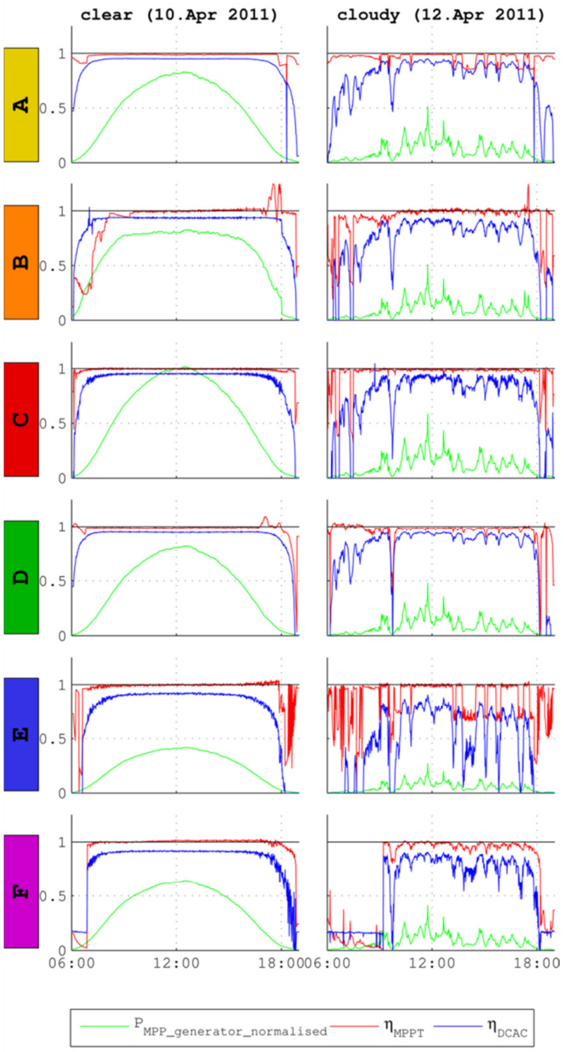

Figure 2: Comparison of the inverter's tracking and conversion efficiency during a bright (left) and a cloudy (right) day. The respective input power ($P_{MPP\_generator}$) is normalised to the inverters' maximal AC power (P_n AC Max). System B shows effects of shading in the morning and evening on on a sunny day in the characteristic of η_{MPPT}. η_{DCAC} shows dropping efficiency under fluctuating input conditions.

On cloudy days $\eta_{tot}=\eta_{MPPT}\cdot\eta_{DCAC}$ is lower in general, primarily due to low DC power which causes the DC-AC conversion to operate less efficiently at all systems.

Powering-up problems for F are obvious.

4.2 Inverter performance over one year

Plotting η_{DCAC} against the AC power ($P_{AC\_generator}$) shows the inverters' measured conversion characteristic (figure 3).

Scattering is avoided by filtering the data for steady conditions [6]. This also allows comparability to characteristics given in the datasheet, describing performance dependency on P_{AC} under steady conditions.

To avoid the influence of switching of the inverters between on, off and standby mode, a further filter criterion requests the data points to have synchronous irradiance measurements above 10W/m^2.

Due to the nominal power proportions between generator and inverter (table III), most characteristics do not cover the full range up to 100% nominal output power (P_{n_AC} Max), even for a dataset of one year (2011).

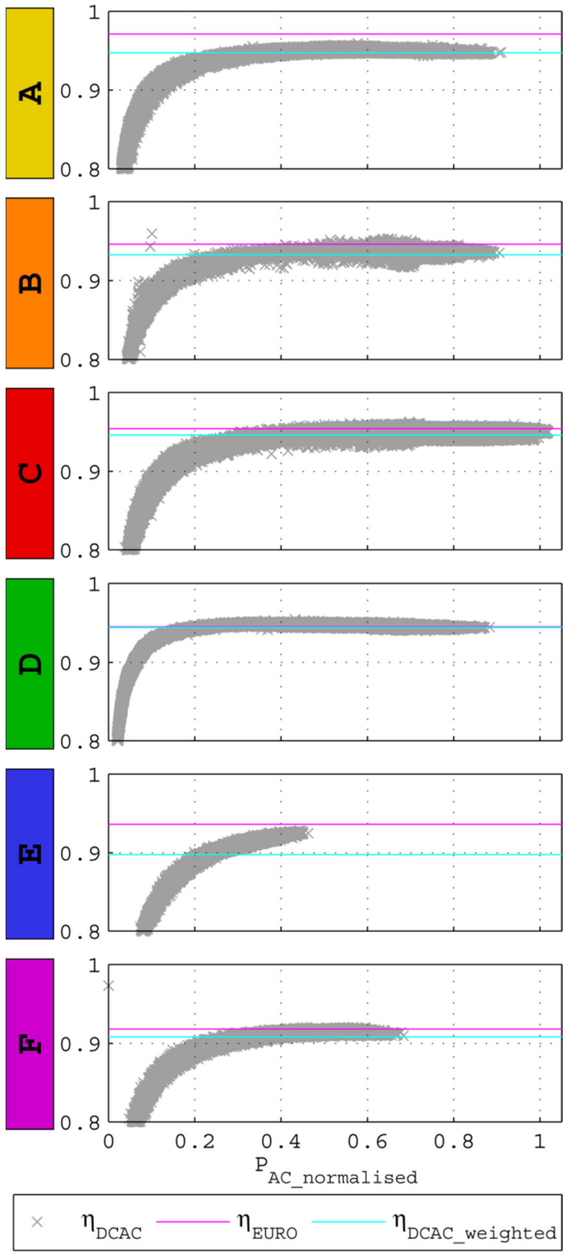

Figure 3: DC-AC conversion performance measured from 01.Jan 2011 to 31.Dec 2011 and filtered for steady conditions (maximal allowed change between two sequential measurements: G_I(Pyranometer): max. ±0.5%, T_{module}: max. ±1°C) and irradiance greater 10W/m^2.

The under-sizing of system E and F's generator, relative to the respective inverter, is clearly visible. Judging from the data's shape, system E never even reaches levels of output power where DC-AC conversion would be maximised, commonly to be found around 50% of the inverter's maximal AC power.

The vertical spread of the data points has shown, by colouring the data points according to their measurement timestamp, to be seasonally dependent. The data points measured in winter generally reside on the upper boarder while those measured in summer reside on the lower boarder. This suggests temperature dependence of η_{DCAC}.

However since the room containing the inverters is not monitored for temperature this cannot be proven. Detailed analysis of this behaviour could render information about profitability on cooling of inverters.

Also influencing the vertical spread is the method by which the data is recorded. Two kinds of measurements are available, minutely mean values from 30 measurements equally distributed within a minute and momentarily values measured synchronous to the execution of the IV-scan. Usage of the mean values results in small scattering bands in the DC-AC transfer characteristics, as shown in figure 3. Using momentarily values on the other hand causes much wider scattering bands for the characteristic of the inverters of systems B, C, E and F. This effect is not seen in system A and only little for system D, correlating thus with the smoothness of the intraday behaviour of η_{DCAC} seen for those two systems. Further investigations have shown the cause of the scattering being the AC measurements. Comparing the ratio of the mean values and the momentarily values for P_{AC} against the ratio of those values for P_{DC} shows a scattered ratio for P_{AC}, while the ratio for P_{DC} is not. Concluding from these observations time lags or smearing behaviour of the inverter's DC-AC conversion is assumed, rendering smoother characteristics for mean values. Hence filters for steady conditions should be applied on data of much higher resolution than presently available.

By weighting the efficiency of each measurement by its respective input power, the relevance of each value is taken into account. $\eta_{DCAC\_weighted}$ is computed by weighting each measurement by the input power $P_{DC\_generator}$ according to equation 2. The normalised mean of those weighted values, $\eta_{DCAC\_weighted}$, represents the actual, measured conversion efficiency of energy for the selected timeframe and is presented numerically in table IV.

By removing measurements with unsteady conditions and irradiance levels below $10W/m^2$ the dataset has been reduced from over 210'000 measurements to merely 34'000. The effect can be seen throughout all systems by a rise of $\eta_{DCAC\_weighted}$ from 0.5% up to 3.8%, proving the negative effect of fluctuating input power.

However the values for $\eta_{DCAC\_weighted}$ filtered still do not describe η_{EURO} adequately and underperformance compared to η_{EURO} Label of up to nearly 4% can still be seen. For systems like system E this mismatch is evident and it is clear, that $\eta_{DCAC\_weighted}$ (filtered) of this kind of system cannot be compared to η_{EURO} Label. Since the calculation of η_{EURO} Label is based on an optimal system design and a not representative irradiation distribution [12], a more appropriate value should be determined for comparison's sake.

Hotopp's method of calculating the the weighting factors is based on irradiance measurements leading to an irradiation distribution, as shown in figure 4, for the analysed site, based on Hotopp's weighting factors (red) (scaled to the same total irradiance as measured by the pyranometer in the plane of the generators (30°) for the entire year 2011 ($1398kWh/m^2$)) and actual irradiance measurements from 2011 in Dietikon, Switzerland (cyan and blue). The relative portion of each predefined irradiance band determines the value of the corresponding weighting factor x (see equation 5). Using the same method by means of the on-site irradiation measurements renders very different weighting factors,

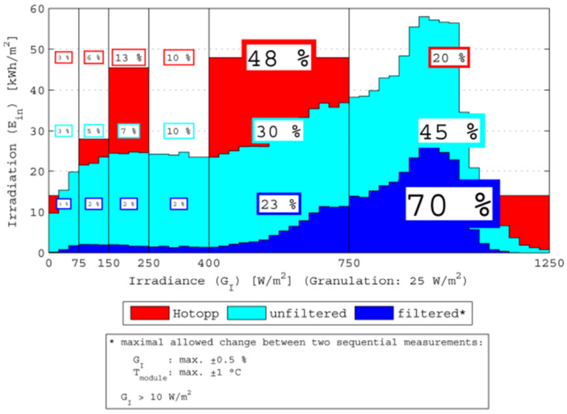

Figure 4: Irradiation distribution reconstructed and scaled according to the total measured irradiation for the year 2011 (in Dietikon, Switzerland) from Hotopp's weighting factors (red) and on filtered (blue) and unfiltered (cyan) measurement data from the year 2011 measured in Dietikon, Switzerland.

shown in the first graph in figure 5. The difference shows that a lot more irradiation is measured at irradiance levels above $750W/m^2$ than suggested by the weighting factors used for the calculation of η_{EURO} Label, which suggests the most irradiation to be absorbed between $400W/m^2$ and $750W/m^2$. By filtering the data of irradiation measurements for steady conditions this identification becomes even more pronounced, further increasing the relative amount of energy irradiated above $750W/m^2$. The factors for low irradiation thus loose relevance while the one for high (above $750W/m^2$) is gaining. The filtered dataset contains merely one fourth of the total irradiation of the unfiltered, however exactly describing the irradiance of data used to calculate $\eta_{DCAC\_weighted}$.

Compensation for the under- and oversized generators can be achieved by stretching the irradiation distribution along irradiance by the system's nominal power proportion. For each system the irradiance measurement is therefore multiplied by its nominal power proportions. The resulting system dependent coefficients (weighting factors), shown in figure 5 for each system, are only available where the orientation of the generator corresponds to the irradiance sensor and can thus not be determined for system B mounted on a one axis tracker without a tracked irradiance sensor. The more the inverter is oversized compared to the generator, the more the weight of the coefficients is shifted towards lower AC power.

Using irradiance measurements does not allow compensation for the generators temperature- and lowlight dependencies. Also other system losses like cable resistance, soiling, shading, IV imbalance and MPP-tracking are ignored. Therefore the weighting factors have also been calculated by the inverter's input power distribution. These values are expected to give the most accurate estimation of $\eta_{DCAC\_weighted}$, since they compensate for both, power proportion and generator losses, representing the systems actual operational behaviour under steady conditions. Generally the system dependent coefficients based solely on irradiance measurements correspond well with those calculated from DC power measurements. Only systems E and F show noteworthy difference between the the two system dependent calculation methods of the weighting factors. For both of these systems the irradiation based method suggests more input energy at higher power levels, suggesting severe power losses in those systems. Marginal differences are also seen for the other three systems. The tendency is the same as for the two previously mentioned systems. Only for system C the opposite trend is seen, possibly due to the oversizing of the generator, causing inverter inefficiencies at high input power ($P_{DC\_generator}$).

Based on these weighting factors adapted Euro

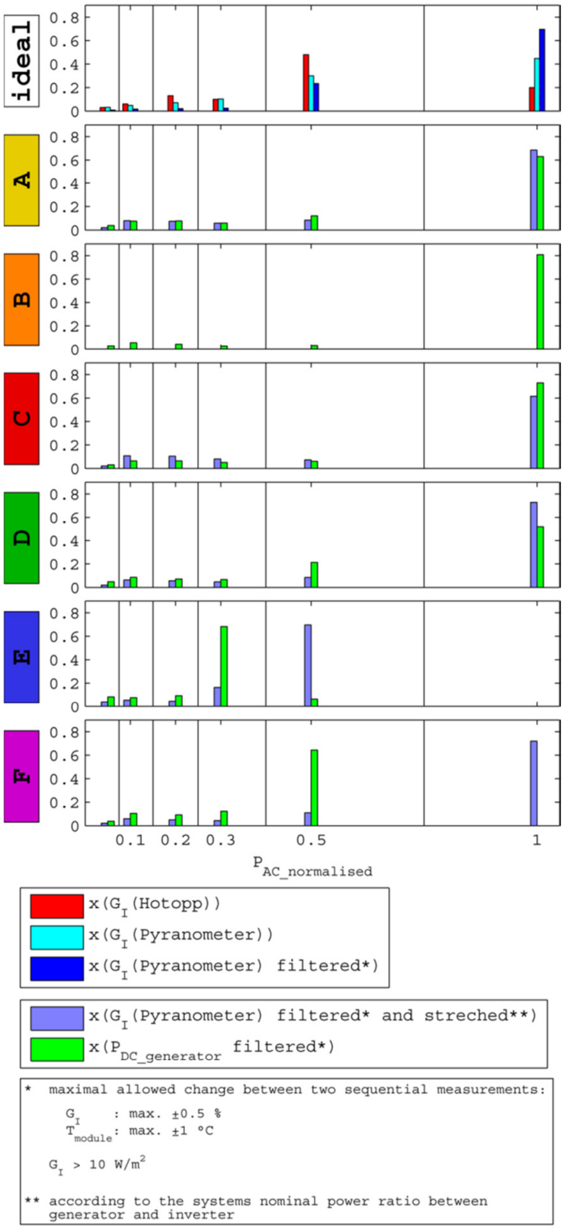

Figure 5: Comparison of the ideal weighting factors given by Hotopp (and used for the calculation of η_{EURO} Label) and calculated factors, according to the Pyranometer's irradiance measurements with and without filter for steady conditions. And system dependent weighting factors calculated for each system according to AC power measurement and the Pyranometer's irradiance measurements, stretched by the nominal power proportions between generator and inverter and filtered for steady conditions. All calculated values are based the dataset of minutely mean values form the year 2011.

efficiencies (η_{EURO} adapted) can be calculated with optimised matching considering either only the site specific irradiation based on the weighting factors from irradiation distribution or the entire system based on the factors from the inverter's input energy distribution. These adapted efficiencies are expected to match better with the weighted DC-AC conversion efficiency ($\eta_{DCAC\_weighted}$ filtered) measured for the each system under steady conditions.

Calculating the adapted Euro efficiency (according to equation 5) requires knowing the expected conversion efficiencies (η_{DCAC} Label) at the points of support used for the calculation of η_{EURO}. Unfortunately those values are given only in the datasheets of two of the reviewed inverters, namely inverter A and D. Little imprecision is introduced by the fact that the supporting points are defined at normalised output (AC) energy levels, while the weighting factors have been calculated for energy input levels (irradiance or DC power). Calculating the weighting factors based on output energy would include DC-AC conversion efficiency in the weighting factors which is not desired. Knowing conversion efficiency for defined input, instead of output energy would be preferable.

Now, after recalculating the weighting factors of the calculation of η_{EURO} for the present situation and subsequent recalculating of η_{EURO} (η_{EURO} adapted) with the use of the datasheet efficiency values of $\eta_{DCAC}(P_{AC})$ Label, good matching between the calculated value η_{EURO} adapted and the measured value $\eta_{DCAC\_weighted}$ filtered is expected. Best matching is expected for η_{EURO} adapted based on P_{DC} measurements, since it includes all system losses up to the inverter's DC-AC unit's input.

The comparison, shown in table IV, between these calculated and measured efficiencies reveal the unexpected: While the calculated value η_{EURO} adapted based on P_{DC} is slightly below the measured $\eta_{DCAC\_weighted}$ filtered for system D, the opposite situation is seen much more pronounced for system A, with a deviation of over 2%. Generally the calculated η_{EURO} adapted values are lower than suggested by η_{EURO} even though the recalculated weighting factors for η_{EURO} adapted are

Table IV: Comparison between η_{EURO} Label, the newly calculated values of η_{EURO} adapted based on the measured and system dependently stretched irradiation distribution and the DC energy distribution and the actually measured, weighted performance $\eta_{DCAC\_weighted}$ overall (211'449 data points), and filtered for steady conditions (34'035 data points). η_{EURO} adapted could only be calculated where conversion efficiency at the six needed points of support is given by the manufacturers' datasheet.

Systems	A	B	C	D	E	F
η_{DCAC}						
η_{EURO} Label	97.1%	94.6%	95.4%	94.5%	93.6%	91.8%
η_{EURO} adapted based on G_I	96.9%			94.5%		
η_{EURO} adapted based on P_{DC}	96.8%			94.2%		
η_{DCAC} weighted filtered*	94.7%	93.3%	94.6%	94.4%	89.8%	90.8%
η_{DCAC} weighted unfiltered	93.7%	92.4%	93.4%	93.9%	86.0%	89.3%

* filtered for steady conditions

lower for low output power (see figure 5), where conversion efficiency is commonly lower. Nevertheless the recalculated, expected efficiencies (η_{EURO} adapted) differ only by 0.3% to the labelled value η_{EURO}. It seems the recalculation of weighting factors has very little impact on the expected efficiency, although the values of the recalculated weighting factors differ greatly to the values used for the calculation of η_{EURO} Label.

Regarding the performance difference of filtered and unfiltered data, losses of ~1% are seen for systems A to D. For system E and F with low nominal power proportions greater losses are registered.

By plotting the efficiencies at different output levels given by the manufacturer and the measured DC-AC conversion efficiencies in the same graph, the reason for the difference between expected and measured efficiency becomes apparent.

In figure 6 it can be seen, that the actual performance and the performance according to the datasheet do not agree at all. While for system D better performance is measured at lower output power, lower performance is measured at higher output power. Deduced from the difference of η_{EURO} adapted based on P_{DC} and $\eta_{DCAC\_weighted}$ filtered of 0.2% the advantageous conversion behaviour at low output power is thus dominant, leading to a small over-performance compared to the expectations (η_{EURO} adapted based on P_{DC}).

A very different situation is presented for system A. Measured conversion efficiencies are always far below what's suggested by the datasheet. The difference is greater at low output power which further worsens $\eta_{DCAC\_weighted}$ filtered based on the findings of system D. Clearly this inverter is not operating as suggested by the manufacturer, leading to losses of over 2% for steady conditions. Finding the cause within temperature dependency is unlikely since both inverters, A and D are situated in the same surroundings, unless very different dependency for both inverter is assumed.

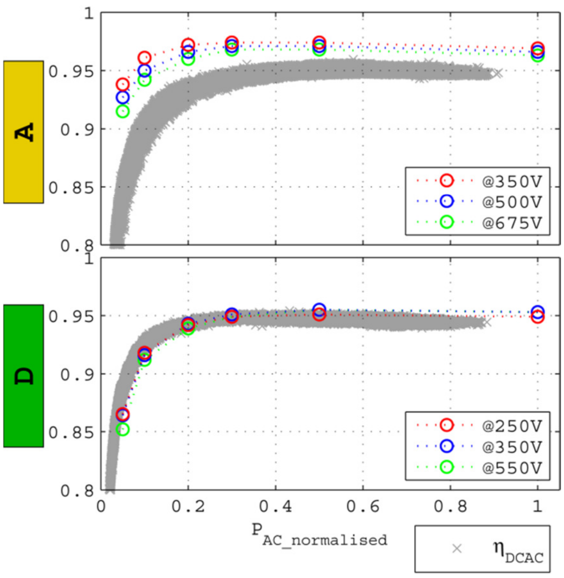

Figure 6: Measured DC-AC conversion efficiencies under steady conditions for the year 2011 and expected efficiencies according to the manufacturer's datasheet. Manufacturer data in this level of detail are only available for the two displayed inverters.

Regarding measurement uncertainty it must be noted, that measured η_{DCAC} is determined with a measurement uncertainty type B of ±1.1% (k=2), while under optimal laboratory conditions ±0.5% (k=2) are reached [11]. To calculate the combined measurement uncertainty according to the guideline of measurement and uncertainty (GUM) the type A uncertainty have to be added, resulting from the statistics of the recorded samples. Optimisation of measurement uncertainty, focusing on the dynamic behaviour of the sensors will have to be focused on in this on-going project.

Equally as in figure 3 for η_{DCAC}, η_{MPPT} has been analysed too. Although the determined values for η_{MPPT} weighted seem plausible (≥0.98) the data show heavy scattering even above 1, caused by over performance of the generator compared to the single module. Differences in η_{MPPT} weighted between filtered and unfiltered data of up to 2.2% could be found.

Inconsistency between reference module and generator behaviour lead to unrealistic, momentarily tracking performance above 100% as well as very low performance values which must be explained by cable losses, IV imbalance, shading, soling and unknown type A measurement uncertainties. This problematic shows, that the determination of η_{MPPT} under field conditions is a model based problem which cannot be adequately solved for the analysed site by translating the output power of a single reference module to the generator. To determine field performance of η_{MPPT} other methods of describing the generators momentarily maximum power ($P_{MPP\_generator}$) must be found.

5 CONCLUSION

Inverters serve two purposes: They have to keep the generator in the optimal point of operation (Maximum-Power-Point MPP) and they have to convert DC energy to AC.

Validating the manufacturer information on performance of those tasks under field conditions can only be done by measurement for the DC-AC conversion efficiency (η_{DCAC}). Since the generator's MPP is unknown and cannot be measured under operational field conditions, tracking performance (η_{MPPT}) can only be determined by modelling the generator's MPP. Doing so by deduction from a reference module's MPP has proven unreliable due to inconsistencies between reference module and generator like shading, IV-imbalance, cable resistance, soiling and dynamic characteristic of DC sensors.

DC-AC performance (η_{DCAC}) is described very differently by each manufacturer. While some manufacturers only inform about a weighted efficiency under predefined conditions (η_{EURO}), others give information concerning voltage and output power dependency in different levels of detail. Given enough information on conversion efficiency, a site and system specific, weighted efficiency (η_{EURO} adapted) can be calculated from either irradiance or generator output power (P_{DC}), describing the expected overall DC-AC conversion efficiency under steady conditions. While very different weighting factors, compared to those used for the calculation of η_{EURO}, have been determined, the resulting η_{EURO} adapted are very close to η_{EURO}.

Comparing manufacturer data on conversion efficiency at different output power levels with actual measurements under steady conditions has shown great difference. Laboratory measurements from the inverters' datasheets could not be confirmed in the field. Differences of over 2% (not considering the measurement uncertainty of 1.1% (k=2)) in overall efficiency under steady conditions could be found leading to equally great energetic losses. Considering also the conversion behaviour under unsteady conditions further losses are found. These additional losses gain severity with increasing mismatch of nominal power between generator and inverter.

REFERENCES

[1] Y. Tsuno et al.; Evaluation of different PV modules in Hokuto mega-watt project; 25th EU PVSEC, Valencia 2010

[2] Y. Ueda et al.; Comparison between the I-V measurement and the system performance in various kinds of PV technologies; 25th EU PVSEC, Valencia 2010

[3] H.-D. Mohring et al.; Annual energy harvest of PV systems – advantages and drawbacks of different PV technologies; 25th EU PVSEC, Valencia 2010

[4] D.L. King et al.; Photovoltaic Array Performance Model; 2004, SAND2004-3535

[5] J. Sutterlueti et al.; Detailed Outdoor Performance Analysis of Thin Film and Cristalline Silicon Based Reference PV Power Plants in Switzerland; 3rd Int. Conference of Thin-Film Photovoltaics, Munich 2011

[6] N. Allet et al.; Evaluation of PV System Performance of five different PV Module Technologies; 26th EU PVSEC, Hamburg 2011

[7] J. Sutterlueti et al.; Outdoor characterisation and modeling of thin-film modules and technology benchmarking; 24th EU PVSEC, Hamburg 2009

[8] H. Häberlin et al.; Total Efficiency – A new Quantity for better Characterisation of Grid-Connected PV Inverters; 20th EU PVSEC, Barcelona 2005

[9] R. Hotopp: Private Photovoltaik-Stromerzeugungsanlagen im Netzparallelbetrieb; RWE Energie AG, Essen 1990

[10] B. Bletterie et al.; Redefinition of the European Efficiency – Finding the compromise between Simplicity and Accuracy; 25th EU PVSEC, Valencia 2010

[11] F. Baumgartner et al.; Status and relevance of the DC Voltage Dependency of the Inverter Efficiency; 22th EU PVSEC, Milan 2007

[12] B. Burger et al.; Are we benchmarking inverters on the basis of outdated definitions of the European and CEC efficiency?; 24th EU PVSEC, Hamburg 2009