International Journal of Applied Power Engineering (IJAPE)
Vol. 14, No. 3, September 2025, pp. 761~768
ISSN: 2252-8792, DOI: 10.11591/ijape.v14.i3.pp761-768

OFF-grid efficiency evaluation of an inverter dependent on solar PV generator in Iraq

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Article Info

Article history:

Received Sep 14, 2024
Revised Jun 29, 2025
Accepted Aug 3, 2025

Keywords:

Energy yield
Irradiance-duration curve
Metrical efficiency
PV inverter
Solar PV system

ABSTRACT

The solar photovoltaic (PV) inverter weighted efficiency is more precise and favorable as it mainly deems the inverter output power properties when exposed to disparate solar PV irradiance. The European metrical efficiency (η_{EURO}), presently, is the bulk broadly admissible in inverter efficiency calculation. This is due to, historically, the European countries have been the biggest exporters and spent of solar PV inverters everywhere in the world. The European efficiency (η_{EURO}) is a concluded metric relying on a standardized European irradiance profile. However, the rendition weightings embedded in this metric may not be fully representative or appropriate for photovoltaic inverters deployed in regions characterized by different climatic conditions, particularly in equatorial and subtropical environments. Accordingly, this study aims to validate the proposed assumption and develop a novel metrical efficiency equation for inverters operating in the Iraqi climate, specifically Baghdad city, relying on the IEC 61683:1999 criterion and the inverter load-duration curve. The proposed formula, validated with field data from an SMA-SB-4000-TL inverter, estimated the energy outcome of a 5.0 kW off-grid SPV system in Baghdad with a 2% deviation from measured values. These results validate the use of η_EURO tailored to Baghdad conditions as a reliable alternative to η_{EURO} or η_{MAX}. This enhances the accuracy of system energy yield estimation, investment return calculations, and payback period assessment for solar PV systems.

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1. INTRODUCTION

Before the erection of the solar photovoltaic (SPV) system, the designer executes a site scan to appreciate the suitability of the site position for system construction. Subsequently, the designer delivers an energy outcome η_{sys} decision to the customer, facilitating the evaluation of payback time, investment returns, and the overall financial viability of the photovoltaic (PV) system. In estimating η_{sys}, inverter efficiency is a critical parameter. However, many solar PV system designers rely on the inverter's maximum efficiency from the datasheet, which may not reflect actual operating conditions. The inverter's maximum efficiency η_{MAX} is achieved under standard test conditions (STC), defined as 1000 W/m² irradiance and 25 °C temperature. However, solar PV systems seldom operate under such ideal conditions in real-world settings [1]-[3].

Alternatively, metrical inverter efficiencies, such as the European η_{EURO} and the California Energy Commission η_{CEC} values can be used to estimate the system energy outcome. These metrics account for the fact that inverters typically operate under variable irradiance and temperature conditions throughout the year, rather than under STC. The inverter efficiency rating is adjusted to account for variations in operating conditions. Inverter efficiency is influenced by constant losses (primarily from control circuitry) and variable losses associated with load fluctuations. Therefore, metrical efficiency better reflects the inverter's actual rendition across varying load conditions [4].

Because metrical efficiency is climate-dependent, using it under dissimilar meteorological conditions can compromise the accuracy of η_{sys} speculation. An inverter powered in Europe will not give the same power output if it is erected in the equatorial or subtropical area due to the irradiance profile and temperature between the two areas being different. To date, most solar PV system providers continue to use η_{EURO} and η_{MAX} as benchmarks for efficiency assessment. However, with the fast expansion of solar PV installations in subtropical regions like Iraq, there is a growing required for more accurate speculation of system energy outcomes.

The study aims to first show the inaccuracy of using η_{MAX} and η_{EURO} for solar PV systems in Iraq's subtropical climate, and secondly, propose a Baghdad-specific metrical efficiency model depending on the IEC 61683:1999 standard. A 1-year irradiance dataset from a local weather station is collected and utilized as input to the PV array feeding the tested inverter to achieve these aims. Input DC and output AC powers of the inverter, connected to the load, are monitored under defined operating conditions. Using these data, the metrical efficiency of the SMA-4000-SB-TL inverter is calculated and compared with the efficiency values provided in the manufacturer's datasheet. To validate the accuracy of the Baghdad metrical efficiency η_{BAG}, the concluded expression was employed to estimate the annual energy yield η_{SYS} and compared against estimates based on η_{EURO} and η_{MAX}. These three estimations were evaluated against actual measurements for a 5 kW inverter-based solar PV system.

2. METRIC EFFICIENCY OF SOLAR PV INVERTERS

The solar PV inverter constitutes a fundamental and critical component of the photovoltaic system, given the system's extended lifecycle exceeding 25 years. Inverter efficiency directly affects system output, enabling estimation of the system energy outcome η_{SYS} in kWh as (1) [1], [2].

$$E_{sys} = P_{panels} \,.\, PSH \,.\, f_{mm} . f_{temp} . f_{dirt} . \eta_{cable} . \eta_{inv} \quad (1)$$

P_{panels} is the rated PV module power; the peak sun hours (PSH) for the specified period. The term f_{mm} represents the manufacturer-provided mismatch coefficient, while f_{temp} accounts for energy losses due to elevated module temperatures. f_{dirt} reflects the losses caused by dust and dirt accumulation on the module surface. η_{cable} indicates the efficiency of the DC cabling connecting the PV modules to the inverter. The final term, η_{inv} represents the inverter efficiency, defined as the ratio of AC output power to DC input power. In particular, an inverter with 1% lower efficiency is often considered approximately 10% less expensive [5]. A maximum power point tracker (MPPT) continuously tracks the peak of the solar panel P–V characteristic curve, thereby maximizing the power delivered to the inverter under varying irradiance and temperature conditions. Accessibly E_{sys} speculations, designers often assume η_{inv} to be equal to η_{max} or η_{EURO}.

Optimizes and EURO-metrical efficiency are typically provided in the inverter datasheet, based on measurements under STC. However, relying on these values is often impractical, as inverters seldom operate under STC in real-world conditions, leading to inaccurate estimations of energy yield, payback period, and return on investment. Weighted efficiency accounts for inverter performance under varying climatic conditions and irradiance profiles. Given the direct relationship between irradiance and inverter input power—and the dependence of inverter efficiency on operating power levels—weighted efficiency provides a more accurate representation of real-world inverter rendition.

3. DEVELOPMENT OF THE METRICAL EFFICIENCY MODEL

Following to IEC 61683:1999 criterion, the inverter metrical efficiency is calculated using standardized procedures [4]. This standard requires the use of a PV simulator to derive the weighted efficiency equation. The emulator output is emulated as the output of the truest PV array panels linked to the inverter to be tested. The simulation uses an averaged one-day irradiance profile derived from one year of data. Input and output inverter power are monitored at a steady panel temperature of 25 °C, with irradiance fluctuations simulating various environmental scenarios [6].

The metrical average energy efficiency η_{wt} of an inverter depends on its mode of operation. For grid-connected systems without storage, η_{wt} is calculated using the irradiance-duration curve, as power flow to the grid is continuous and bidirectional. In contrast, for stand-alone or off-grid systems with storage,

η_{wt} is determined based on the load power-duration curve, accounting for energy stabilization through batteries and associated losses in both the inverter and storage subsystem.

In the actuation of the inverter in a stand-alone solar PV system, the input DC power generated from the solar PV system is transformed into organized DC power to feed the DC loads or converted into constant AC voltage and frequency to feed the AC loads. In this case, the η_{WT} needs metrical coefficients for respective load classes. By using a load-duration curve, T_i as a duration time, P_{dci} as DC input power, P_{oaci} as AC output power of the inverter, and η_i as inverter efficiency for private load class (i). The inverter metrical efficiency is given as (2)-(6) [4].

$$\eta_{MT} = \frac{\sum P_{oaci} \cdot T_i}{\sum P_{dci} \cdot T_i} \quad (2)$$

$$\text{Or } \eta_{MT} = 1/[K_o + K_1/\eta_1 + K_2/\eta_2 + \cdots + K_n/\eta_n] \quad (3)$$

$$K_o = \frac{P_{n\ell} \cdot T_o}{\sum_{i=1}^{n} P_{oaci} \cdot T_i} \quad (4)$$

$$K_i = \frac{i\, T_i}{T_{MT}} \quad (5)$$

$$T_{MT} = 1.T_1 + 2.T_2 + 3.T_3 + \cdots + n.T_n \quad (6)$$

Where K_o is the metrical factor at the no-load operation of the inverter, T_o is the duration time at which the inverter actuated at no load, K_i is the metrical coefficient for each load class of operation (i), (n) is the number of inverter load classes, η_i is the efficiency of the inverter when its load level is i^{th} a percentage of its rated value, and $P_{n\ell}$ is the no-load inverter wasted power. If the load-duration profile is constructed for one year of data as shown in Figure 1, the (3) of stand-alone operation can be utilized.

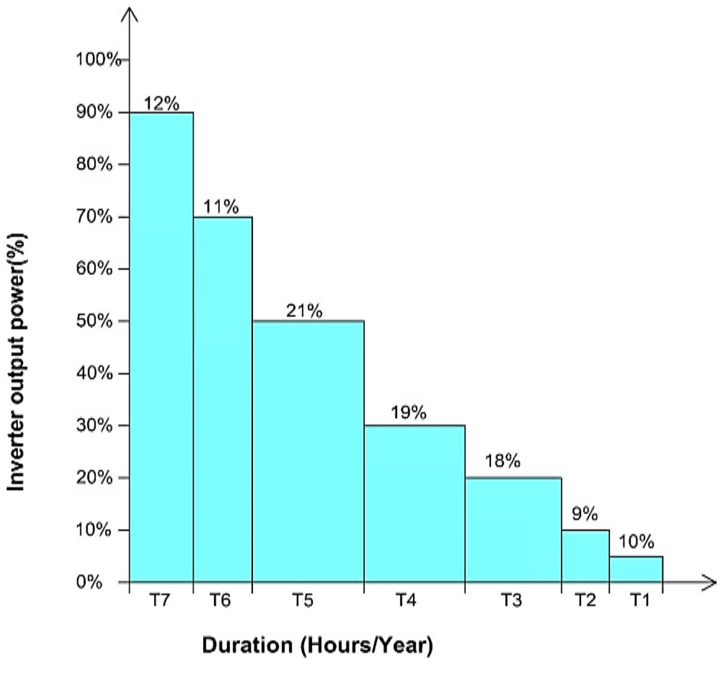

Figure 1. Yearly inverter output power-duration curve

4. EXAMINATION OF INVERTER METRICAL EFFICIENCY

Among existing metrics, η_{EURO} is the most frequently applied for speculating the energy output of solar PV systems. Tailored to the irradiance conditions typical of Europe, this metric is defined by (7) [7].

$$\eta_{EURO} = 0.03 * \eta_{5\%} + 0.06 * \eta_{10\%} + 0.13 * \eta_{20\%} + 0.1 * \eta_{30\%} + 0.48 * \eta_{50\%} + 0.2 * \eta_{100\%} \quad (7)$$

The η_{EURO} is discriminated by six classes of actuation: 5%, 10%, 20%, 30%, 50%, and 100%. The scale of inverter output power / rated output power ($P_{oaci}/P_{oaci} - (rated)$), which formalizes the class of operation is shown in Table 1.

Table 1. The scale of P_{oaci} / $P_{oaci} - (rated)$ and metrical factor for each level of operation

Class of operation (%)	Scale of $P_{oaci}/P_{oaci} - (rated)$ (%)	Metric factor
5	0 → 7.5	0.03
10	> 7.5 → 15	0.06
20	> 15 → 25	0.13
30	> 25 → 40	0.10
50	> 40 → 75	0.48
100	> 75	0.2

The 50% load class carries the highest metrical factor (0.48), suggesting that the inverter spends about 50% of its runtime operating at half load. Also, the inverter metric efficiency η_{CYC} [8], established by the California Energy Commission, is widely recognized for assessing rendition in regions with elevated irradiance levels [7]. Analogous to η_{EURO} it has six classes of operation, and each class imposes various premiums of metrical factors as (8).

$$\eta_{CEC} = 0.04.\eta_{10\%} + 0.05.\eta_{20\%} + 0.12.\eta_{30\%} + 0.21.\eta_{50\%} + 0.53.\eta_{75\%} + 0.05.\eta_{100\%} \tag{8}$$

By comparing (7) and (8), the η_{CEC} is further refined based on the inverter's efficiency across different irradiance classes. Besides η_{EURO} and η_{CEC}, other metric efficiency formulations have been developed to reflect specific local climatic conditions, such as the Izmir efficiency η_{IZM} for Turkey [9], [10], Chennai metric efficiency (η_{CHE}) in India [11], Kanpur metric efficiency (η_{KAN}) in India [12]-[14], Brazilian cities metric efficiency [15], [16], and equatorial metric efficiency (η_{EQUA}) [17]. Unfortunately, these metric efficiency calculation methods not fully comply with the IEC 61683:1999, which requires efficiency determination based on solar PV-generated power supplied by the site-specific irradiance profile at a fixed temperature to the emulator. In contrast, the referenced approaches used varying irradiance and temperature conditions, and the irradiance was measured on a horizontal plane rather than in a plane, thus deviating from the IEC 61683 standard requirements [4].

5. FORMULATION OF INVERTER METRIC EFFICIENCY FOR BAGHDAD CITY

Baghdad, situated in the southwestern region of Asia, lies at a latitude of 33°13′N, a longitude of 44°13′E, and an elevation of 34 meters above sea level. According to the Köppen–Geiger climate classification system [10], Baghdad's climate is classified as 'BWH' under the Köppen–Geiger system, indicating a hot, dry subtropical desert environment. It is reasonable to anticipate that the actual rendition of solar PV inverter systems powering in such subtropical climates may differ significantly from those installed in other climatic zones.

This study aims to show that η_{max} and η_{EURO} from datasheets are inadequate for speculating the energy outcome of inverters outside European and equatorial climates. Accordingly, a novel metric efficiency formula for solar PV inverters in subtropical climates (specifically Baghdad) is developed. To get this target: i) add 1-year inverter output power data from a running solar PV inverter type SMA-4000-SB-TL with daily load profile data as shown in Figure 2, ii) gauging the contribution of power of the inverter to draw the inverter efficiency according to the output power levels (P_{oaci}) as shown in Figure 3, and iii) paraphrasing the stand-alone Baghdad metric efficiency (η_{BAG}) according to the IEC61683:1999 standard, however, the inverter output power in place of irradiance classes is grouped by seven levels of operation according to the inverter load duration for one-year measured data as shown in Figure 1.

The metrical factor for each level is found in Figure 1 using (5) for $K_1 \rightarrow K_7$, and the factor K_o is first determined using (4), followed by the calculation of the inverter's stand-alone weighted efficiency via (3), as shown in Table 2. From Table 2, due to some of the generated power being wasted as losses in the inverter and batteries the inverter η_{BAG} is 87.4% while from the datasheet η_{max} is 98% and η_{EURO} is 97.5%. Inverter 1% less efficient is concluded to be 10% undersold relative to other inverters. To verify η_{BAG}, the annual system energy outcome η_{SYS} obtained from measured data was compared with the corresponding value concluded from the formulated (1) using η_{BAG}, η_{max}, and η_{EURO}, to show the difference between these calculations with the feasible metering.

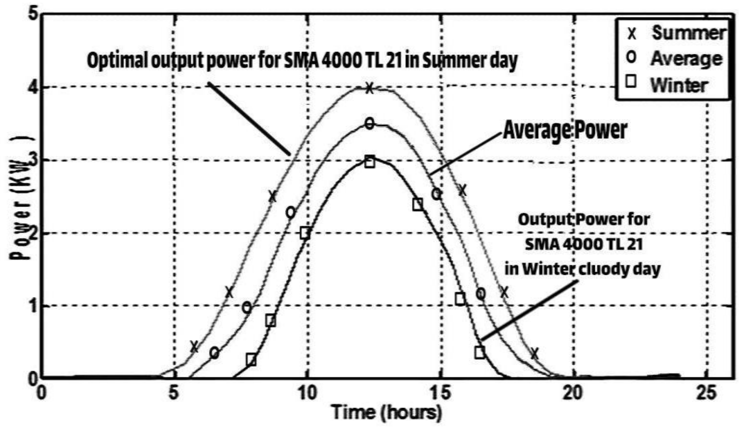

Figure 2. Daily output power of inverter type SMA- 4000- SB- TL- 21

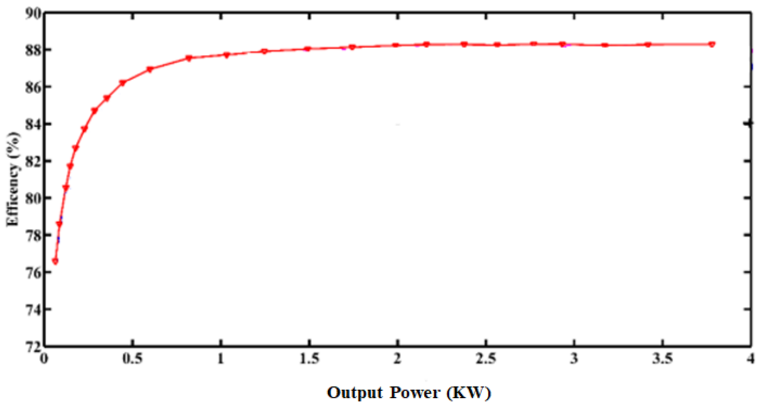

Figure 3. SMA- 4000- SB- TL- 21 Inverter output power versus efficiency

Table 2. Stand-alone inverter metric efficiency

Inverter output power (%)	Inverter efficiency (%)	Stand-alone metric factor (Ki)	Stand-alone inverter metric efficiency (%)
0.0	0.0	K0 = 0.0045	0.0
5	75	K1 = 0.0237	1.78
10	82	K2 = 0.0459	3.76
20	86	K3 = 0.1290	11.1
30	87.5	K4 = 0.1836	16.06
50	88.0	K5 = 0.2600	22.88
70	88.5	K6 = 0.1570	13.89
90	89	K7 = 0.2008	17.87
	Total metric efficiency		87.4

6. RESULTS ASSERTION

Due to the temperature seldom being fixed through the system operation [18]-[25], and the metric efficiency being obtained at a fixed temperature, the operable approach to asserting the result of Baghdad metric efficiency (η_{BAG}) by comparing the yearly metered energy outcome (E_{sys}) taped during the year 2022, as shown in Figure 4, to the determined energy outcome using η_{BAG}, η_{max}, and η_{EURO} in (1).

To compute the E_{sys}, the sun hours in one year are (3380) [18], P_{panels} at 5.0 kW, f_{temp} at 98%, f_{mm} at 96%, f_{dirt} at 97%, and η_{cable} at 98%. These made the accretion of errors less than 0.6% and these values are investigated in [1]. The η_{inv} is different using either η_{BAG}, η_{max}, or η_{EURO}. Table 3 shows the results of the three accounted energy outcomes using (1), Table 2, and the inverter datasheet. By comparison with the metered energy, it is clear that η_{BAG} is the better selection to symbolize the inverter efficiency, with only a 2% difference between determined and metered premiums. The truest solar PV system is a 5 kW roof-top stand-alone linked system to the SMA-4000-SB-TL inverter.

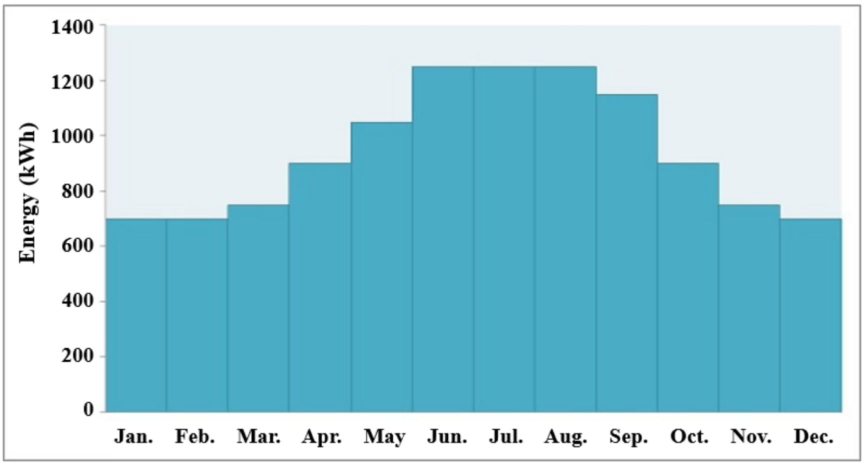

Figure 4. Yearly energy (kWh) produced by SMA-4000- TL inverter

Table 3. Outcomes of E_{sys} with different solar PV inverter efficiencies

Efficiency type	Efficiency value η_{inv} (%)	E_{sys} calculated kWh	E_{sys} measured kWh	E_{sys} difference kWh	E_{sys} difference (%)
η_{BAG}	87.4	11090	11350	260	2%
η_{max}	97.0	12147	11350	797	7%
η_{EURO}	96.4	12071	11350	721	6%

7. CONCLUSION

Since each climatic region has a distinct irradiance profile, the weighted efficiency of an SPV inverter is influenced by the solar irradiance-duration curve. Accordingly, the Baghdad metric efficiency η_{BAG} was concluded, depended on the IEC 61683:1999 standard to better represent the inverter rendition in subtropical climates. Validation was performed by comparing the calculated energy outcome $\eta_{sys}cal$ using η_{BAG} with the measured annual energy yield $\eta_{sys}\,mean$ from a stand-alone SMA-4000-SB-TL inverter system. The findings demonstrated that $\eta_{sys}cal$ depended on η_{BAG} closely corresponded to the actual system output, outperforming speculations depending on η_{MAX} or η_{EURO} from the inverter datasheet. This confirms that utilizing η_{BAG} for energy outcome determinations, provide a more accurate prediction of system rendition, enabling precise determination of payback period and return on investment for solar PV system owners.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Bilal Abdullah Nasir	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Kutaiba Khalaf Khaleel		✓				✓		✓	✓	✓	✓	✓		
Mohammed Ahmed Khalaf	✓		✓	✓			✓			✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data supporting the findings of this study are available within the article.

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