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Weighted efficiency measurement of PV inverters: introducing $\eta_{İZMİR}$

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Conversion efficiency of DC/AC inverters depends on some parameters and fluctuates over the input power of the inverter. Since the PV inverters operate under a fluctuating input power supplied by the PV modules, conversion efficiency must be measured against the weights of the probable power ranges which represent the various irradiation values. This approach of having different weights for different irradiation ranges resulted in two basic weighted conversion efficiency models of η_{EURO} and η_{CEC}. These two models consider the irradiation distribution over the whole annual sunny time and prioritize the ranges with various weight factors. Since the irradiation profiles vary around the planet, inverter efficiencies must be evaluated against local irradiation profiles to get more precise annual energy yield estimation. This paper presents $\eta_{İZMİR}$, a weighted conversion efficiency evaluation model, derived from the İzmir irradiation profile. This model has been developed in a way that it should be simple and accurate so it has been matched with other models for its estimation capabilities. The results are discussed here and suggestions being made.

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1. Introduction

Penetration of grid connected photovoltaic power systems (PVPS) is rapidly increasing for two decades. As they are being an embedded part of the electric networks, their electricity generations have started to be studied more intensively. The incentives given by the governments for those systems due to the paradigm change in the energy field has triggered a further acceleration in those studies.

Electricity generation of a PV power system depends on the solar irradiation received by the PV modules and the efficiency of the system. The efficiency of a PVPS on the other hand, is a multifold concept covering conversion efficiency of the PV modules along with the conversion efficiency, MPPT performance and some other properties of PV inverter used.

PV inverters are evaluated with their overall efficiency. Overall efficiency is described as the ratio of the energy delivered by the PV inverter at the AC terminals to the energy provided by the PV array [1]. The two efficiencies involved in the inverters are conversion efficiency ($\eta_{\mathbf{conv}}$) and MPPT efficiency ($\eta_{\mathbf{MPPT}}$) described as,

$$\eta_{conv} = \frac{\int_0^{T_M} p_{AC}(t)\cdot dt}{\int_0^{T_M} p_{DC}(t)\cdot dt} \tag{1}$$

and

$$\eta_{MPPT} = \frac{\int_0^{T_M} p_{DC}(t)\cdot dt}{\int_0^{T_M} p_{MPP}(t)\cdot dt} \tag{2}$$

respectively, where,

$p_{AC}(t)\cdot dt$ is instantaneous value of the delivered power at the AC terminal,

$p_{DC}(t)\cdot dt$ is instantaneous value of the power drawn by the inverter,

$\mathrm{p_{MPP}(t)\cdot dt}$ is instantaneous value of the MPP power provided by the PV array (or PV simulator).

Thus, the overall efficiency including both efficiencies becomes;

$$\eta t = \eta conv \cdot \eta MPPT = \frac{\int_0^{T_M} p_{AC}(t)\cdot dt}{\int_0^{T_M} p_{MPP}(t)\cdot dt} \tag{3}$$

Besides the straightforward mathematics here, especially with the grid connected power plants, annual yield estimation needs further effects to be studied accurately for realistic revenue projections. One these would be the input power fluctuations resulting from climatic conditions, since the value of PV array power explicitly affects both conversion and MPP tracking efficiencies of the PV inverter.

The first weighted efficiency calculation concerning the effect of irradiation profile on the inverter efficiency has been introduced with north-western Germany climate data (Trier) in 1991 [2], [3]. The formula given in a footnote of a magazine article then became a well-known comparison tool among PV inverters Although the weather data used for calculating the weighting factors do not represent whole Europe – especially the South – the formula know is now known as the “European Efficiency – [4]. European Efficiency formula is given as;

$$\eta_{EURO} = a_{EU1}\cdot\eta_{MPP1} + a_{EU2}\cdot\eta_{MPP2} + a_{EU3}\cdot\eta_{MPP3} + a_{EU4}\cdot\eta_{MPP4} + a_{EU5}\cdot\eta_{MPP5} + a_{EU6}\cdot\eta_{MPP6} \tag{4}$$

where is the weighting factor and is the static MPPT efficiency at partial MPP power. The indices for these values are listed in Table:1.

The variations in the lower irradiation levels are highly emphasized in this formula, making it less suitable for the geographical locations with higher solar irradiation. With the increasing penetration of PVPSs, and more installations have been made in southern locations, another comparison tool has been introduced by California Energy Commission utilizing the Sacramento climatic data [5].

Using same structure with the European Efficiency, η_{CEC} formula considering the higher irradiation conditions was suggested as;

$$\eta_{CEC} = a_{CEC1} \cdot \eta_{MPP1} + a_{CEC2} \cdot \eta_{MPP2} + a_{CEC3} \cdot \eta_{MPP3} + a_{CEC4} \cdot \eta_{MPP4} + a_{CEC5} \cdot \eta_{MPP5} + a_{CEC6} \cdot \eta_{MPP6} \tag{5}$$

whose coefficients are shown in Table 2.

Table 1. Weighted efficiency formula coefficients for η_{Euro}.

Weighting Factor						
	0,03	0,06	0,13	0,1	0,48	0,2
Partial MPP power $P_{MPP,\,PVS}/P_{DC,r}$						
	0,05	0,1	0,2	0,3	0,5	1

Table 2: Weighted efficiency formula coefficients for η_{CEC}.

Weighting Factor						
	0,04	0,05	0,12	0,21	0,53	0,05
Partial MPP power $P_{MPP,\,PVS}/P_{DC,r}$						
	0,1	0,2	0,3	0,50	0,75	1

The quick comparison of two tables show that CEC evaluates higher irradiation region in more detail and EE emphasizes more on the lower part. Both can be used to achieve more precise annual yield estimation for a PV inverter, than a maximum conversion efficiency of that inverter.

Evaluation of weighted efficiency approach shows that, local climatic conditions (latitude) and tracking strategies affects inverters' energy efficiencies [6].

2. ETA İzmir

Since the effect of climatic conditions is known to be effective on efficiency, further research for various locations could be done. Here, İzmir has been chosen to represent Turkey (lat. E42º-E36º), for it geographically is almost in the middle (lat. E38º30'). During the evaluation process, the State Meteorology Directorate's climate measurements database was used as primary data source. In some assessments, Ege Universiy Solar Energy Institute's measurement data base has also been used. Basic measurement set is taken during 2009 through 2012 in DMİ Menemen Observation Station no. 17789 at minute resolution. Annual distribution of these data is shown in Fig 1.

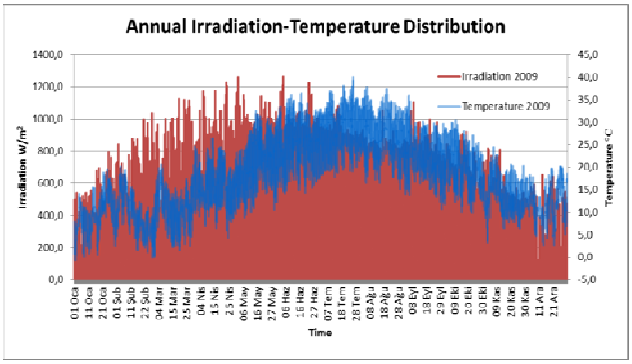

Fig. 1. 2009 irradiation and temperature data from DMİ Menemen observation station.

Energy calculations have been made for cSi modules according to EN 50530. In this document, irradiance and temperature dependent open circuit voltage of a cSi module has been calculated as,

$$V_{OC} = V_{OC,STC} \cdot \left(1 + \beta \cdot (T_{PV} - T_{STC})\right) \cdot \left(\ln\left(\frac{G}{C_G} + 1\right) \cdot C_V - C_R \cdot G \right) \tag{6}$$

and irradiance and temperature dependent closed circuit current of a cSi module has been calculated as,

$$I_{SC} = I_{SC,STC} \cdot \frac{G}{G_{STC}} \cdot \left(1 + \alpha \cdot (T_{PV} - T_{STC})\right) \tag{7}$$

where,

T_{PV} is PV module temperature ºC;

T_{STC} is standard test condition temperature 25 C°;
G is solar irradiation W/m^2;
α is temperature coefficient of current 0,25%/ ºC;
β is temperature coefficient of voltage 0,4%/ ºC;
and technology depending correction factors
C_{R}, is $2{,}514 \cdot 10^{-3}$ W/m^2
C_{V}, is $8{,}593 \cdot 10^{-2}$
C_{G} is $1{,}088 \cdot 10^{-4}$ m^2/W.

For simplification reasons, a 1 000 W PV array with $U_{\text{oc,STC}}$=100 V and $I_{\text{sc,STC}}$=10 A has been considered.

The irradiation data has first been evaluated for annual energy distribution against irradiation classes. Results are presented in Fig:2. A quick inspection of the graph reveals that, one third of annual energy yield would be harvested at and below 500 W/m^2 irradiation levels. The other one thirds would be harvested between 500-750 W/m^2 and above 750 W/m^2 irradiation classes respectively.

This clearly shows that yield estimations made based on European efficiency wouldn't be valid for İzmir irradiation since it assumes 79% of annual yield would be harvested at and below 500 W/m^2 irradiation levels (referring Table:1).

CEC efficiency on the other hand, shows a closer match with İzmir irradiation profile at lower levels since it assumes 42% energy yield for that range (referring Table:1). However, this model still don't show a proper match for medium and high irradiation levels for it assumes 95% of annual yield would be harvested below 750 W/m^2 irradiation levels, which is not the case with İzmir data.

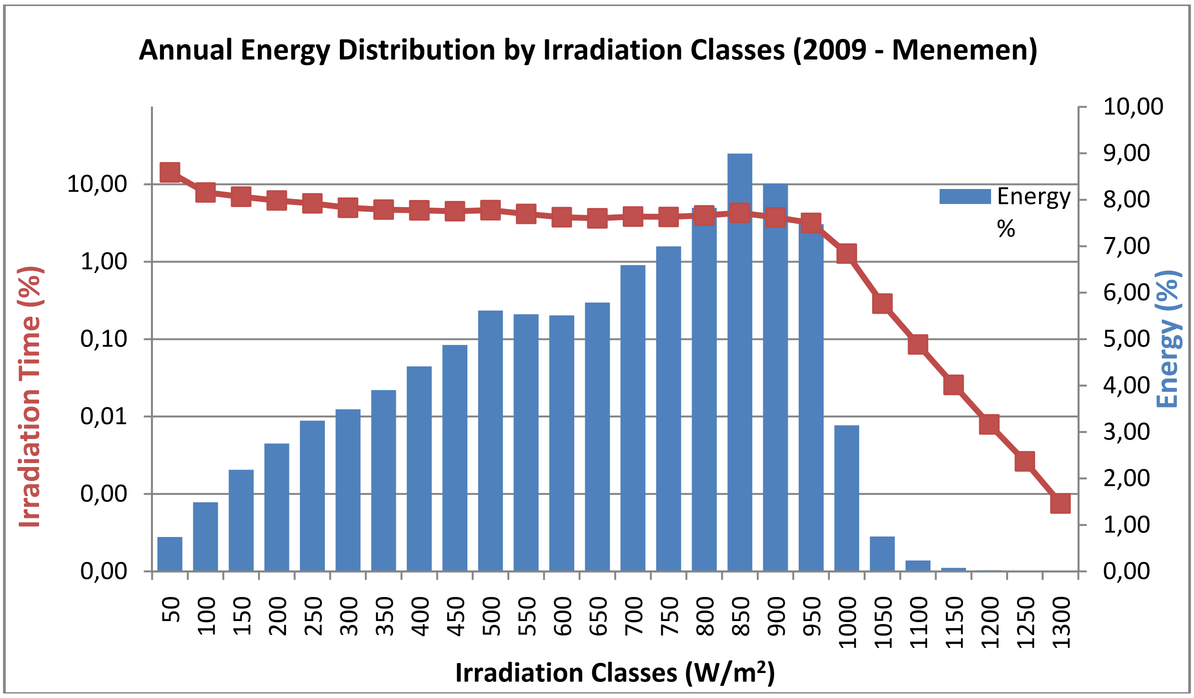

Fig. 2. 2009 irradiation profile evaluation for annual energy yield distribution.

The reason for European efficiency formula is not grasping İzmir energy yield can be its being based on hourly irradiation averages [4] instead of a high resolution irradiation measurement data set.

The failure of CEC efficiency may be resulted from its lack of considering temperature effect significant enough.

Further inspection of İzmir irradiation data and the energy yield calculations gives the weights in the Table:3 for 10% irradiation classes, values in the $P_{\text{MPP}}/P_{\text{STC}}$ row is representing the midpoints of these bins.

Table 3. Weighted efficiency formula coefficients for η_{Euro}.

$P_{\text{MPP}}/P_{\text{STC}}$ (%)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
IZM (ALL) (%)	1,31	2,83	4,02	4,90	5,72	6,80	8,24	9,12	9,49	11,45	14,41	13,35	7,11	1,03	0,18	0,03	0,01
Cumulative energy yield	1,31	4,14	8,16	13,06	18,78	25,58	33,82	42,94	52,43	63,88	78,29	91,64	98,78	98,78	99,96	99,99	100

One of the most important result derived from the calculations here is, there is no instance above 90% P_{MPP}/P_{STC} ratio, due to the diminishing effect of the module temperature. This means that there is no way a 1 000 Wp cSi PV array could produce 1 000 W power throughout the year in İzmir, unless it is cooled by some manners.

A comparison of İzmir data based calculations for European and CEC efficiencies are presented in the Table 4.

Table 4: Weights for İzmir data calculated for Euro and CEC classes.

P_{MPP}/P_{STC}	5%	10%	15%	20%	25%	30%	50%	75%	100%
EURO	3%	6%		13%		10%	48%		20%
CEC		4%		5%		12%	21%	53%	5%
IZM (EURO)	1%	6%		10%		16%	29%		39%
IZM (CEC)		2%		7%		12%	19%	26%	34%

The values in the table reveal that, energy generation distribution of a PVPS in İzmir is different than in Trier or Sacramento. Inverter efficiency values for higher powers would have higher weights in İzmir conditions.

Since the lower generation classes do not represent much of the yield, the resolution shown both in European and CEC efficiencies at lower parts does not seem necessary for hot climates with high solar irradiation. Thus, a reduced number of weightings are proposed as İzmir efficiency formula. Five and four evaluation classes and their respective weights are shown in Table 5.

Table 5: Reduced number of evaluation classes for İzmir efficiency formula.

P_{MPP}/P_{STC}	10%	30%	50%	70%	90%
IZM (5)	2,3%	13,1%	21,8%	27,6	35,2%
IZM (4)	4%	12%	21%	53%	-

These values in the table yields,

$$\eta_{IZM(5)} = 0,02\cdot\eta_{10\%} + 0,13\cdot\eta_{30\%} + 0,22\cdot\eta_{50\%} + 0,28\cdot\eta_{70\%} + 0,35\cdot\eta_{90\%} \tag{8}$$

and

$$\eta_{IZM(4)} = 0,04\cdot\eta_{10\%} + 0,12\cdot\eta_{30\%} + 0,21\cdot\eta_{50\%} + 0,53\cdot\eta_{70\%} \tag{9}$$

These suggested evaluation formulas have together been tested against European and CEC efficiencies for a number of commercially available PV inverters' efficiency measures at the AIT Inverter Test Laboratory. Three of these evaluation graphs are shown Fig. 3 through Fig. 5 below.

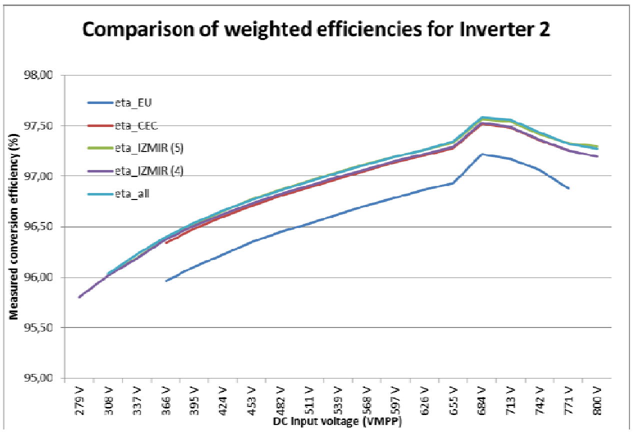

Fig. 3. Comparison for a wide voltage range inverter.

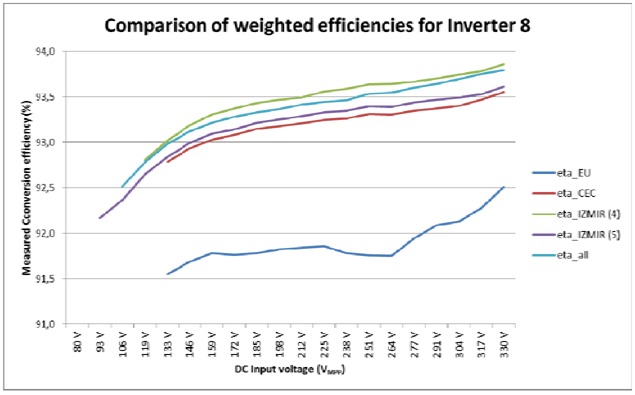

Fig. 4. Comparison for a relatively low voltage inverter.

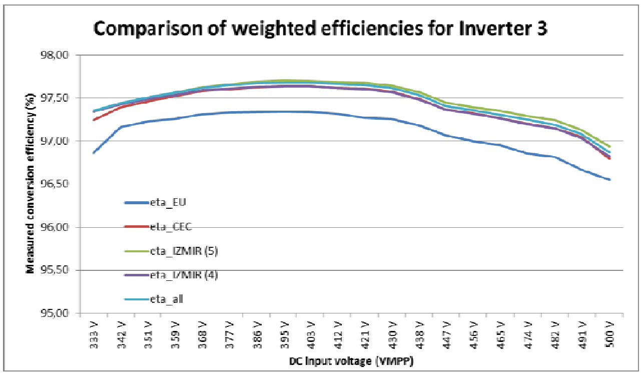

Fig. 5. Comparison for a relatively high voltage inverter.

3. Conclusion

The remarkable conclusions of this study are summarized below:

There is a distinctive indication that, due to the climatic conditions, MPP power generated by a PV array installed in İzmir would not exceed 85% of STC power. This brings in a need for further research using a multiyear data set to achieve a more reliable result.

Although it provides a good basis for performance evaluation of PV inverters, European efficiency formula is not suitable for yield estimations in southern locations since it is based on a northern climate data evaluation. This inadequacy has been fixed by CEC efficiency formula which makes use of the same approach with different weighting pattern.

Here with the İzmir efficiency formula, the evaluation could be made with localized data set in an enhanced reliability. Besides the increased reliability, new formula is also simpler than the others with 33% less terms to consider.

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