# FORMULATION OF PERFORMANCE OF INVERTERS FOR SOLAR PHOTOVOLTAIC POWER PLANTS – INDIAN CASE STUDY

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***Abstract*— Indian Government has set ambitious targets for solar PV of 100 GW under the National Solar Mission by the year 2022. The installed capacity has already reached 28GW as on March 2019 .The inverter is one of the main components of solar PV conversion system. Due to varying irradiation profile in India, the inverters used in Solar PV applications are subjected to varying levels of DC input power. At present two weighted average methods namely EURO and California Energy Commission (CEC) efficiency formulae have been used by inverter manufacturers worldwide to evaluate the performance of inverters. These methods are representative of inverter efficiencies at Europe and California, thus cannot be suitable benchmarks to find out the conversion efficiency of the inverters in other locations. The present research and this paper proposes about introducing new weighting factors for calculation of inverter efficiency as per irradiation profile in India.**

**As a step 1, for computing the weighting factors the data from Solar Radiation Resource Assessment (SRRA) stations implemented by National Institute Of Wind Energy (NIWE) is used and are categorized into five climatic zones .In step 2 validation of three inverters were done by calculating the weighted average efficiency of these inverters operating in all the climatic zones by considering the new weighting factors. Further in step 3, it was cross-compared with the standard values of EURO and CEC efficiency. In step 4, the modelled overall weighted average efficiency is subsequently compared with the actual measured weighted average efficiency. The measured DC Energy and AC Energy of the plant was used for this purpose. The proposed approach has been generalized to consider the irradiation profile of a particular location for calculating the inverter efficiency and hence it can provide significant insights related to the performance of inverters for the solar projects.**

***Keywords— Efficiency, Irradiation, Euro, CEC, SRRA***

## I. INTRODUCTION

India has a target of installing solar power plant of capacity 100 GW by 2022. The solar industry experienced a 370% increase in capacity within three years from 2014 to 2017. The inverter is an important component of solar PV systems that is used to convert the DC power produced by the PV module into AC power that can be fed to the grid. Manufacturers make all possible effort to improve the electrical efficiency of their inverters and to match their efficiency profiles to the needs of the industry. In general, PV inverters are evaluated with their overall efficiency. Overall efficiency is defined as the ratio of the energy supplied by the PV inverter at the AC terminals to the energy provided by the PV array. However, the inverters used in solar PV applications are subjected to varying levels of DC input power due to the fluctuating irradiation. This leads to the deviation of the actual efficiency from the manufactures peak efficiency. A relation between the varying irradiation at a particular location and the corresponding inverter efficiency can be brought about by effectively using the weighted average efficiency measurement, in which the efficiency of the inverter is weighted for different input power levels that the device is most likely to operate in over a period of time. At present two weighted average methods namely EURO and California Energy Commission (CEC) efficiency formulae have been used by inverter manufacturers worldwide to evaluate the performance of inverters. These methods are representative of inverter efficiencies at Europe and California, thus cannot be suitable benchmarks to find out the conversion efficiency of the inverters in other locations. This work aims to formulate the weighted average efficiency for upon considering the irradiation pattern and the energy yield distribution using Solar Radiation Resource Assessment(SRRA) station measurements across India. This SRRA measurement provides a good understanding of the evaluation of the inverter performance with respect to the location specific irradiation profile. [9]The inverter efficiency is crucial in estimating the annual generation capacity of solar PV power plants.

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 1990 by Rolf Hotopp using hourly averages of the irradiation data for one year.[1] During the following years this weighted annual conversion efficiency factor was called "European Efficiency" and is regarded as a standard for the evaluation of PV inverters. Later , CEC Efficiency has been defined by the California Energy Commission (2006), it was calculated for the Sacramento Typical Meteorological Year (TMY).[2] Compared to the European Efficiency a different set of nominal points is used. In order to perform the investigations on the impact of the location on the weighted efficiency, measurement data with a high frequency rate are necessary.. The increasing number of solar PV installations worldwide has driven the need for further work on refining the existing weighting co-efficients of the Euro and CEC efficiency. A new formulation of the weighted average efficiency for Izmer, Turkey is modelled by Ilker et. AL, 2013 considering the Izmer irradiation profile.[3] 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 paper by Anish et.AL discusses the effects of varying irradiation on the efficiency of inverters for tropical climatic conditions in Chennai, India (2014).[4] An algorithm implemented on three phase voltage source inverter is proposed by M.Jayakumar et.AL, can be installed at all places and will decrease the cost and losses compared to conventional system(2018).[5] The importance of renewable energy especially distributed generation to manage the energy crisis of India is emphasized by Tania Tony et.AL[6]. This papers objective is to formulate weighting coefficients for formulation of PV inverters efficiency for the identified climatic zones across India that will help the users in selection of inverters for that particular location based on higher efficiency. This will help in calculating more appropriate weighted average efficiency for the inverters for Indian climatic zones and result will lead into selection of suitable inverter which will results in higher generation as well as increased revenue.

SRRA is a large scale project involving measurement and collection of data from SRRA stations spread across India.[7] Fully automated quality control procedure is in force in the data processing and analysis. Data which has passed the Quality Control (QC) test and has been flagged as good is segregated and used for this project work. QC includes flagging and gap filling method using quality check algorithm applied on raw data. Reports are generated on daily, monthly and yearly basis beside 1 minute, 10 minute and 1 hourly time series data. For the work done here one minute data is averaged to 15 minute data and used. Data period considered for computing weighting factors is one year data, from 1st January 2016 to 1st January 2017.

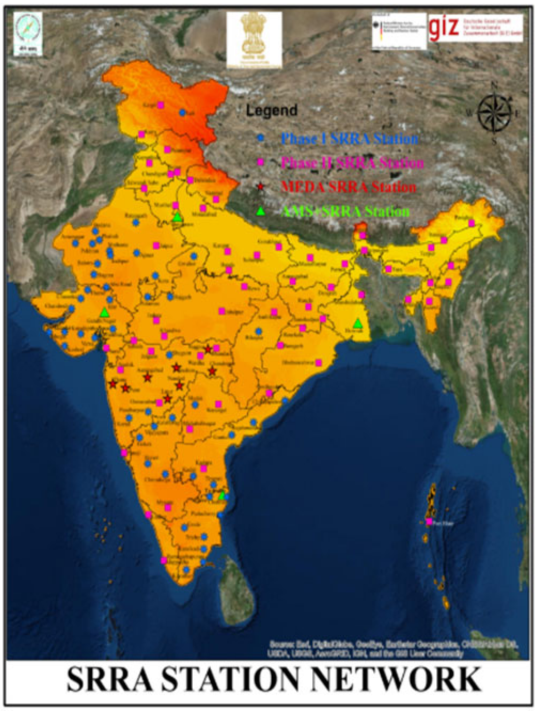


Fig.1 SRRA Stations India

## II. Methodology and Approach

Locations of SRRA stations are identified according to the climatic zones of India. Data which has passed the quality control test and has been flagged as good was segregated and used for this analysis. The one min data was averaged to 15 minute interval and used for the analysis. Weighted average efficiency co-efficients are derived from the location specific irradiation profile. This is calculated upon by considering the irradiation pattern and by selecting the major operating points of the inverter. The ranges selected are representative of the standardized equations namely – EURO and CEC. All the locations are segregated according to five climatic zones. Weighted average efficiency co-efficient calculated for individual location that are grouped according to climatic zones are averaged. Overall weighted average inverter efficiency equation for five climatic zones was thus formulated.

Three inverters were taken as case study for this work. Modelling the inverter efficiency curve was done using measured DC and AC of power data of the power plant using Schmidt-Sauer model. The data were quality controlled prior to the modelling exercise. The overall weighted average efficiency of the inverters was calculated according the modelled equations specific to each climatic zone. The variations in the overall efficiency of the inverter for the identified climatic zones was observed by calculation of – η EURO, η CEC, Indian η EURO , Indian η CEC . Considering the overall energy produced from the power plants, measured weighted average efficiency was computed. This was cross compared with the four values computed from the modelled equations.

Relatively more accurate energy yield output of inverter could be predicted using the values obtained using the newly proposed weighted average equations and this could be of significant assistance for the solar project developers. Significant insights could be drawn related to the performance of inverters for the solar projects.

Flow Chart for the methodology carried out in this project.

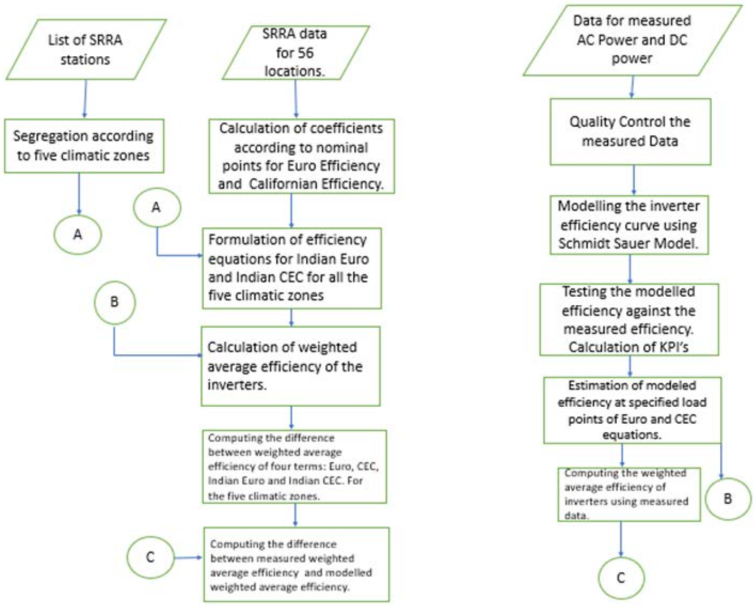


Fig. 2 Methodology carried out

## III. Formulation of $\eta$ Indian Climatic Zones

The Euro efficiency and the CEC efficiency are the representative of the inverter efficiency at Trier and Sacramento respectively These two efficiency models take into account the irradiation distribution over the whole annual sunny time and prioritize the ranges with various operating points prioritized. 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. Hence the weighted average efficiency will need to be formulated for each location taking the local irradiation profile. Area of India is 3.287 million km2 which is very large. A large and typical geographical condition make its climate conditions very different from European and Californian climate conditions. . It is possible to group the different locations of India under certain climatic zones and formulate a equation for inverter efficiency for each of them. The coefficients for equations will depend on irradiation profile of sites under each of the climatic zones. The five climate zones illustrated in the following map are cold, composite, Hot and dry, Temperate and Warm and humid.[7]

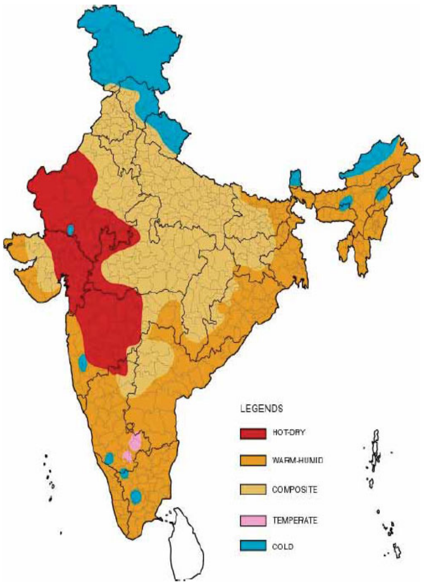


Fig. 3 Climatic Zones India[7]

## A. *CALCULATION OF WEIGHTED AVERAGE COEFFICIENTS IN INVERTER MODEL*

The application of the weighted inverter efficiency has given these weighting factors a significant edge for inverter marketing and design purposes.The weighted average efficiency of inverters can be represented mathematically as

$$\eta wt = \sum_{i=1}^{n} ai \ * \eta i \qquad (1)$$

Where,

ai is the weighting co-efficient corresponding to the ith input power level,
ηi is the efficiency of the inverter at the ith input power level
ηWT is the weighted average inverter efficiency.
The weighting co-efficient for a particular DC input power level of the inverter is derived from the below equation

$$ai = \frac{\sum energy\ yield\ within\ the\ range\ considered}{total\ energy\ yield\ over\ the\ time\ frame\ considered}$$

**(1)**

The coefficients 'weigh' the importance of inverter output efficiency at different efficiency levels. Weighted factors used for Euro and CEC are represented in Table 1.

| % NOMINAL ($P_{AW}/P_{STC}$ , NOMINAL POINTS | 5% | 10% | 20% | 30% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|---|
| EURO | 0.03 | 0.06 | 0.13 | 0.10 | 0.48 | | 0.2 |
| CEC | | 0.04 | 0.05 | 0.12 | 0.21 | 0.53 | 0.05 |

Table 1. Coefficient value for different nominal points for Euro and Californian Efficiency.[6]

**Euro Efficiency** =0.03 x η5% + 0.06 x η10% + 0.13 x η20% + 0.1 x η30% + 0.48 x η50% + 0.2 x η100%.

(2)[1]

**CEC Efficiency** = 0.04 x η10% + 0.05 x η20% + 0.12 x η30% + 0.21 x η50% + 0.53 x η75%. + 0.05 x η100%.

(3)[1]

Indian climate conditions are very different from Europe and California, though India itself is not having same climate conditions throughout the country. New weighted factors for efficiency calculation as per irradiation profile in Indian is thus proposed where five climatic zones are selected as all regions have different irradiation profile. Weightages are calculated for all the climatic zones mentioned with suffixed name as Indian Euro and Indian CEC as the same % loading described for Euro and CEC is considered.
Formula for utilizing above mentioned weightage to calculate the overall efficiency

Indian_Euro Weighted average efficiency

= a1*η5% +a2*η10% +a3*η20% +a4*η30% +a5*η50% +a6*η100% (4)[8]

Indian_CEC Weighted average efficiency

= a1*η10% +a2*η20% +a3*η30% +a4*η50% +a5*η75% +a6*η100% (5)[8]

Here: a1, a2, a3, a4, a5, a6 are weighted coefficient factors which are to be calculated for different Indian climatic zones specified according to above mentioned formulae. The weighted average efficiency of the inverters considered was calculated according to equation (5) and (6) and compared with the values of Euro and CEC efficiency calculated for all the climatic zones considered.

## B. *MODELLING OF INVERTER EFFICIENCY*

Measured instantaneous power plant data is taken from power plant located in Rajasthan 10MW – six months data and Tamil Nadu 1.25MW – One month data is considered for validation. AC and DC power data from the inverter is passed through stringent quality control algorithms. Using Schmidt Sauer model, the inverter efficiency curve is modelled from the data. The efficiency of an inverter, which determines how much of the DC power generated by a solar array is converted to AC power, is generally not a fixed value. Instead, this parameter varies with input DC power and voltage, and the amount of variation is specific to the inverter.

η =PAC/PDC = (PDC - PLoss) /PDC. (6)[l2]
the parameters ploss and pac are normalized with rated DC power.

Ploss = Pself + vloss* PAC + rloss *$\mathbf{P^2}$AC. (7)[12]

The parameters "ploss", "vloss" and "rloss" are computed by passing the input data in the above equation. Once the parameters are computed, the equation below gives us the values of modelled efficiency.

$$\eta^* = -\frac{1+v^*_{loss}}{2\cdot r^*_{loss}\cdot p_{in}} + \sqrt{\frac{(1+v^*_{loss})^2}{(2\cdot r^*_{loss}\cdot p_{in})^2} + \frac{p_{in}-p^*_{self}}{r^*_{loss}\cdot p^2_{in}}}$$

**(8)[12]**

In the above equation, Pin==PDC, Pout==PAC.[12]

From this inverter efficiency curve model we obtain the value of efficiency of inverter at different %nominal points.

### *C. Overall Weighted Average efficiency estimation*

The overall weighted average efficiency is calculated according to equation (5) and equation (6). The coefficients are computed to equations mentioned in section A. The inverter efficiency values at specified load points are taken according to equations prescribed in section B. The modelled overall weighted average efficiency is subsequently compared with the measured weighted average efficiency.

## IV. RESULTS

Performance of SPV power plants depends on the site . The new weighting factors to formulate Indian efficiency based on irradiation distribution similar as European and Californian efficiency which is suitable to Indian climatic conditions is proposed . In the following, the coefficients for European eta and Californian Eta for Indian climatic zones are represented:

### *A. Co-efficients for each climatic zone*

The coefficients for different sites for each climatic zone was computed for the equations of Indian European Eta and Indian Californian eta. The corresponding terms in the equation are averaged for all the sites under each climatic zone.

| | % NOMINAL (PMPP/PSTC , NOMINAL POINTS) -- Euro | | | | | |
|---|---|---|---|---|---|---|
| Climatic zones India | 5% ( a1) | 10% ( a2) | 20% ( a3) | 30% ( a4) | 50% ( a5) | 100% ( a6) |
| Cold | 0.0369 | 0.0684 | 0.1171 | 0.2028 | 0.3839 | 0.1903 |
| Composite | 0.0558 | 0.0447 | 0.0779 | 0.1312 | 0.4859 | 0.2012 |
| Hot and dry | 0.0153 | 0.0290 | 0.0501 | 0.1201 | 0.5149 | 0.2703 |
| Temperate | 0.0161 | 0.0319 | 0.0615 | 0.1388 | 0.5132 | 0.2382 |
| Warm and humid | 0.0147 | 0.0295 | 0.0547 | 0.1308 | 0.4785 | 0.2914 |

Table 2- Coefficient values for weighted average efficiency equation – Indain_Euro

| | % NOMINAL (PMPP/PSTC , NOMINAL POINTS) -- CEC | | | | | |
|---|---|---|---|---|---|---|
| Climatic zones India | 10% (a1) | 20% (a2) | 30% (a3) | 50% (a4) | 75% (a5) | 100% (a6) |
| Cold | 0.1053 | 0.1171 | 0.2028 | 0.2723 | 0.2053 | 0.0964 |
| Composite | 0.1004 | 0.0779 | 0.1312 | 0.3125 | 0.3145 | 0.0630 |
| Hot and dry | 0.0443 | 0.0501 | 0.1201 | 0.3052 | 0.3877 | 0.0921 |
| Temperate | 0.0481 | 0.0615 | 0.1388 | 0.3174 | 0.3533 | 0.0805 |
| Warm and humid | 0.0443 | 0.0547 | 0.1308 | 0.2763 | 0.4091 | 0.0844 |

Table 3 Coefficient values for weighted average efficiency equation – Indain_CEC

### *B. Modeling of inverter efficiency*

From this inverter efficiency curve model we obtain the value of efficiency of inverter at different %nominal points.

*1) 10MW Power plant in Rajasthan*

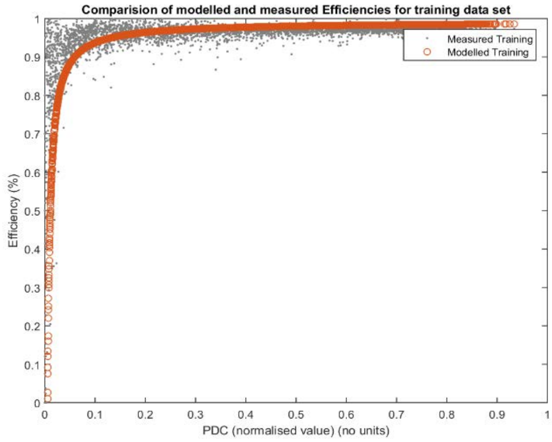


Figure 4 Efficiency plot for dataset

| % NOMINAL ($P_{MPP}/P_{STC}$ , NOMINAL POINTS | 5% | 10% | 20% | 30% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|---|
| ηEURO | 0.88 | 0.93 | 0.96 | 0.97 | 0.98 | | 0.99 |
| ηCEC | | 0.93 | 0.96 | 0.97 | 0.98 | 0.984 | 0.986 |

Table 4 Modelled efficiency of inverter at different input power level

*2) 1.25 MW power plant in Tamil Nadu*

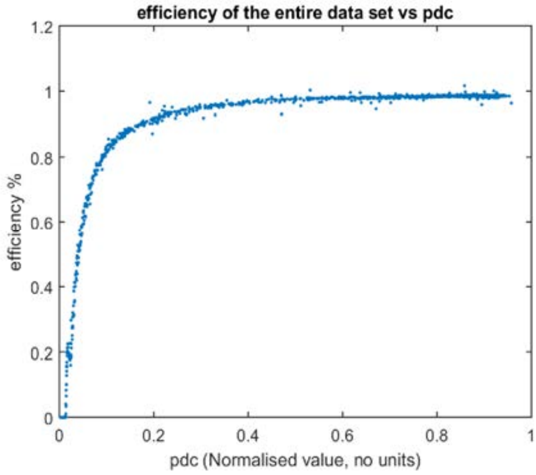


Figure 5 Efficiency plot for data set

| % NOMINAL (PMPP/PSTC , NOMINAL POINTS | 5% | 10% | 20% | 30% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|---|
| ηEURO | 0.82 | 0.90 | 0.94 | 0.96 | 0.97 | | 0.98 |
| ηCEC | | 0.90 | 0.94 | 0.96 | 0.97 | 0.98 | 0.985 |

Table 5 Modelled efficiency of inverter at different input power level

### *C. Overall efficiency of inverter computed for different climatic zones.*

The overall efficiency of the inverter computed for different climatic zones is represented below along with the actual measured weighted average efficiency for validation. The measured DC Energy and AC Energy of the plant was used for this purpose. The overall weighted average efficiency is calculated according to equation (5) and equation (6).

*1) 10MW power plant in Rajasthan*

| Climatic Zones | ηCEC (%) | ηIndian_CEC (%) |
|---|---|---|
| Cold | 97.32 | 97.07 |
| Composite | 97.32 | 97.16 |
| Hot and dry | 97.32 | 97.71 |
| Temperate | 97.32 | 97.64 |
| Warm and Humid | 97.32 | 97.71 |

Table 6 Overall Indian_Euro Efficiency

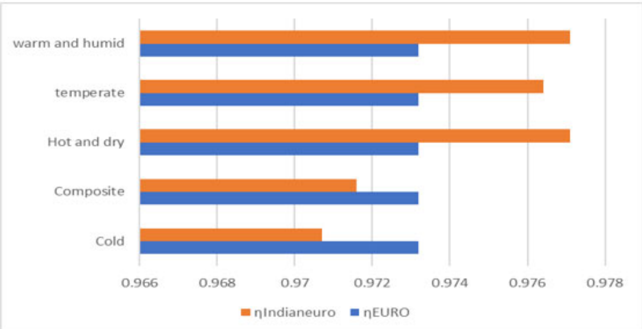


Figure 6 Comparison of weighted average efficiency(EURO) for 10MW Inverter

| Climatic Zones | ηCEC (%) | ηIndian_CEC (%) |
|---|---|---|
| Cold | 97.93 | 97.3 |
| Composite | 97.93 | 97.49 |
| Hot and dry | 97.93 | 97.82 |
| Temperate | 97.93 | 97.76 |
| Warm and Humid | 97.93 | 97.82 |

Table 7 Overall Indian_CEC efficiency

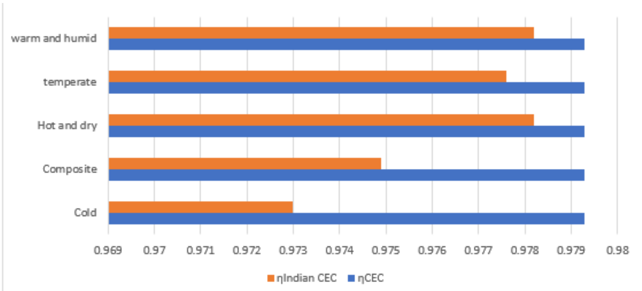


Figure 7 Comparison of weighted average efficiency(CEC) for 10MW inverter

*2) 1.25 MW Power plant in Tamil Nadu*

| Climatic Zones | ηCEC (%) | ηIndian_CEC (%) |
|---|---|---|
| Cold | 94.64 | 94.05 |
| Composite | 94.64 | 94.12 |
| Hot and dry | 94.64 | 96.2 |
| Temperate | 94.64 | 95.97 |
| Warm and Humid | 94.64 | 96.17 |

Table 8 Overall Indian_Euro efficiency

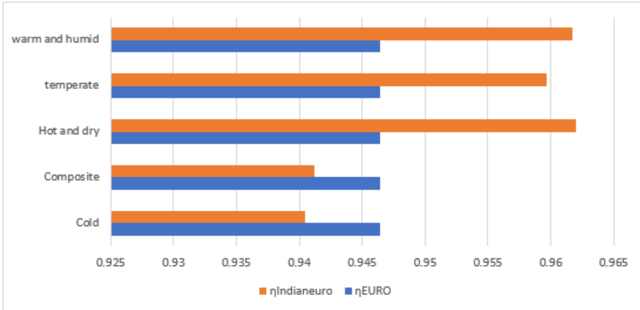


Figure 8 Comparison of weighted average efficiency (euro) for 10 MW inverter

| Climatic Zones | ηCEC (%) | ηIndian_CEC (%) |
|---|---|---|
| Cold | 96.87 | 95.03 |
| Composite | 96.87 | 95.62 |
| Hot and dry | 96.87 | 96.69 |
| Temperate | 96.87 | 96.48 |
| Warm and Humid | 96.87 | 96.65 |

Table 9 Overall Indain_CEC efficiency

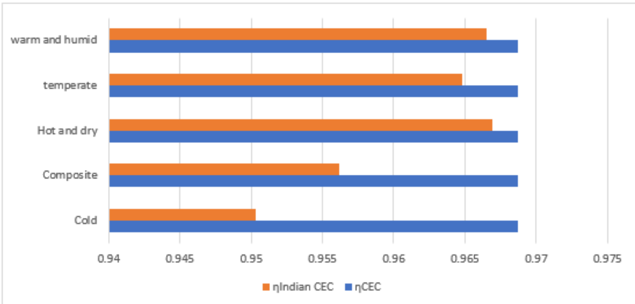


Figure 9 Comparison of weighted average efficiency for (CEC) 10MW inverter

## V. Conclusion

Newly formulated weighing coefficient factors is proposed for estimation of PV inverter's weighted average efficiency for respective climatic zones will help Indian project developers for selection of a profitable inverter based on performance of inverters. Also, it will help in more accurate prediction of yearly output of inverter. Overall Efficiency of PV Inverter for Indian climatic zones obtained from proposed weighting factors after validation shows that Indian_CEC are providing more reliable and accurate results whereas Euro efficiency values are far away from actual observed efficiency. From the results section, it can inferred that :

1) *Value of the **euro efficiency** is seen to deviate in the range:*

**Rajasthan plant**

0.2% to 0.3% from the value calculated using location specific irradiation profile.

**Tamil Nadu plant**

-0.6% to 1.5% from the value calculated using location specific irradiation profile.

2) *Value of the **CEC efficiency** is seen to deviate:*

**Rajasthan plant**
-0.5% to 1.56% from the value calculated using location specific irradiation profile.
**Tamil Nadu plant**
-2% to -0.18% from the value calculated using location specific irradiation profile.

A conclusion can be made that because of not using location specific equation for determining the efficiency it leads to underestimating or overestimating the performance of the inverter in that location. The weighted average efficiency formulated for Indian climatic zones will prove to be more accurate compared to the euro and CEC standardized equations. A more reliable figure that can be used by project developers for doing so is the proposed weighted average efficiency has been formulated specifically for Indian climatic zones. Informed decisions could be taken on the estimated energy yield from the solar PV power plants. Therefore, from this study, significant insights could be drawn related to performance of inverters in different locations in India considering site-specific irradiation profile.

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