REDEFINITION OF THE EUROPEAN EFFICIENCY – FINDING THE COMPROMISE BETWEEN SIMPLICITY AND ACCURACY

Benoit Bletterie[1], Roland Bründlinger[1], Heinrich Häberlin[2],
Franz Baumgartner[3], Heribert Schmidt[4], Bruno Burger[4], Gerald Klein[5], Miguel Alonso Abella[6]
[1]arsenal research, Giefinggasse 2, A-1210 Vienna, Austria
[2]Berne University of Applied Sciences (BFH-TI), PV laboratory, Jlcoweg 1, CH-3400 Burgdorf, Switzerland
[3]Zürcher Hochschule für Angewandte Wissenschaften, Technikumstrasse 9, CH-8401 Winterthur, Switzerland
[4]Fraunhofer-Institut für Solare Energiesysteme ISE, Heidenhofstraße 2, 79110 Freiburg, Germany
[5]Institut für Solare Energieversorgungstechnik, Koenigstor 59, 34119 Kassel, Germany
[6]Ciemat - Avda. Complutense, 22 - 28040 Madrid, Spain
E-Mail: benoit.bletterie@arsenal.ac.at

ABSTRACT: This paper deals with the definition of the European efficiency of photovoltaic (PV) inverters, which is since the recent introduction of a marking system to compare the performance of PV inverters one of the most topical issues in this field. This paper questions the adequacy of the current definition(s) of the European efficiency to reflect accurately the performance of inverters. It proposes a new quantity to quantify the performance of inverters: the maximal reachable European efficiency. This new definition of the European efficiency is either based on the distribution of the annual yield as a function of MPP power and voltage or on the existing weighting factors. The definition of the maximal reachable efficiency is basically based on the concept of required MPP voltage band. It therefore considers a realistic operation domain in which an average efficiency can be computed. A comparison between the current definition of the European efficiency and the proposed quantities is provided, also taking into account the impact of the location. As a good compromise between simplicity and accuracy, the proposed concept of maximal reachable European efficiency should be adopted to quantify inverters efficiency.

Keywords: Inverter, Performance, Efficiency

1 INTRODUCTION

While the electricity supply system is undergoing a major change with an increasing penetration of renewable energy sources, the exact composition of the energy mix will mainly depend on the costs evolution of the various technologies. The costs of photovoltaic electricity generation can mainly be reduced by decreasing the manufacturing costs of PV modules and inverters, by improving the reliability and last but not least by enhancing the system performance. In this context, increasing attention is paid to the efficiency of PV inverters.

The detailed characterisation of inverters' efficiency consisting in measuring the inverter efficiency for various maximum power point (MPP) powers and voltages has been introduced some years ago. On the other hand, new techniques for optimising the dimensioning of PV plants through MPP voltage monitoring have also been proposed [1].

In the meantime, extensive experiences have been gained [2]. Until the recent developments, the European efficiency as introduced in the nineties was still used as the most important figure to compare inverters or to observe trends on the market. While the introduction of this European efficiency more than one decade ago as a simple widely acknowledged figure probably contributed to the significant improvement of inverters' performance in the past ten years (by more than five percent points [3]), recent discussions question its adequacy to provide a representative picture. The main concerns in this context relate to the influence of the irradiation distribution depending on the location, the well known dependency of the conversion efficiency on the DC-input voltage [1] [2], and last but not least the influence of the MPP Tracking [4] [5] [6] [7]. All these factors which have been recently investigated are still not taken into account by the current definition of the European efficiency. This paper introduces a new way of computing the European efficiency which is a good compromise between simplicity and accuracy.

In the first part, the operation conditions for inverters are compared for various locations. In the second part, the concept of maximal reachable efficiency is introduced and illustrated. A comparison between products and locations is provided. Finally, the adequacy of the proposed concept to compare the performance of inverters is discussed.

2 ANALYSIS OF OPERATION CONDITIONS AT VARIOUS EUROPEAN LOCATIONS

In order to identify the typical operation conditions under which a PV inverter is requested to operate, a good set of weather data is needed. For an accurate characterisation of the operation conditions over a whole year, in-plane irradiance and module temperature at least are needed. Several previous studies [5] [8] [9] stressed the importance of using data with a high time-resolution and at the same time their scarcity. For the presented investigations, data with a time resolution between one second and five minutes have been used. Using a 1 s-time resolution leads to very large amount of data for a whole year (more than 16×10^6 time steps during day time). The analysis of such amounts of data is challenging if adequate tools are not used.

Within this paper, the weather conditions of various European locations have been analysed into details:

- four locations in central Europe
  - Location 1a: Vienna, Austria
    1-s sampling rate for 09/2004-09/2005
  - Location 1b: Burgdorf, Switzerland
    1-s sampling rate for 2007
  - Location 1c: Wroclaw, Poland
    90-s sampling rate for 2004
  - Location 1d: Kassel, Germany
    15-s sampling rate for 2004-2005
- Location 2 (alpine location): Birg Cableway station, 2670 m altitude, Switzerland
  5-min sampling rate for 11 years (1995-2005)
- Location 3: Athens, Greece
  47-s sampling rate for 2006

2.1 Methodology and assumptions

The results presented in this chapter are based on detailed analyses of the weather data. In a first step, the distribution of the annual yield as a function of irradiance and module temperature has been computed. The obtained distribution allows visualising the parts of the operation area corresponding to the largest energy capture. In a second step, the measured irradiance and temperature data were translated into MPP power and MPP voltage using an appropriate cell-model. The corresponding distribution is computed similarly. Figure 1 shows the used methodology.

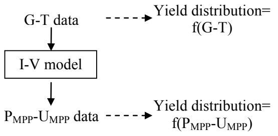


Figure 1: Methodology to compute the yield distribution as a function of irradiance and temperature or MPP power and voltage

For the computations, the following assumptions have been made:

- The measured irradiance corresponds to the irradiance in the plane of the module for the optimal tilt angle. All the conclusions made in this paper apply to installations without tracking systems.
- The used I-V model corresponds to a crystalline module with a fill factor of 0.75 (adapted from [10]) and a temperature coefficient β=-0.4 %/K. This model leads to an irradiance dependency of the MPP voltage (U_{MPP}(G=1000 W/m^2)-U_{MPP}(G=200 W/m^2), both at T^{STC}) of about 3 % [11].
- For location 3 (Athens), only the ambient temperature was available. The module temperature has been computed using a first order transfer function identified from data sets 1a and 1c:

$$T_m = T_{amb} + T_0 + \frac{k}{1+\tau \times s} \times G \qquad (1)$$

T_m	*computed module temperature*
T_{amb}	*measured ambient temperature*
G	*measured irradiance*
T_0	*correction temperature (T_0=-3°C)*
k	*irradiance gain (k=0.03 KW^{-1}m^{-2})*
τ	*module time constant (τ=5 min)*

Parameters T_0, k and τ have been adjusted (data sets with both temperatures) by minimising the difference computed vs. measured module temperature.

2.2 Comparison between various European locations

Figure 2 shows the distribution of the annual yield as a function of in-plane irradiance and module temperature for Location 1a (Vienna) whereas Figure 3 shows its distribution as a function of MPP power and voltage.

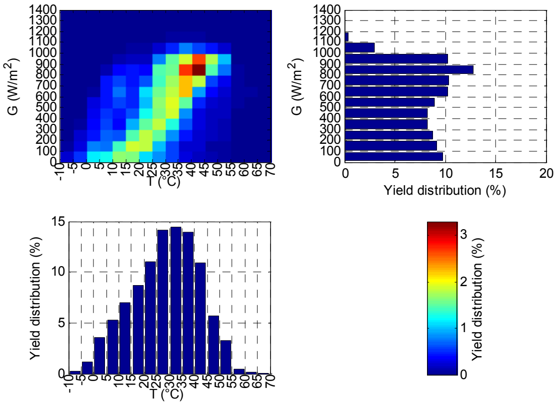


Figure 2: Distribution of the annual yield as a function of module temperature and irradiance, measurements from Location 1a, Vienna, Austria

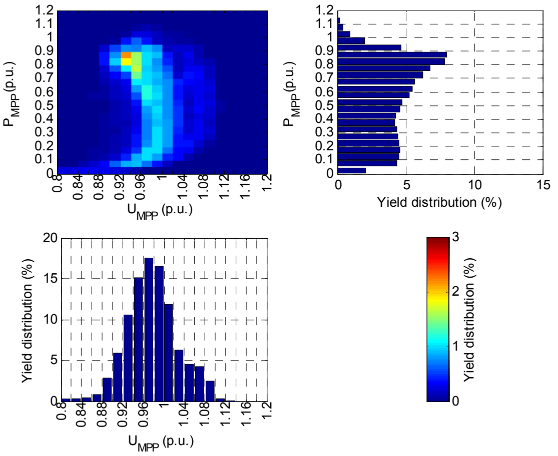


Figure 3: Distribution of the annual yield as a function of MPP voltage and MPP power, measurements from Location 1a, Vienna, Austria

A comparison between Figure 2 and Figure 3 leads to the conclusion that the temperature seems to have a rather large effect on the yield distribution: the points corresponding to high irradiance levels and temperatures (i.e. sunny summer day) are moved towards lower MPP voltages, significantly modifying the distribution's shape. A similar observation was made in [1]: the density plot of the measured P_{MPP} and U_{MPP} values of several grid connected PV plants also showed a shift to lower voltages for high module temperature and high irradiance level due to the negative temperature coefficient of U_{MPP}.

Figure 4 and Figure 5 provide the distribution of the annual yield as a function of MPP power and voltage for Locations 1b (Burgdorf, Switzerland) and 1d (Kassel, Germans) respectively. A comparison with the distribution for Location 1a (Vienna, Figure 3) shows that:

- a smaller part of the annual yield is gained for Location 1b for low irradiance levels.
- the distribution for Location 1d is quite similar to the distribution for Location 1a.

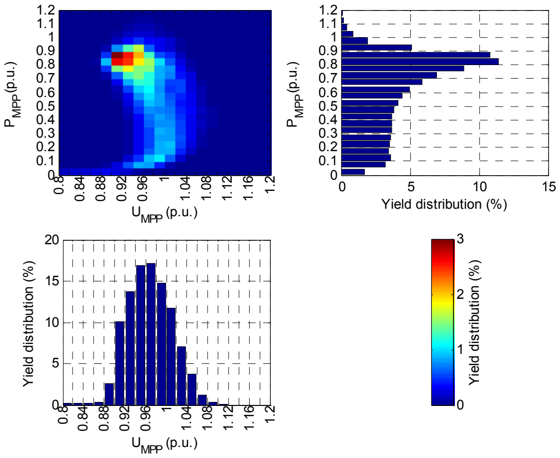


Figure 4: Distribution of the annual yield as a function of MPP voltage and MPP power, measurements from Location 1b, Burgdorf, Switzerland

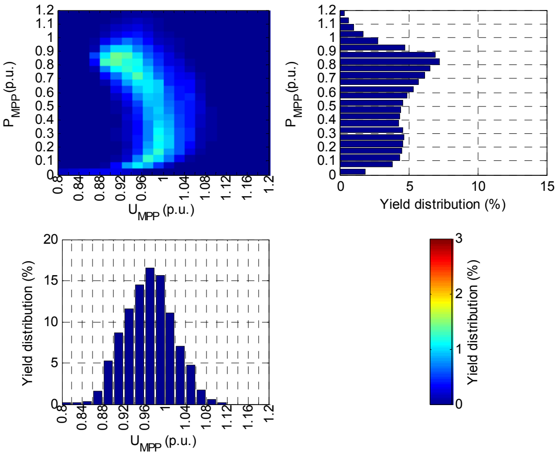


Figure 5: Distribution of the annual yield as a function of MPP voltage and MPP power, measurements from Location 1d, Kassel, Germany

Figure 6 shows the distribution of the yield as a function of MPP power and voltage for the southern European location Athens, Greece (Location 3).

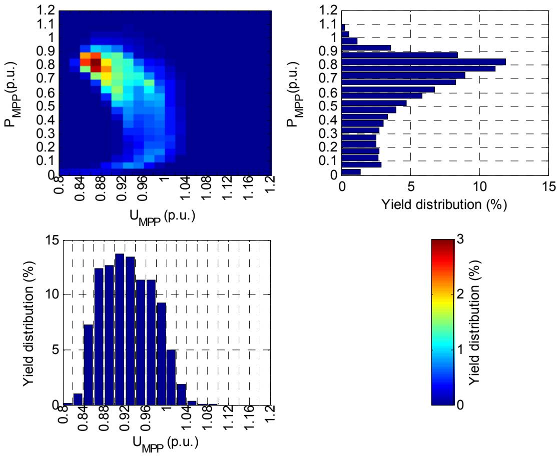
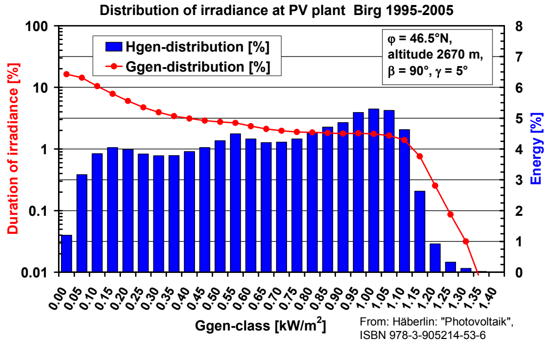


Figure 6: Distribution of the annual yield as a function of MPP voltage and MPP power, measurements from Location 3, Athens, Greece

It can be seen that the distribution is significantly different for this southern location: it is more curved toward lower MPP voltages, and the part of the yield gained for smaller power levels is significantly smaller. About 33 % of the annual yield is gained for power levels below 0.5 p.u. As a comparison, this share exceeds 45 % for Location 1a (Vienna).

Figure 7 shows the distribution of the annual yield as a function of the irradiance for Location 2 (alpine cable way station). It can be seen that a significant part of the annual yield is gained for high irradiance values. For this location, more than 19 % of the annual yield corresponds to irradiance levels greater than 1 kW/m^2. In comparison, such irradiance levels only represent about 3.5 % of the annual yield for Location 1a (Vienna).



From: Häberlin: "Photovoltaik", ISBN 978-3-905214-53-6

Figure 7: Distribution of the annual yield as a function of the irradiance, Location 2, Birg Cable way station, Switzerland (Source: [12])

3 INTRODUCING THE MAXIMAL REACHABLE EUROPEAN EFFICIENCY

3.1 Preamble

The results presented in the following are based on computations made with several assumptions:

- For all the computations, the relative MPP power (in p.u.) has been used. It is normalised to the nominal DC power (as in [13]).
- In the study, a uniform over-sizing factor (as introduced in [12], pages 298-300) has been chosen. Due to the flattening of inverters efficiency curves (η_{EU}=f(P_{MPP})), the over-sizing of PV generators in comparison to the inverters has been reduced in the last years. The value of 1.05 has been chosen in this study. Later investigations showed that this factor has a rather limited impact on the computed efficiency (about 0.2 %).
- The computations presented here are made for the total efficiency as introduced in [4], which results from the multiplication of the conversion efficiency by the static MPP efficiency. In the following, the word *total* will be omitted for conciseness.
- The inverters used for this study to compare the various definitions of European efficiency have all a maximal output power lower than 5 kW. They have been selected among products tested by Photon magazine [13] and can be considered as covering the whole performance range (from *sufficient* to *very good*). The list of the selected inverters (Table I) is provided for completeness and traceability. It is not the intention of the authors to make a comparison between products.

Table I: Considered inverters (alphabetical order)

Index	Full name	Issue in [13]
Inv 1	Conergy IPG5000 vision	7-2007
Inv 2	Delta Energy SI3300	5-2008
Inv 3	DiehlAKO Platinum 4600S	4-2008
Inv 4	Ingeteam Ingecon Sun 3,3 TL	8-2007
Inv 5	Kaco 2500xi	12-2007
Inv 6	Mastervolt Sunmaster QS2000	11-2007
Inv 7	Mitsubishi PV-PNS06ATL-GER	6-2008
Inv 8	Riello HP4065	9-2007
Inv 9	SMA SMC8000TL	10-2007
Inv 10	Suntension Sunville 2800 (v.2008)	5-2008

- The MPP voltage ranges considered in this study are based on those used in [13]. They differ slightly from the manufacturers' specifications since:
  - Part of the specified MPP range is irrelevant (maximal DC voltage limitation: $U^{MAX}_{MPP} < 0.8 \times U^{MAX}_{OC}$).
  - The inverter may be unable to operate with the nominal power in the whole specified range due to e.g. current limitations.
- Terms and definitions

G	*In-plane irradiance*
T	*Module temperature*
T^{MIN}	*Minimal temperature*
T^{MAX}	*Maximal temperature*
T^{STC}	*STC temperature*
β	*Module temperature coefficient (for U_{MPP})*
$U_{MPP,gen}$	*Generator MPP voltage (function of G and T)*
$U^{MIN}_{MPP,gen}$	*Minimal generator MPP voltage*
$U^{MAX}_{MPP,gen}$	*Maximal generator MPP voltage*
$P^{STC}_{MPP,gen}$	*Generator STC MPP power (design)*
$P^{STC-MIN}_{MPP,gen}$	*Minimal possible generator STC MPP power*
$P^{STC-MAX}_{MPP,gen}$	*Maximal possible generator STC MPP power*
$U^{MIN}_{MPP,inv}$	*Specified minimal inverter MPP voltage*
$U^{MAX}_{MPP,inv}$	*Specified maximal inverter MPP voltage*
η_{EU}	*European efficiency for a particular MPP voltage*
η^{MIN}_{EU}	*Minimal (over MPP voltage range) European efficiency*
η^{MAX}_{EU}	*Maximal (over MPP voltage range) European efficiency*
η_{Pmed} [1]	*European efficiency averaged over the whole inverter MPP voltage range for medium irradiation [13]*
η_{Phigh} [2]	*Californian Efficiency averaged over the whole inverter MPP voltage range for high irradiation [13]*
η_{EU-R}	*Reachable European efficiency for a particular PV plant configuration (U^{STC}_{MPP} and P^{STC}_{MPP}) (for medium or high irradiation)*
η_{L1a-R}	*Reachable efficiency for a particular PV plant configuration (U^{STC}_{MPP} and P^{STC}_{MPP}) for Location 1a*
η^{MAX}_{EU-R}	*Maximal reachable European efficiency (for medium high or irradiation)*
η^{MAX}_{L1a-R}	*Maximal reachable efficiency for Location 1a*

[1] $\eta_{Pmed}=0.03\times\eta_{5\%}+0.06\times\eta_{10\%}+0.13\times\eta_{20\%}+0.1\times\eta_{30\%}+0.48\times\eta_{50\%}+0.2\times\eta_{100\%}$

[2] *Efficiency defined by the Californian Energy Commission (CEC):* $\eta_{Phigh}=0.00\times\eta_{5\%}+0.04\times\eta_{10\%}+0.05\times\eta_{20\%}+0.12\times\eta_{30\%}+0.21\times\eta_{50\%}+0.53\times\eta_{75\%}+0.05\times\eta_{100\%}$

3.2 Methodology

In the following, the way to consider the MPP voltage dependency of the inverter efficiency is presented. In a first step, the necessary MPP voltage band which is necessary for proper operation for a particular location is quantified (equations (2) to (7). This MPP voltage band mainly depends on the expected temperature difference and on the voltage temperature coefficient β of the module (equations (2) and (3)).

$$U^{MIN}_{MPP,gen} < U_{MPP,gen} < U^{MAX}_{MPP,gen} \tag{2}$$

$$U^{MIN}_{MPP,gen} = \left(1+\beta\times\left(T^{MAX}-T^{STC}\right)\right)\times U^{STC}_{MPP} \tag{3}$$

$$U^{MAX}_{MPP,gen} = \left(1+\beta\times\left(T^{MIN}-T^{STC}\right)\right)\times U^{STC}_{MPP} \tag{4}$$

$$\eta^{MAX}_{EUR} = \max\left\{\eta_{EU-R}\left(U^{STC}_{MPP,gen}\right)\right\}, U^{STC}_{MPP,gen} \in \left[U^{STC-MIN}_{MPP,gen} - U^{STC-MAX}_{MPP,gen}\right] \tag{5}$$

$$U^{STC-MIN}_{MPP,gen} = \frac{U^{MIN}_{MPP,inv}}{\left(1+\beta\times\left(T^{MAX}-T^{STC}\right)\right)} \tag{6}$$

$$U^{STC-MAX}_{MPP,gen} = \frac{U^{MAX}_{MPP,inv}}{\left(1+\beta\times\left(T^{MIN}-T^{STC}\right)\right)} \tag{7}$$

For Location 1a (Vienna, T^{MIN}=-10°C and T^{MAX}=60°C), the necessary MPP voltage band amounts: $0.28\times U^{STC}_{MPP}$ ($U_{MPP}\in[0.86\times U^{STC}_{MPP}-1.14\times U^{STC}_{MPP}]$).

The reachable efficiency is defined for a particular plant configuration (P^{STC}_{MPP} and U^{STC}_{MPP}) as the value obtained by multiplying the European efficiency (function of P_{MPP} and U_{MPP}) by the corresponding weighting factors after having determined the considered voltage band. Figure 8 provides an illustration of the voltage band computation presented previously. For the explanations, a simplified efficiency characteristic has been chosen (monotonous decreasing curve $\eta_{EU}=f(U_{MPP})$ as it would be for example for an inverter without DC/DC converter).

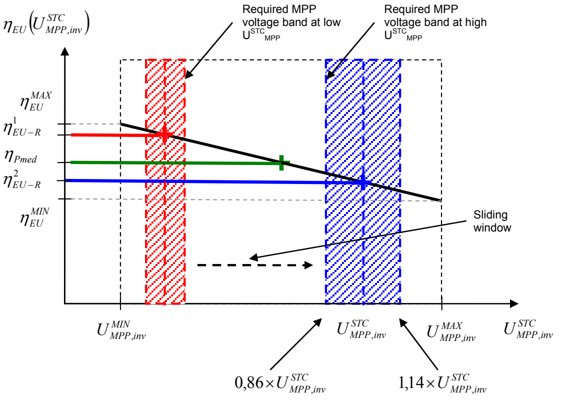


Figure 8: Computation of the reachable efficiency – concept of sliding window and required MPP voltage band

For Location 1a for example, the weighting factors shown in Figure 3 must be multiplied by the efficiency values of the considered inverters. Before multiplying both two-dimensional magnitudes, a linear interpolation is performed in order to obtain values for efficiency and weighting factors on a common grid. The maximal reachable efficiency is simply obtained by varying the plant configuration (U^{STC}_{MPP}) within the range allowable for the considered inverter (equation (5)).

These computations can in principle be performed for the following two magnitudes:

- $\eta_{L1a\text{-}R}$: Reachable efficiency for a particular PV plant configuration for Location 1a (or any other)
- $\eta_{EU\text{-}R}$: Reachable European efficiency for a particular PV plant configuration (using the standard weighting factors)

Using the second magnitude is in fact a particular case for which uniform (not considering the temperature distribution) weighting factors (those currently used in the definition of the European efficiency) are used.

The computation of the reachable European efficiency and its maximum is summarised in Figure 9. The reachable efficiency (Location 1a) is considered; the same would apply to the reachable European efficiency.

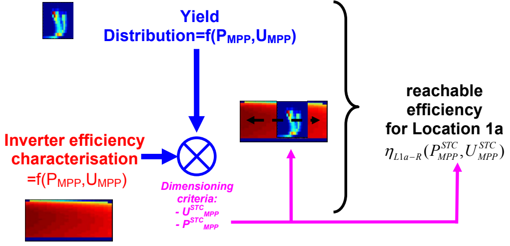


Figure 9: Computation of the reachable efficiency – principle

Figure 10 and Figure 11 show how the multiplication of both distributions for a particular inverter and a particular configuration (U^{STC}_{MPP}) is made. The width of the sliding window corresponds, as previously explained, to $0.28\times U^{STC}_{MPP}$. For the reachable efficiency for Location 1a, the weighting factors shown in Figure 3 are used, whereas uniform factors are used for the reachable European efficiency (Figure 11). These uniform factors are smaller than the original European weighting factors since they are spread over the sliding MPP voltage window and normalised ($\Sigma=1$).

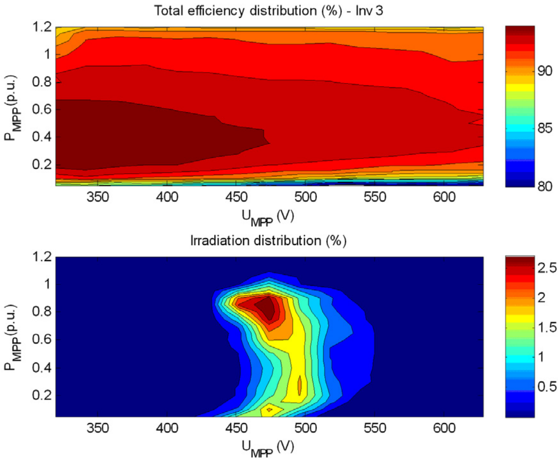


Figure 10: Computation of the reachable efficiency for Location 1a for U^{STC}_{MPP}=500 V (Inverter 3) – the result is obtained by multiplying and summing both distributions

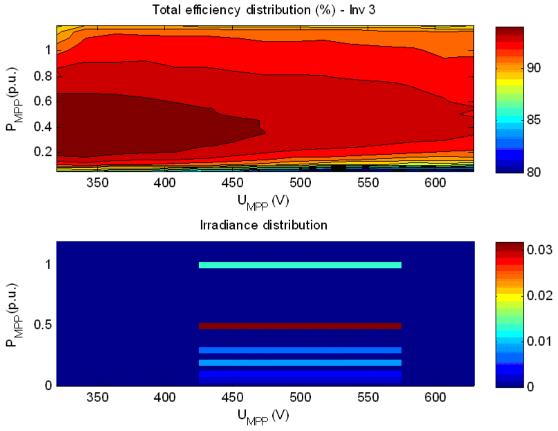


Figure 11: Computation of the reachable European efficiency (for medium irradiation P_{med}) for U^{STC}_{MPP}=500 V (Inverter 3)

3.3 Case study: Computation of the various European efficiency definitions for a particular inverter

In this case study, only the first four locations are considered (central Europe). For all figures, Location 1a has been used.

Figure 12 shows the comparison between the European efficiency averaged over the whole MPP voltage range, the European efficiency averaged over a sliding voltage window (reachable European efficiency) and the reachable efficiency for Location 1a for inverter 5. For each of the inverters, the obtained figures have been carefully analysed.

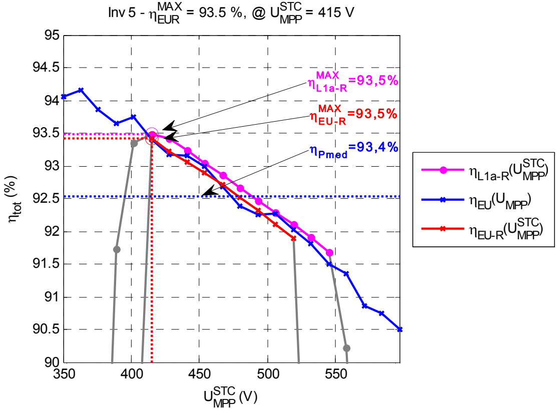


Figure 12: Comparison between the average European efficiency, the reachable European efficiency (averaged over a sliding voltage window) and the reachable efficiency for Location 1a (Inverter 5)

The grey portion of the curves indicates that part of the yield lies out of the operation range which results in a strong decrease of the total efficiency.

This figure shows that the reachable efficiency for Location 1a is for this particular inverter about 0.2 % greater than the reachable European efficiency. The maximum of the reachable efficiency for this location amounts 93.5 %; it is reached at U^{STC}_{MPP}=415 V.

In order to illustrate the fact that averaging the efficiency curve ($\eta_{EU}=f(U_{MPP})$) over the whole inverter MPP range is not adequate, the simple case introduced previously (Figure 8) is considered. The error can be simply calculated with the following formulas (8-10):

$$\Delta\eta = \left(\eta_{EU}^{MAX} - \eta_{EU}^{MIN}\right)\times\left[\frac{1}{2} + \frac{\beta\times\left(T^{MAX} - T^{STC}\right)}{1+\beta\times\left(T^{MAX} - T^{STC}\right)}\times\frac{U_{MPP,inv}^{MIN}}{U_{MPP,inv}^{MAX} - U_{MPP,inv}^{MIN}}\right] \quad (8)$$

$$\Delta\eta = \left(\eta_{EU}^{MAX} - \eta_{EU}^{MIN}\right)\times\left[\frac{1}{2} + f\left(\Delta T^{+}\right)\times\frac{1}{\Delta U_{rel}}\right] \quad (9)$$

$$\Delta U_{rel} = \frac{U_{MPP,inv}^{MAX} - U_{MPP,inv}^{MIN}}{U_{MPP,inv}^{MIN}} \quad (10)$$

$$\Delta\eta = \left(\eta_{EU}^{MAX} - \eta_{EU}^{MIN}\right)\times\left[\frac{1}{2} - f\left(\Delta T^{-}\right)\times\left[1+\frac{1}{\Delta U_{rel}}\right]\right] \quad (11)$$

Equation (8) shows that the error is proportional to the efficiency difference (best-worst). It is basically half of this efficiency difference minus a term which depends on the relative voltage band defined in (9). $f(\Delta T^{+})$ is a negative function of the temperature difference, i.e. constant for a defined location. Equation (10) would correspond to the case of an increasing curve.

These simple considerations show that

- inverters with a large difference between the maximal and the minimal efficiency
- inverters with a large relative MPP voltage range

are disadvantaged by averaging over the whole MPP voltage range. For inverters with a large relative voltage range (e.g. 3 p.u. for Inverter 7), the deviation converges to half of the difference between maximal and minimal efficiency.

Taking as example Inv 5 (maximal European efficiency of 94.1 % and minimal European efficiency of 90.5 %) leads to a deviation of about one percent. This deviation matches the value from the automatic computations which can be seen on Figure 12 (difference between red and blue curve). If the specifications of the inverter were modified (narrower MPP voltage range), for example 400 V-500 V instead of 350 V-600 V (ΔU_{rel}=0.25 p.u. instead of 0.71 p.u.), the average European efficiency would amount to 93 % instead of 92.3 %. This simple example perfectly illustrates the problem of averaging over the whole inverter MPP range.

Figure 13 shows a comparison between the European efficiency averaged over the whole inverter MPP voltage range (P_{med}) and the maximal reachable European efficiency (averaged over a sliding window).

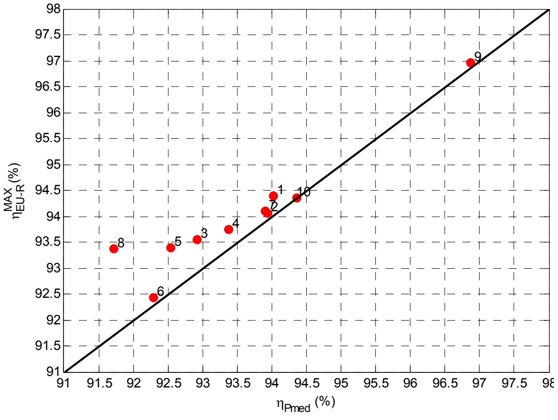


Figure 13: Comparison η_{Pmed} / η_{EU-R}^{MAX}

This figure shows that the distortion introduced by averaging over the whole inverter MPP voltage range is not the same for all the considered inverters. This is as previously explained mainly due to the fact that the inverters exhibit different maximal and minimal European efficiency and different relative voltage ranges. The largest deviation is observed for inverter 8: almost 2 %. For inverter 5 the deviation is as previously estimated about 1 %.

Figure 13 therefore shows that averaging over the whole inverter MPP voltage range may lead to:

- an underestimation of the efficiency for all inverters
- a distortion (error) between inverters.

For this example set of inverters, the ranking according to the marking system used in [13] obtained for the three computed efficiencies is shown in Table II for illustration purpose only.

In the first column is the maximal reachable efficiency for Location 1a (Vienna, Austria), in the second, the maximal reachable European efficiency, and in the last, the European efficiency averaged over the whole MPP voltage range. It can be seen that for the maximal reachable European efficiency (computed over a sliding window), the grade *sufficient* is not assigned to any inverter. Differences of more than 1.5 % lead to a different grade. This table further shows that two inverters would jump into the next grade using the maximal reachable European efficiency (computed over a sliding window).

Table II: Ranking of the selected inverters for the various definitions of the European efficiency

η_{L1a-R}^{MAX}			η_{EU-R}^{MAX}			η_{Pmed}		
9	96.8	*very good +*	**9**	97.0	*very good +*	**9**	96.9	*very good +*
1	94.4	*good*	**1**	94.4	*good*	**10**	94.4	*good*
10	94.2	*good*	**10**	94.4	*good*	**1**	94.0	*good*
2	94.2	*good*	**7**	94.1	*good*	**2**	93.9	*good*
7	94.2	*good*	**2**	94.1	*good*	**7**	93.9	*good*
4	93.7	*good*	**4**	93.8	*good*	**4**	93.4	*satisfactory*
8	93.6	*good*	**3**	93.6	*good*	**3**	92.9	*satisfactory*
5	93.5	*good*	**5**	93.4	*satisfactory*	**5**	92.5	*satisfactory*
3	93.4	*satisfactory*	**8**	93.4	*satisfactory*	**6**	92.3	*satisfactory*
6	92.4	*satisfactory*	**6**	92.5	*satisfactory*	**8**	91.7	*sufficient*

3.3 Influence of the location on the computed efficiency

In a further step, the influence of the location (through the weighting factors) on the maximal reachable efficiency was investigated.

Figure 14 shows that the maximal reachable European efficiency (computed for medium irradiation P_{med}, [13]) and the maximal reachable efficiency for Location 1a are close (deviation smaller than 0.2 %). For some inverters (1, 3, 4, 6, 9 and 10), the maximal reachable efficiency for Location 1a is slightly smaller than the maximal reachable European efficiency whereas it is the contrary for the other inverters (2, 5, 7 and 8).

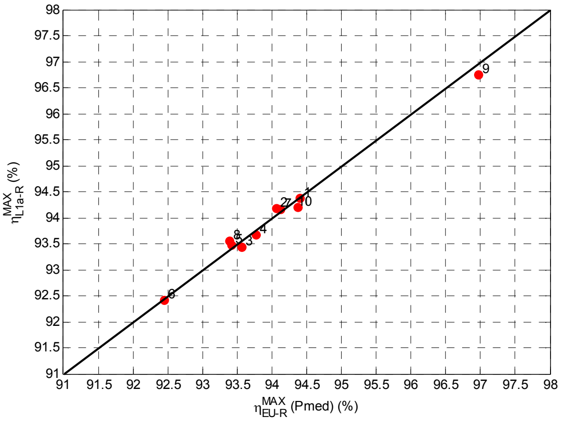


Figure 14: Comparison η_{EU-R}^{MAX} (P_{med}) / η_{L1a-R}^{MAX}

Similar computations have been performed for Location 3 (Athens, Greece). The objective was to compare the obtained maximal reachable efficiency for this Southern European location to the maximal European efficiency computed for high irradiation (P_{high}, [13]). The results can be seen in Figure 15.

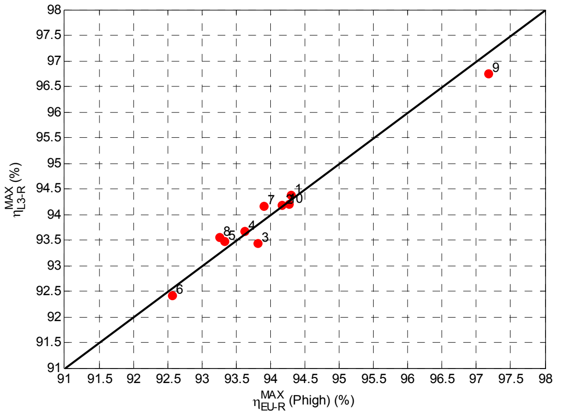


Figure 15: Comparison η_{EU-R}^{MAX} (P_{high}) / η_{L3-R}^{MAX}

Figure 16 provides a comparison between the maximal reachable efficiency for the four central European locations and the maximal reachable European efficiency. Inverters are sorted starting from those presenting the largest dispersion.

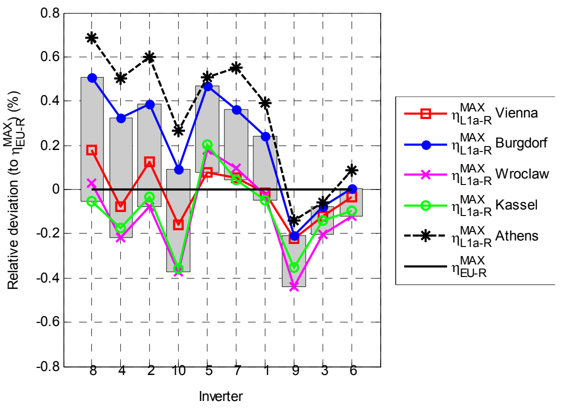


Figure 16: Comparison between the maximal reachable efficiency from four locations in central Europe (Vienna, Burgdorf, Wroclaw and Kassel) and the maximal European efficiency

It can be seen in Figure 16 that the difference between the maximal reachable efficiency computed for these four central European locations (for different years) and the maximal reachable European efficiency is quite high: about 0.5 %. On the basis of these observations, two conclusions can be drawn:

- The difference between the values of the efficiencies computed from measurements data from the central European locations is not negligible (almost 0.3 %). It is significantly smaller if only Locations 1a, 1c and 1d are considered (about 0.1 %).
- The difference between the efficiencies computed from measurement data at these three locations and the efficiency computed using the widely used European weighting factors is significant (about 0.5 %).

4 CONCLUSIONS

The use of an accurate and realistic efficiency definition is crucial since the European efficiency is the main criterion for comparing inverters' performance. Due to the fact that comparing the performance of PV inverters by looking at the datasheet is not possible, a new system for computing the efficiency taking into account both impacts of MPP power and voltage on the efficiency has been recently introduced. This paper proposes an enhancement of this method which is more accurate while at the same time staying simple and easy to implement.

The following main conclusions have been given:

- Significant errors are introduced by averaging the European efficiency over the whole inverter MPP voltage range (almost 2 % for a particular inverter). These errors are not uniformly impacting all the inverters but mostly affect:
  - inverters with a large (relative) MPP voltage range, and
  - inverters exhibiting a large difference between best and worst efficiency over the MPP voltage range.

  A new way of computing a representative average efficiency, the so-called maximal reachable efficiency has therefore been introduced. It is insensitive to inverters' specifications (too large MPP voltage range resulting in lower efficiency values at the border) and therefore more suitable for comparing products.
- The introduced reachable efficiency can be computed for any configuration (U_{STCMPP}) on the basis of:
  - weighting factors derived from high resolution measurements
  - weighting factors already used (i.e. European or CEC efficiency)

  The maximum of this reachable efficiency can then be used for comparing products since it provides an idea of the highest *average efficiency* which can be realistically obtained.

  As a consequence of the distortion introduced by averaging over the whole inverter MPP voltage range, the ranking between products is significantly modified by using the proposed efficiency definition.

- Regarding the impact of the location on the maximal reachable efficiency, the following conclusions must be highlighted:
    - Deviations among the maximal reachable efficiency for the considered central European locations are non negligible (up to 0.3 %).
    - Deviations between the maximal reachable efficiency for the considered central European locations and the maximal reachable European efficiency are significant (up to 0.5 %).
- However, defining a set of weighting factors for various European locations is not feasible for the purpose of comparing products. The use of the maximal reachable European efficiency as a trade-off between accuracy and simplicity is therefore proposed, keeping in mind that significant deviations can occur depending on the location. For this maximal reachable European efficiency, either the set of factors P_{med} (central Europe) or P_{high} (southern Europe) can be used.
- The deviations between the maximal reachable efficiency for the considered central European locations and the maximal reachable European efficiency showed that the weighting factors of the current definition of the European efficiency should probably be modified. In particular, the factor for high irradiance levels (0.2 for 100 %) seems to be too small in comparison to the factor for medium irradiance levels (0.48 for 50 %).
- The new approach allows a more accurate comparison between products considering the total efficiency only. On the other hand, the topical question of the real value of a wide MPP voltage range remains unanswered. Keeping in mind that the selection of an inverter for a particular PV generator is subject to many constraints (e.g. available surface, module dimensions, modules and inverters availability), the value of a wide MPP voltage range should not be underestimated. For this reason, providing the user with the maximal and minimal reachable efficiency would provide valuable information (how good the inverter is and how carefully the STC MPP voltage should be selected).
- In order to carry forward the investigations on the impact of the location on the weighted efficiency, measurement data with a high sample rate (sampling period less than 1 min) are required. Although some institutions working in this field already started to exchange such data, further cooperation is needed. Once a broad set of measurement data for various European locations is available, the weighting factors of the European efficiency could be adapted in order to better match the observations.
- The proposed method for computing the reachable European efficiency (sliding voltage window, using the weighting factors from the current definition of the European efficiency) could be easily implemented. This would not require any additional efficiency measurements in comparison to the ones currently available and would remove the distortion introduced by the current definition.
- The results confirm that even considering only the total efficiency as performance criterion, comparing inverters is a delicate task. In addition to the measurement uncertainty, which can be considered to be in the range 0.3 %-0.5 % [2] for the total efficiency, the location and the considered year have a non negligible impact on the maximal reachable European efficiency (about 0.3 %).

5 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the helpful contribution of Solar Verlag GmbH (inverter efficiency data) as well as the kind contributions of SolarLab, Wroclaw University of Technology, Poland and the National Technical University of Athens, School of Electrical and Computer Engineering, Electric Power Engineering Division, Greece (weather data).

6 REFERENCES

[1] F. Baumgartner et al., *MPP voltage monitoring to optimise grid connected system design rules*, 19th European Photovoltaic Solar Energy Conference, Paris, 2004

[2] F. Baumgartner et al., *Status and relevance of the dc voltage dependency of the inverter efficiency*, 22nd European Photovoltaic Solar Energy Conference, Milano, 2007

[3] *A Review of PV inverter Technology Cost and Performance Projections*, NREL/SR-620-38771, January 2006

[4] H. Häberlin et al., *Total Efficiency η-tot – A new Quantity for better Characterisation of Grid-Connected PV Inverters*, 20th European Photovoltaic Solar Energy Conference, Barcelona, 2005

[5] B. Bletterie et al., *Quantifying dynamic MPPT performance under realistic conditions first test results – The way forward*, 21st European Photovoltaic Solar Energy Conference, Dresden, 2006

[6] R. Bründlinger et al., *Performance und Sicherheit Netzgekoppelter Stromrichter -Internationale Praxis und Erfahrungen beim Test*, 13. Kasseler Symposium Energie-Systemtechnik 2008, to be published

[7] C. Bendel et al., Ch. Bendel, G. Keller, G. Klein; *Ergebnisse von Messungen an Photovoltaik-Wechselrichtern*, 8. Nationales Symposium Photovoltaik, Staffelstein, 1993

[8] B. Burger, *Auslegung und Dimensionierung von Wechselrichtern für netzgekoppelte PV-Anlagen,* 20. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 2005

[9] S. Ransome et al., *Why hourly averaged measurement data is insufficient to model PV system performance accurately*, 20th European Photovoltaic Solar Energy Conference, Barcelona, 2005

[10] Gerd Bettenwort, *Anforderungen an den Aufbau modularer Photovoltaikanlagen im Netzparallelbetrieb*. Number 322 in Fortschritt-Bericht VDI Reihe 21. VDI Verlag, 2002

[11] B. Bletterie et al., *I-V curve modelling for inverter testing – a critical review of current approaches*, 22nd European Photovoltaic Solar Energy Conference, Milano, 2007

[12] H. Häberlin, *Photovoltaik, Strom aus Sonnenlicht für Verbundnetz und Inselanlagen*, VDE Verlag Berlin, 2007, ISBN 978-3-8007-3003-2

[13] Photon magazine, Solar Verlag GmbH