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Rooftop photovoltaic systems. New parameters for the performance analysis from monitored data based on IEC 61724

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A B S T R A C T

Rooftops Photovoltaic systems present a feasible choice to mitigate the adverse effects of electricity costs and climate crisis. Different parameters have been defined to analyse this type of systems from monitored data. However, they only focus on the matching capability between the load and AC generation profiles together with the utility grid usage. Therefore, they do not consider the performance of the PV generator and the rest of components of the photovoltaic system. Moreover, although IEC-61724 standard defines common criteria to assess the performance of photovoltaic systems, this standard does not consider calculated parameters and yields adapted to the idiosyncrasy of Rooftops Photovoltaic systems. Thus, in this paper it will be provided new calculated parameters and yields (i.e. a self-consumption yield and a to grid yield) and performance ratios (i.e. self-consumption Performance Ratio together with a to grid Performance Ratio) which combine self-consumption with system performance providing a proper analysis from monitored data. Moreover, they may facilitate comparisons between installations with different array power. These new parameters may not only help to ensure that design objectives have been achieved but they may better assess the potential of this technology which are key issues for the deployment of this type of facilities.

1. Introduction

Energy constitutes a key issue to overcoming the climate crisis. According to the Intergovernmental Panel on Climate Change (IPCC) [1], about two-thirds of global greenhouse gas emissions are carbon dioxide from the burning of fossil fuels and other industrial processes. As a result, an urgent and large-scale transition to renewable energy sources are paramount to achieve the goals of the Paris Agreement [2] and to reduce greenhouse gas emissions. Global Renewable Energy Outlook by Renewable Energy Association (REA) [3] provides an ambitious, yet technically and economically feasible pathway for deploying low-carbon technologies to create a clean, sustainable energy future and reaching net zero emissions by 2060. Moreover, Europe may halve the consumption of depleted natural resources in the electricity sector and increase energy independence by 2030 if it rapidly increases its renewable capacity [4]. This approach is extremely important given the recent events in Ukraine [5].

Cost declines in wind, solar photovoltaics (PV) and battery technologies have profoundly impacted the rate of deployment of renewables in power systems and at least nine countries produced more than 20% of their electricity from variable renewable energy sources in 2020 as reported by Renewable Energy Policy Network for the 21st Century (REN21) [6]. Moreover, the electrical energy generation through renewable energies grew 8% in 2021, where solar PV and wind energies represented two-thirds of that growth [7].

Solar energy may be considered as the most important source of renewable energy to achieve the established objectives of electricity consumption. The report of International Energy Agency (IEA) in 2022 shows how global cumulative solar PV capacity additions expanded to 151 GW, with a forecast of 370 GW in 2030 and 600 GW in 2050 [8]. In November 2022, the solar photovoltaic capacity in Spain reached a total figure of 18.165 MW, which is approximately equivalent to 15.5% of total capacity and close to 10.66 % of renewable electricity energy generated in 2022 [9]. Of these figures, more than 2700 MW of photovoltaic capacity in Spain correspond to photovoltaic self-consumption systems, also called Rooftop Solar Photovoltaic systems (Rooftop PVs) [10]. It must be highlighted that Germany is one of the top 10 Rooftop PV solar market, with about 3.2 GW of new capacity added. In Germany, Rooftop PV capacity installed was 6 GW in 2021, a 23% growth compared to 2020. In Netherlands a 3.6 GW of Rooftop PV capacity was added in 2021 [10].

Self-consumption can be defined as the share of the total PV production used to face the load consumption. Among the existing

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Nomenclature

Abbreviations

REA	Renewable Energy Association
REN21	Renewable Energy Policy Network for the 21st Century
IEA	International Energy Agency
PV	Photovoltaic
PR	Performance ratio
SCR	Self-consumption ratio
SSR	Self-sufficiency ratio
DAS	Data acquisition system
STC	Standard Test Conditions
TRC	Target reference conditions
IEC	International Electrotechnical Commission
AEI	Agencia Estatal de Investigación
PWM	Pulse width modulation
CUF	Capacity utilization factor
SAPV	Standalone photovoltaic systems
IPCC	Intergovernmental panel on climate change

Symbols

φ_{SC}	Self-consumption index
φ_{SS}	Self-sufficiency index
P_{MPP}	Maximum power point power
V_{MPP}	Maximum power point voltage
I_{MPP}	Maximum power point current
V_{OC}	Open circuit voltage
I_{SC}	Short circuit current
E_A	Array energy
E_L	Load energy
E_{out}	Output energy
E_{PVSC}	Photovoltaic self-consumed energy
E_{TG}	Energy exported to the grid
PR_{TG}	To grid Performance Ratio
PR_{SC}	Self-consumption Performance Ratio
H_i	In-plane irradiation
η_{BOS}	Balance of system efficiency
Y_A	PV array energy yield
Y_f	Final system yield
Y_r	Reference yield
Y_{fPVSC}	Final self-consumption yield
$Y_{f,TG}$	Final to grid yield
L_C	Array capture loss
L_{BOS}	Balance of system loss
L_{NSC}	Non-self-consumption losses
L_{CT}	Thermal capture losses
P_{out}	Generated photovoltaic power
P_L	Load power
τ_k	Length of the k^{th} recording interval
τ	Reporting period
P_{PVSC}	Photovoltaic self-consumed power
PA	Array power
GI	In-plane irradiance

alternatives to mitigate the adverse effects of electricity costs Rooftop PVs stand out as a feasible choice [11] both in the residential and industrial sector. Due to its modularity, this type of systems covers a wide range of sizes, from residential roofs with systems of a few kW to large-area commercial and industrial roofs which may reach hundreds of kW. Rooftops PVs imply distributed generation where generation is close to consumption and provides a new scenario where energy flows allow users to become "prosumers" producing their own energy in combination with energy-storage technologies [12]. Due to steadily decreasing costs of PV installations, decentralised renewable energy production through Rooftop PV systems can significantly increase the power capacity thanks to a large number of smaller-scale installations [13]. Furthermore, the cost of self-consumed electricity from a residential Rooftop PV without batteries may be lower than the residential electricity price from the grid and may be a feasible investment to future owners of these systems [14,15]. It is estimated, taking into account statistical and satellite-based data sources, that European Union (EU) rooftops could potentially produce 680 TWh of solar electricity annually (representing 24.4% of general electricity consumption) [13]. An assessment of the potential contribution of Rooftop PVs in Spain to the future electricity balance carried out using different data sources and comparing different proportions of centralized renewables, rooftop PV and storage identified a cost-effective portfolio mix. The results showed that Spain could obtain a sustainable electricity system at a price lower than the current prices in the wholesale market [16]. A best-case scenario study where the maximum possible capacity which could be installed on the full rooftop surface available shows that the Rooftops PVs may generate almost the same (99%) as the electricity consumption in the residential sector and 37% of the total demand in the city of Valencia (Spain) [17].

Consequently, it may be very important to provide a proper performance analysis of PV Rooftops systems and their efficiency from monitored data not only to ensure that design objectives have been achieved but to assess the potential of this technology which constitute key issues for the deployment of this type of facilities. In the literature, regarding Rooftops PVs, many different parameters have been defined to analyse this type of system.

Fig. 1(a) shows the daily consumption and photovoltaic generation profiles corresponding to a 3 kWp residential Rooftop PV. As mentioned above, this power corresponds to the one obtained at the inverter output. If the instantaneous onsite PV power generation, $P_{out}(t)$, and the instantaneous building power consumption, $P_L(t)$, are considered, the photovoltaic self-consumed power, $P_{PV,SC}(t)$, can be expressed as follows [18]:

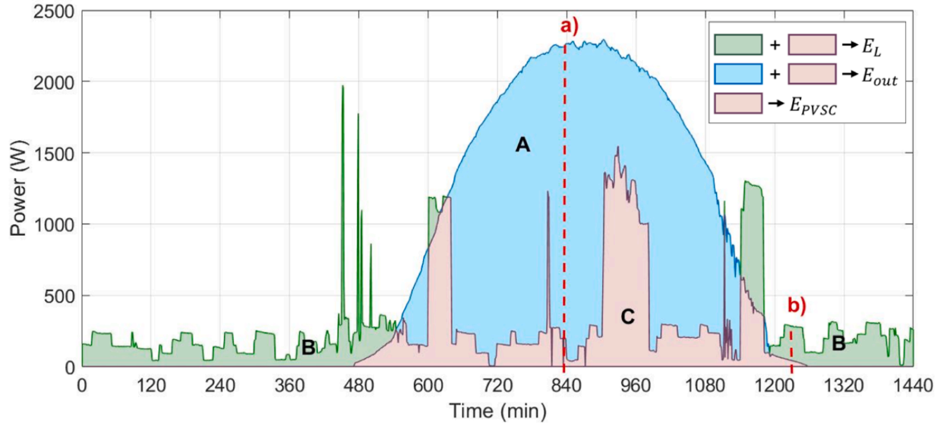
$$P_{PV,SC}(t) = \begin{cases} P_{out}, & \text{if } P_L \geq P_{out} \\ P_L, & \text{if } P_L < P_{out} \end{cases} \tag{1}$$

As can be seen in Fig. 1(a), when the generated photovoltaic power is greater than the load power the photovoltaic self-consumed power corresponds to $P_L(t)$ (a). On the other hand, when the output generation is lower than the load consumption, $P_{PV,SC}(t)$ is given by $P_{out}(t)$ (b). Moreover, $P_{PV,SC}(t)$ can also be defined as the minimum of these two values.

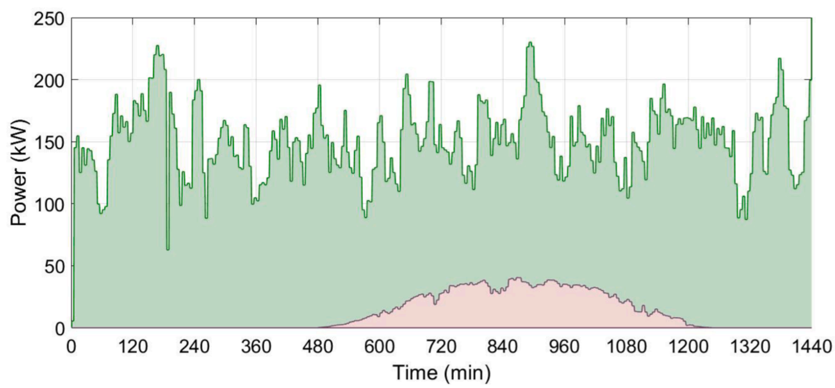
The most common indices used to estimate the photovoltaic generation selfconsumed by the producer and the degree reached by the photovoltaic generation to face the load consumption are the self-consumption and self-sufficiency indices [18]. In the literature they may be found in different although similar ways usually defined as supply cover factor and load cover factor [19,20]. In addition, self-consumption index, φ_{SC}, is defined as the quotient between the self-consumed photovoltaic energy, $E_{PV,SC}$ (Area C in Fig. 1a), and the photovoltaic generated energy, E_{out} (Areas A + C), during a determined period given by t_2-t_1, Equation (2). Area A represents the surplus of generated energy.

$$\varphi_{SC} = \frac{\int_{t1}^{t2} P_{PV,SC}(t)}{\int_{t1}^{t2} P_{out}(t)} = \frac{E_{PV,SC}}{E_{out}} = \frac{C}{C+A} \tag{2}$$

Self-sufficiency index, φ_{SS}, is defined as the fraction of self-consumed photovoltaic energy with respect to the total load consumption, E_L (Area B + C), Equation (3). Area B shows the load energy that cannot be faced instantaneously or directly by the photovoltaic system.



(a)



(b)

Fig. 1. (a) Daily load and generation profiles corresponding to a Rooftop PV installed in a dwelling. No storage system has been considered. $P_0 = 3kW_p$ [14] (b) Daily Load and photovoltaic generation profiles corresponding to a Industrial Refrigeration industry with a Rooftop PV of 52.7 kWp [21]. Both systems are located in Spain.

$$\varphi_{SS} = \frac{\int_{t1}^{t2} P_{PV,SC}(t)}{\int_{t1}^{t2} P_L(t)} = \frac{E_{PV,SC}}{E_L} = \frac{C}{C+B} \quad (3)$$

In [22] the ratio between φ_{SS} and φ_{SS} is defined to provide a graphical approach to analyze the generation and load matching both in size and in time. Moreover, as the aforementioned indices do not suggest a technical optimum for array size, the self-production index, SP, and the grid liability, G_L, are provided [23]. SP is a calculated parameter that shows the level of self-consumed energy coverage with respect to the total energy flows. Therefore, this index is calculated as the fraction $E_{PV,SC}$ between the sum of the load consumption energy and the generated energy energies E_L and E_{out}. This index may be an useful indicator as it allocates photovoltaic capacity that delivers maximum renewable utilization on-site. On the other hand, and regarding grid interaction, G_L may be an interesting indicator when trying to minimize grid usage. Moreover, the variability of the exchanged energy between the grid and the building may be estimated with the grid interaction index, f_{grid}, [19]. It is also possible to estimate the self-sufficiency index of solar hours, $\varphi_{ss,SH}$, which is calculated by dividing $E_{PV,SC}$ by the energy consumed only during solar hours, $E_{L,SH}$ [21]. The self-sufficiency index in solar hours indicates the level of energy coverage that a PV Rooftop system may provide considering exclusively the electrical consumption when the photovoltaic energy source can be active, i.e. during solar hours. Therefore, it may characterize better the photovoltaic self-consumption systems in the industrial sector taking into account, unlike the residential sector, the considerable nocturnal consumption that can occur in the former. Moreover, this index may be more suitable for energy analysis in direct self-consumption systems. Furthermore, different load match indicators which assess the matching degree between the on-site energy generation and load consumption together with the grid interaction factors in smart buildings are further described and discussed in [24].

As mentioned above, when analysing PV Rooftop systems, the literature focuses on the matching capability between the load and the generation profiles together with the interaction with the utility grid. It must be highlighted that the photovoltaic generation profile is obtained at the inverter output. Therefore, the performance of the PV generator and the rest of components of the photovoltaic system, also called Balance of system (BOS) is not considered. It is necessary to combine both the matching capability together with the grid interaction and the PV Rooftop system performance to detect anomalies which can play a fundamental role in maintaining the desired performance and meeting the design requirements and specifications [25]. Moreover, it may be very interesting to provide calculated parameters that manage the comparisons between installations with different rated array power. In order to analyse this performance from monitored data, it must be highlighted that the monitoring system must provide detailed, simple and quick information on the system performance of the installation. It is extremely important to define common criteria regarding the number of parameters to monitor, the format of the data collected and the analytical method followed to detect possible failures, evaluate the efficiency of the system and its performance through the corresponding calculated parameters, yields and indices. These ones will provide a correct decision making to carry out the necessary preventive and corrective actions on a photovoltaic system. The International Electrotechnical Commission (IEC) launched the International Standard 61724-1 [26] in 2017, which is a revision of the previous IEC 61724 that was published in 1998. However, in this standard, and actually, although the performance analysis of the PV system is defined, it is not considered any calculated parameter regarding the matching capability analysis of Rooftop PVs. Moreover, this standard does not provide calculated parameters and normalized yields adapted to the idiosyncrasy of Rooftops Photovoltaic systems.

As stated above, it is essential to manage a proper performance analysis in any photovoltaic system which may be adapted to its own characteristics and idiosyncrasy. As a result, different studies have been carried out. An analysis method is proposed using charge parameters instead of energy ones (which are those indicated in IEC 61724) to improve the performance analysis of standalone photovoltaic (SAPV) systems with pulse width modulation (PWM) charge regulators [27]. In addition, different techniques are also proposed to improve the monitoring of PWM signals in PWM charge regulators used in SAPV systems: this type of charge regulators use signals that are difficult to monitor if expensive monitoring equipment is not available which it is very common in this type of systems [28,29,30]. Likewise, new calculated parameters have also been developed based on monitored data adapted to the IEC 61724 standard and aimed at photovoltaic concentration systems [31]. Moreover, other parameters have been used together with the ones defined by the standard to enhance the performance analysis from monitored data in grid connected systems. Further information may be gathered considering thermal capture losses, L_{CT}, which are a type of capture losses due to module temperature [32]. Another calculated parameter, not defined in the standard, is the capacity utilization factor (CUF), which is defined as the ratio between the alternating current (AC) energy production over a given period of time and the maximum amount of energy that the PV system can generate if it is operated at the nominal rated power for the entire period (usually one year). CUF together with the final yield, Y_f, are significant parameters that can be used for the assessment of grid-connected PV systems [33,34]. What is more, the mitigated CO2 can be also used to provide further information about the system performance benefits [34].

Therefore, regarding Rooftop PVs, new calculated parameters should be provided for analyzing the operation of this type of systems from monitored data adapted to their idiosyncrasy. Thus, the main objective of this paper is to define, according to the IEC standard, calculated parameters, yields, indices and losses that provide from monitored data both the performance and matching capability of this type of systems to provide a proper analysis of Rooftop PV systems.

Currently, the standard does not contemplate normalized indices that provide the performance of photovoltaic self-consumption systems, as well as parameters and calculated parameters that quantify the power and energy that is being self-consumed. As a result, following the standard, which is to facilitate comparisons between installations, in this paper it is intended to define a *direct self-consumption* yield and *a to grid* yield. These calculated parameters may be very useful when trying to compare installations with different rated array power. In addition, the self-consumption and self-sufficiency indices should also be defined according to the new and the existing yields provided by the standard. It must be highlighted that in the literature, self-consumption and self-sufficiency indices have been already defined and, as mentioned above, they may be found in different although similar ways. Consequently, it will be provided a normalized way to estimate them through the self-consumption yield and according to the corresponding IEC standard. Finally, a *self-consumption* Performance Ratio together with a *to grid* Performance Ratio are defined. Moreover, the latter may be substituted for non self-consumption losses in the case the Rooftop PV cannot inject the energy surplus to the grid. These new PRs may be considered together with the Performance Ratio of the system defined by the standard in order to provide a proper system performance analysis. It must be highlighted that Rooftop PVs can be an integral element of Smart grids and Smart Cities where the management of the different energy flows is a key issue. Improving both the design and performance analysis from monitored data are key issues for the deployment of Rooftop PV facilities. Also, only PV Rooftop systems with no storage system are considered.

The outline of the document is as follows: the methodology will be shown in Section 2. New calculated parameters will be provided in subsection 2.3. Then, the results obtained when analysing the performance analysis of a Rooftop PV system using both the existing parameters together with the new developed ones are shown in Section 3. Finally, in Section 4 conclusions are drawn.

2. Methodology

The monitored data obtained from a Rooftop PV installed at the University of Jaén will be used together with the load consumption data obtained throughout a year in a dwelling located in Jaen in order to manage the system performance analysis. Information about the considered load consumption profile can be found in [15]. The photovoltaic system together with the data acquisition system (DAS) will be described in the following subsection. Moreover, the performance analysis will follow the IEC 61724 standard and various reporting periods will be considered, monthly and annual. The recording interval will be one minute [35]. Through the monitored data different daily profiles will be obtained, corresponding with photovoltaic generation, load consumption and self-consumed power. These monitored data will be filtered and validated in order to estimate the calculated parameters indicated in the IEC 61724 standard, subsection 2.2, together with the new developed ones that will be described and analysed in subsection 2.3.

2.1. Rooftop PV and data acquisition system

The photovoltaic array has a nominal power of 2.97 kW, made up of 11 polycrystalline modules (270 Wp) in series, see Table 1, and it is connected to a 3 kW inverter. The array is located at 37°47′14.3′′ N 3°46′38.2′′W, with an inclination of 15° and a −7° azimuth. The modules are fixed to a concrete structure on the surface of the roof of the Polytechnic School of the University of Jaen, Fig. 2.

The current–voltage (IV) curves of the photovoltaic generator at real sun have been obtained through a PVPM1000C40 curve tracer. In this sense, it has been obtained the electrical characteristics of the PV array and, afterwards, these values are extrapolated to the standard test conditions (STC) ones applying the corresponding extrapolation method [36].

Regarding the DAS, it must be highlighted that the monitoring equipment is based on different Carlo Gavazzi modules. Three different points of the photovoltaic system are considered: photovoltaic array,

Table 1
Electrical characteristics at Standard Test Conditions (STC) of the PV array and solar modules used.

Characteristics	PV Array (Data sheets)	PV Array (Measurements)	Solar module (AXITEC AC-270P/156–60)
Peak power (P_{MPP})	2970 W	3005 W	270 W
Peak voltage (V_{MPP})	342.1 V	339.7 V	31.1 V
Peak current (I_{MPP})	8.71 A	8.84 A	8.71 A
Open circuit voltage (V_{OC})	420.2 V	419.2 V	38.2 V
Short circuit current (I_{SC})	9.25 A	9.62 A	9.25 A
Operating temperature	25 °C	25 °C	−40 °C to +85 °C

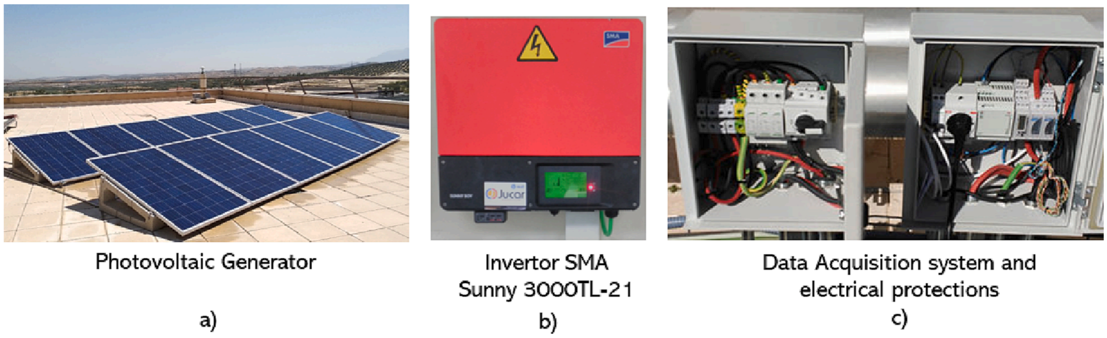


Fig. 2. Rooftop PV. a) Photovoltaic array b) Inverter c) Data Acquisition system and electrical protections.

inverter and connection to the grid, Fig. 3.

In order to monitor meteorological and PV array electrical parameters three modules are considered, Fig. 3 [37]:

- VMUM4AS1T2XT master module (1) which manages the communication with other monitoring modules.
- VMUSAV30XSXX module (2) which measures electrical parameters of the photovoltaic array, such as: voltage, intensity, energy, power, etc.
- VMUP2TIWXSX meteorological module (3) which monitors the meteorological parameters such as ambient temperature, cell temperature and irradiance.

At the inverter output, the following module may be considered:

- EM24DINAV93XISX network analyser module (4) which is an energy meter it measures the different parameters at the output inverter such as voltage, intensity, power, power factor, etc.

The parameters related to energy imported from and injected to the grid are obtained by:

- EM24DINAV93XISX (5) measures the same parameters as the previous one. In this case, it is configured as bidirectional so that the energy to and from the grid may be recorded.

As seen in Fig. 3, the devices share the same communications bus, in this case an RS-485 serial bus. The serial bus is connected to a PC through an RS-485 to RS-232 converter. The photovoltaic system has the appropriate DC and AC protections established by current regulations.

2.2. Data filtering and processing

In order to collect the monitored data, recommendations given by IEC 61724 are followed [26] for data validation. Historical extremes are used for processing environmental data. The highest recorded ambient temperature in Jaen has a value of 50 °C and a minimum value of −15 °C. In this sense, the values obtained by means of a temperature sensor that exceed the aforementioned values are considered incorrect and that value is filtered according to Table 2. Regarding irradiance, and according to the IEC 61724 standard and the databases, the value of target reference conditions (TRC) is considered as 1000 W/m^2. Thus, the maximum and minimum irradiance values are 1200 and 50 W/m^2, respectively.

On the other hand, different solutions can be applied to missing data, for example irradiance databases, interpolation where Stineman interpolation [38] is recommended with different algorithms, Kalman filters [39], weighted average [40], random sample [41] and seasonal decomposition [42]. These methods and tools, which have been

Table 2
Data validation and filtering criteria provided by the IEC 61724 standard.

		Suggested criteria for flagging rejected data			
Criterion type	Description	Irradiance (W/m^2)	Environmental temperature (°C)	Wind speed (m/s)	AC rated power
Range	Value outside of the reasonable	< 0,05•TRC irradiance or > 1,2•TRC[b]	>50° or < -10°	>15 or < 0,5	>1,02• rating or < −0,01• rating

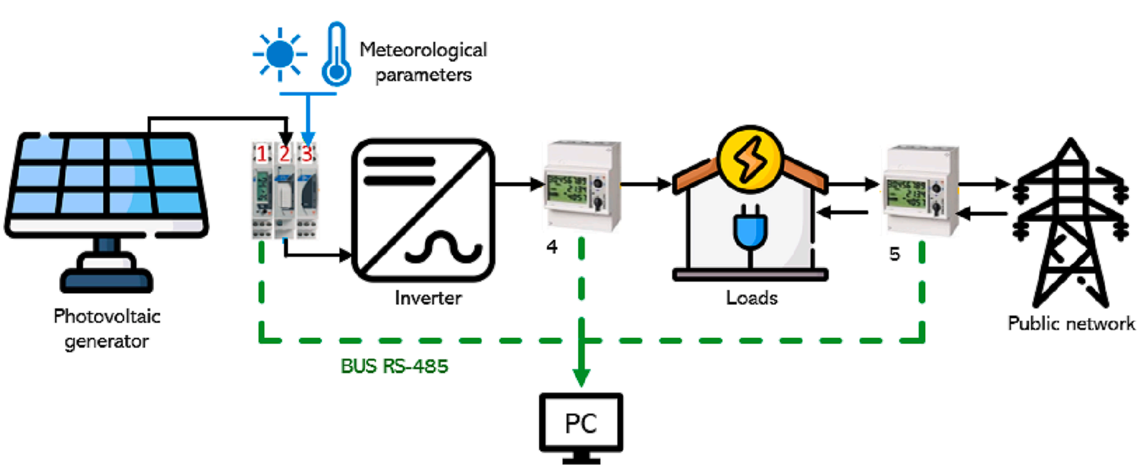


Fig. 3. Data acquisition system (DAS) used when monitoring the Rooftop PV.

developed through MATLAB, manage to complete the data series corresponding to photovoltaic generation and load consumption, Fig. 4. The photovoltaic generated data can now be combined with the load consumption data in order to manage the performance analysis of a Rooftop PV.

2.3. New calculated self-consumption parameters according to the IEC 61724 standard.

In order to better assess the performance of Rooftop PVs, new calculated parameters will be developed that provide further information about the performance analysis of this type of systems.

Once the data is processed and validated, the calculated parameters according to the international standard IEC-61724 [26] can be calculated, Table 3. In the formulas given below which involves summation, τ_k denotes the length of the kth recording interval within a reporting period, τ, which may be daily, monthly or annual. As indicated in the standard, power must be expressed in kW and the recording interval in hours to obtain energy expressed in kWh.

Productivity yields are given in units of [kWh·kW^{-1}], where the units of kWh in the numerator describe the energy production and the units of kW in the denominator describe the nominal array power. The unit ratio is equivalent to hours.

Below, new parameters and calculated parameters will be defined that will allow a better performance analysis of Rooftop PVs from monitored data. The daily consumption and photovoltaic generation profiles of a residential PV Rooftpop is given in Fig. 1(a). The areas below these profiles provide E_L and E_{out}. The self-consumption profile is given by the matching of the two aforementioned profiles. The photovoltaic self-consumed power, P_{PVSC}, may be defined as the power provided by the photovoltaic generator at the output of the inverter that is directly self-consumed by the loads, Equation (1).

As mentioned in Introduction, when the generated photovoltaic power, P_{out}, is greater than the load power, P_L, the photovoltaic self-consumed power corresponds to P_L. On the other hand, when the output generation is lower than the load consumption, P_{PVSC} is given by P_{out}, Fig. 1(a). Moreover, P_{PVSC} can also be defined as:

Table 3
Calculated parameters provided by IEC 61724 [26].

Calculated Parameter	Equation	Units
H_i: in-plane irradiation	$\sum_k G_{i,k} \times \tau_k$	W/m^2
E_A: array energy	$\sum_k P_{A,k} \times \tau_k$	kWh
E_L: load energy	$\sum_k P_{L,k} \times \tau_k$	kWh
E_{out}: output energy	$\sum_k P_{out,k} \times \tau_k$	kWh
η_{BOS}: balance of system efficiency	E_{out}/E_A	–
Y_A.: PV array energy yield	E_A/P_0	kWh·kW^{-1}
Y_f: final system yield	E_{out}/P_0	kWh·kW^{-1}
Y_r: reference yield	$H_i/G_{i,ref}$	kWh·kW^{-1}
L_c: array capture loss	$Y_r - Y_A$	kWh·kW^{-1}
L_{BOS}: balance of system loss	$Y_A - Y_f$	h·kW^{-1}
PR: performance ratio	Y_f/Y_r	–

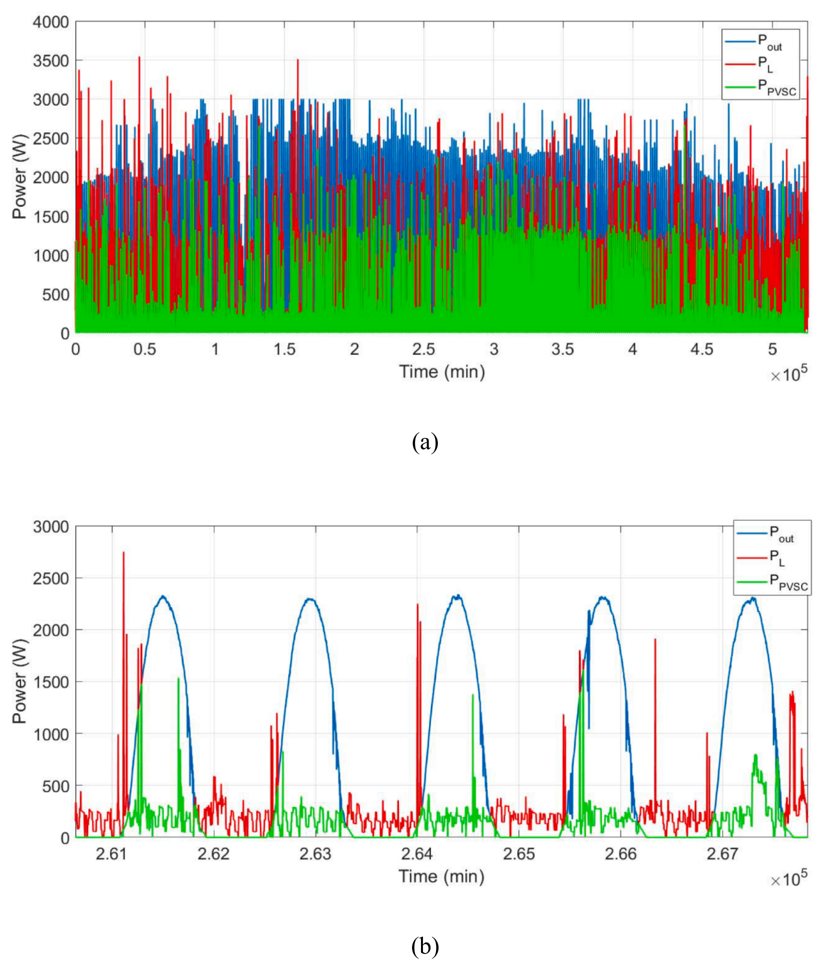


Fig. 4. Photovoltaic, load and self-consumed profiles throughout a year (a) and during five days (b).

$$P_{PVSC} = \min(P_{out}, P_L) \quad (4)$$

This way, the self-consumption photovoltaic profile can be built. Moreover, the photovoltaic self-consumed energy may be found when estimating the area below this profile, E_{PVSC}. This energy that is directly consumed by loads in a given reporting period can be calculated, Equation (5), and is shown as the pink area in Fig. 1 (a):

$$E_{PVSC} = \sum_k P_{PVSC,k} \times \tau_k \quad (5)$$

Moreover, a new yield, the *final self-consumption yield,* which indicates the self-consumed energy per kW can be defined as:

$$Y_{fPVSC} = \frac{E_{PVSC}}{P_0} \quad (6)$$

This calculated parameter may be interesting when comparing Rooftop PVs with different array powers. Likewise, the self-consumption and self-sufficiency indices, SCR and SSR, as defined in [18], are based on the calculated parameters provided by the standard, and the new defined parameters are given by the following equations:

$$SCR = \frac{E_{PVSC}}{E_{out}} \quad (7)$$

$$SSR = \frac{E_{PVSC}}{E_L} \quad (8)$$

SCR and SSR can be also found as supply cover factor and load cover factor [19,20], respectively. Moreover, the self-consumption index can also be expressed as a function of the self-consumption and final yields:

$$SCR = \frac{E_{PVSC}}{E_{out}} = \frac{Y_{fPVSC}}{Y_f} \quad (9)$$

If no storage system is considered, energy that is not directly self-consumed can be exported to grid, E_{TG}. This energy may be calculated as follows:

$$E_{TG} = \sum_k P_{TG,k} \times \tau_k \quad (10)$$

If no wire losses are considered, E_{TG} may be also expressed as:

$$E_{TG} = \left(Y_f - Y_{fPVSC}\right) \bullet P_0 = (1 - SCR) \bullet P_0 \quad (11)$$

A new yield can be defined, i.e. final to grid yield, $Y_{f,TG}$,:

$$Y_{f,TG} = \frac{E_{TG}}{E_{out}} = Y_f - Y_{fPVSC} \quad (12)$$

These new yields may be used to compare Rooftop PVs with different array power, Fig. 5(a). Moreover, if non self-consumed energy cannot be exported to grid, a new derating factor may be defined following the recommendations of the Annex C of the standard as energy that is not directly self-consumed, and which can be seen as non-self-consumption losses, L_{NSC}, Fig. 5(b).

$$L_{NSC} = Y_f - Y_{fPVSC} \quad (13)$$

Finally, a novel self-consumption Performance Ratio, PR_{SC}, can be defined as:

$$PR_{SC} = \frac{Y_{fPVSC}}{Y_r} \quad (14)$$

In this sense, PR_{SC} can be defined as a function of SCR or the latter can be seen as the ratio between PR_{SC} and PR.

$$PR_{SC} = \frac{Y_{fPVSC}}{Y_r} = \mathrm{SCR} \bullet PR \quad (15)$$

Moreover, a performance ratio related to the energy exported to grid may be also defined:

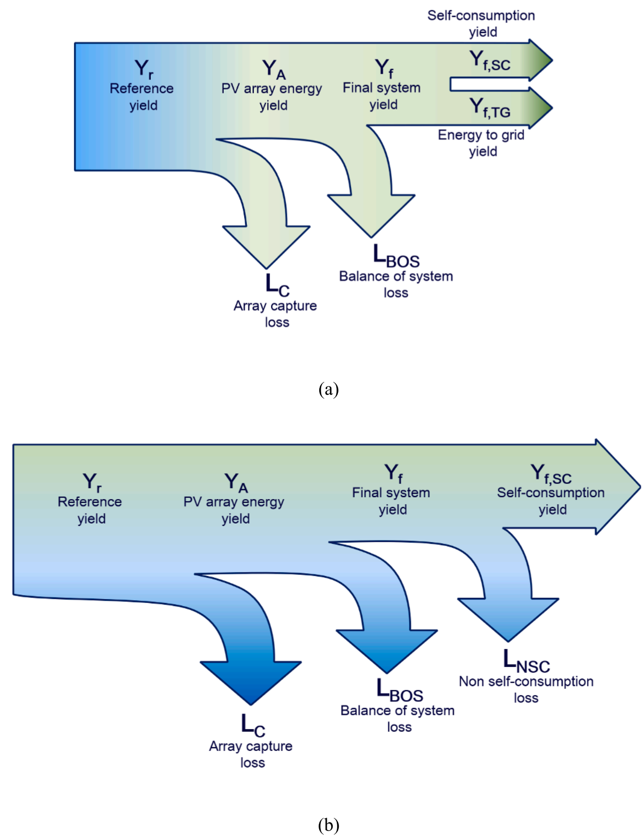


Fig. 5. (a) New final yields in Rooftops PVs where energy surplus may be injected into the grid: *final self-consumption yield* and *final to grid yield* (b) if no energy surplus is injected into the grid, *non self-consumption loss* should be considered.

$$PR_{TG} = \frac{Y_{f,TG}}{Y_r} \quad (16)$$

The sum of PR_{SC} and PR_{TG} provides the global PR.

$$PR = PR_{SC} + PR_{TG} \quad (17)$$

As can be seen, new yields have been defined. Moreover, self-consumption and self-sufficiency indices have been expressed considering these new yields and new Performance Ratios have been developed. The latter may not only provide a better performance analysis of a Rooftop PV but may help to compare the performance of Rooftop PVs with different array powers. PR_{SC} and PR_{TG} may indicate the fraction of the PR that is dedicated to self-consumption and to the exportation to the grid. It must be highlighted that SCR provides information about the matching between the power profile obtained at the output of the inverter and the load consumption profile. In this case, no capture and BOS losses are considered. On the other hand, PR_{SC} together with $Y_{f,SC}$ provides not only information about the matching, it also provides information about the capture and BOS losses involved.

3. Results and discussion

Yields and losses indicated in the standard together with the new proposed calculated parameters defined in subsection 2.3 are shown in Fig. 6. A monthly reporting period has been considered. Regarding calculated parameters indicated in the standard, monthly final yields depend on the considered month. High values are obtained in summer months while the lowest values are obtained during winter months depending on the irradiation values. As can be seen, L_{BOS}, which shows the losses in the BOS components including the inverter, the wiring and

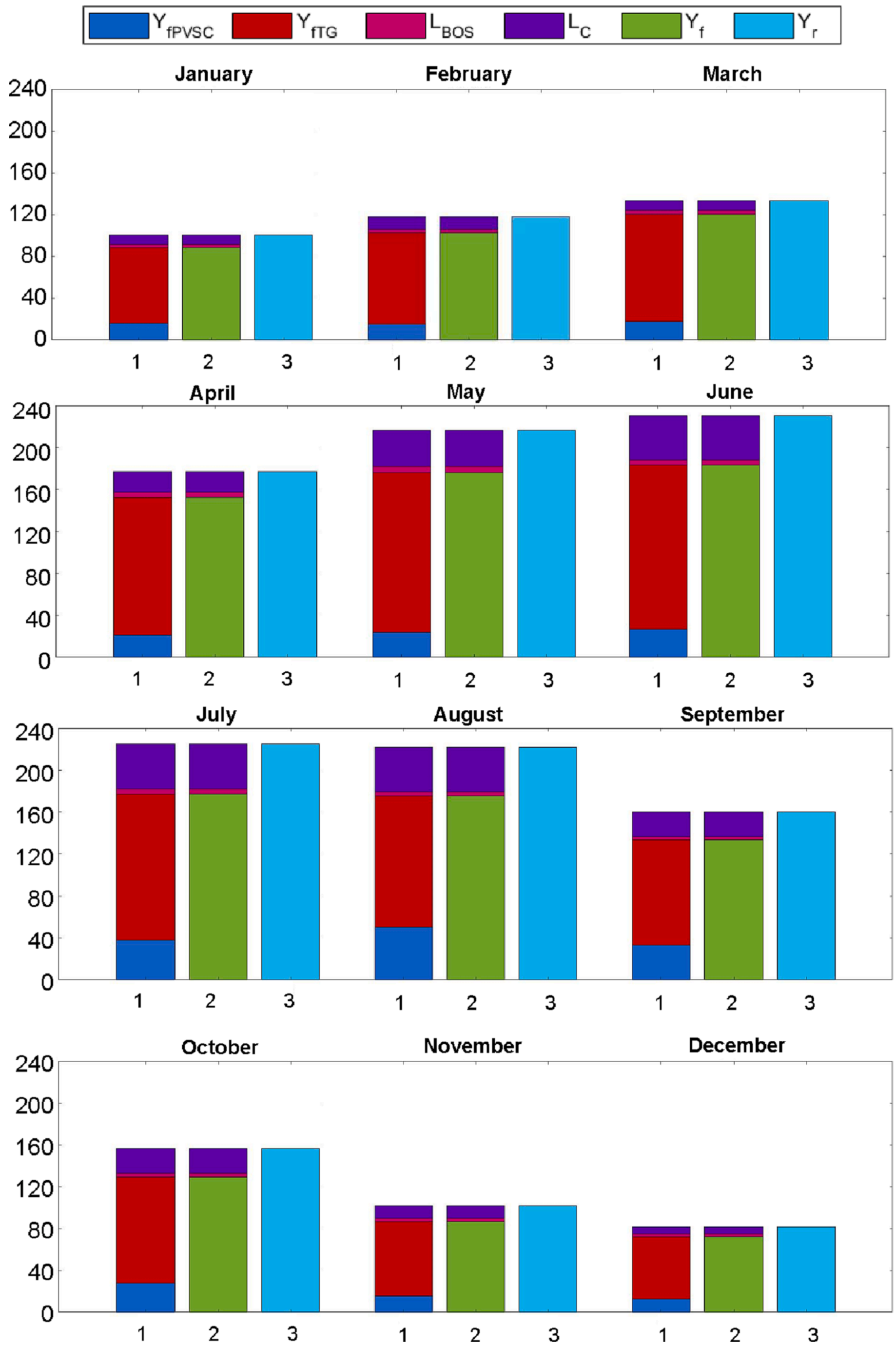


Fig. 6. Yields and losses considering a monthly reporting period. The new yields: Y_{fTG} and Y_{fSC} are shown.

junction boxes are almost negligible. Moreover, capture losses, L_C, which are due to array operation, including array temperature effects or soiling are relatively high, especially during summer where very high cell temperatures were registered, up to 62℃. In this way, monthly PR shows the lowest values in summer months. Monthly PR varies between 0.79 and 0.90. As expected, the highest values correspond to winter months. If an annual reporting period is considered, the annual final yield, Y_f, together with L_{BOS} and L_C are shown in Fig. 8 and Table 4, where an annual PR slightly higher than 0.8 is given. Regarding IEC61724 standard, this may be the whole information that can be obtained.

As amentioned before, final yield, Y_f, can be divided into *self-consumption* and *to grid* final yields, Y_{fSC} and Y_{fTG}, respectively, if the surplus energy can be injected into the grid. In this way, more information about the system performance may be provided. When considering monthly reporting periods, it can be seen that self-consumption yields are considerably lower than to grid yields. Self-consumption yields vary between 12.8 kWh/kWp and 50.3 kWh/kWp, while *to grid* ones range between 59.7 kWh/kWp and 156.5 kWh/kWp. As expected, and in both cases, the highest values are reached during summer months, Fig. 6. Anyway, there is a great amount of energy surplus which may be injected into the grid while the energy which is self-consumed is very low. Most of the months *self-consumption* yields provide very low values and monthly *to grid* final yields are always considerably higher. This fact can also be seen if attention is paid to annual final yields, Fig. 8, where *to grid* yield may be four times higher than *self-consumption* final yield,

Table 4
Calculated Parameters Yields and indices for an annual reporting period. The new proposed calculated parameters have been included.

Calculated Parameters Yields and indices	Units
E_A	4936.9 kWh
E_L	2000.3 kWh
E_{out}	4792.8 kWh
η_{BOS}	0.97
Y_A	1645.6 kWh·kW^{-1}
Y_f	1597.6 kWh·kW^{-1}
Y_r	1923.2 kWh·kW^{-1}
L_c	277.6 kWh·kW^{-1}
L_{BOS}	48.1 kWh·kW^{-1}
PR	0.83
E_{PVSC}	903.3 kWh
E_{TG}	3889.4 kWh
Y_{fPVSC}	301.1 kWh·kW^{-1}
Y_{fTG}	1296.5 kWh·kW^{-1}
SCR	0.19
SSR	0.45
PR_{SC}	0.16
PR_{TG}	0.67

1296 and 301 kWh/kWp. As they are expressed per kW, these new yields may facilitate the comparison between Rooftop PVs with different array nominal powers.

Regarding PRs, the fraction of PR that are dedicated either to self-consumption or to grid may also be obtained considering a monthly and annual reporting period, Figs. 7 and 8 (b), respectively. The achieved PR values indicate a proper system performance regarding photovoltaic production. Although an annual PR of 0.83 is achieved, only a little fraction of it is used for self-consumption: $PR_{SC} = 0.16$. This information may be expanded when taking into account self-consumption and self-sufficiency ratios. This way, an annual SCR and SSR of 0.19 and 0.45 may be obtained. These values show that although a poor on-site use of the generated energy is achieved, almost half the electricity consumption is covered by the Rooftop PV. Nevertheless, these values show a poor matching between consumption and photovoltaic generation profiles and a lower photovoltaic array power should have been considered. A proper array sizing may be achieved using the self-consumption and self-sufficiency curves together with a cost-competitive and profitability analysis [14,15]. Nevertheless, it is crucial that the energy injected to the grid be compensated by the electric facility in order to manage cost-competitiveness or even profitability.

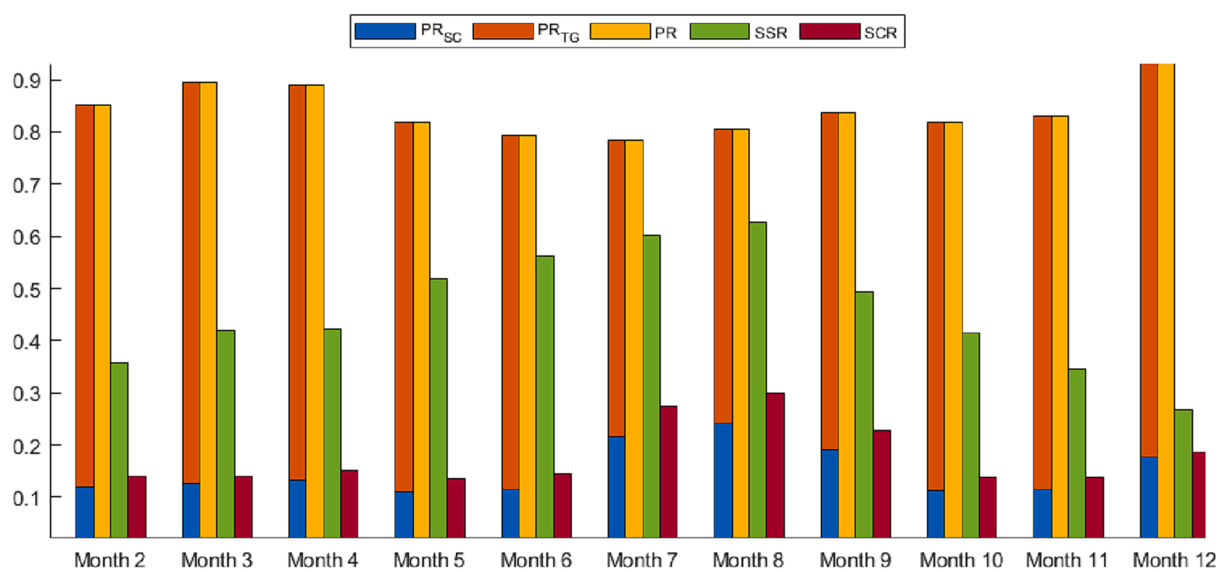


Fig. 7. PR together with the new proposed parameters PR_{SC} and PR_{TG} are shown. It has been considered a monthly reporting period.

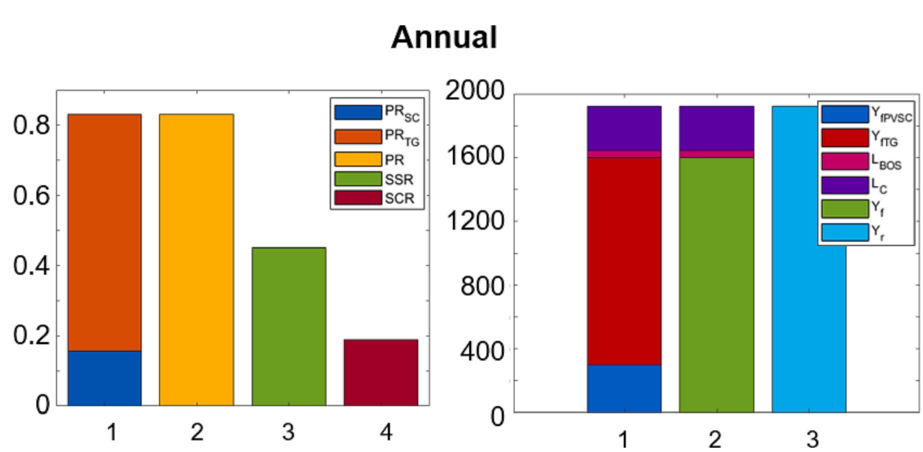


Fig. 8. (a) The new proposed parameters PR_{SC} and PR_{TG}, together with the Performance Ratio defined in the IEC-61724-1 standard for an annual reporting period. (b) Yields and losses considering an annual reporting period. The new yields: Y_{fTG} and Y_{fSC} are shown.

4. Conclusions

Cost declines in wind, solar PV and battery technologies have profoundly impacted the rate of deployment of renewables and Rooftop PVs stand out as a feasible choice not only to reduce electricity consumption but they can be an integral element of Smart Grids and Smart Cities where the management of the different energy flows is a key issue.

In order to assess the potential of this technology, to detect anomalies and to meet the design requirements, it is essential to manage a proper performance analysis from monitored data of Rooftop PVs adapted to their idiosyncrasy. In practice, the parameters that can be found in the literature only focus on the matching capability and grid usage. Moreover, the standard IEC-61724 does not take into account normalized indices that manage the performance of Rooftop PVs, as well as parameters and calculated parameters that quantify the power and energy that is being self-consumed.

Therefore, the main objective of this paper is to define, according to this IEC standard, calculated parameters, yields, indices and losses that provide from monitored data both the performance and matching capability of this type of systems to manage a proper analysis of PV Rooftop systems.

As a result, new final yields are defined, i.e. a direct self-consumption yield and a to grid yield. In the case studied, a final self-consumption and a to grid final yield of 301 and 1296.5 kWh/kWp, respectively, have been obtained. These values show that, in this case, most the final yield is used to inject energy to the grid. As can be seen, they provide further information than the final yield alone as they asses not only the system performance but the matching capability together with the grid usage. Moreover, they differentiate the energy per kWp that is used to self-consumption and to exportation to the grid and they may be used when comparing this type of systems with different array nominal power, following the lines advocated by the IEC standard.

These new final yields may be used to provide two new calculated parameters, a self-consumption Performance Ratio (PR_{SC}) and a to grid Performance Ratio (PR_{TG}), that not only estimate the matching capability and the energy injection to the grid but include, in both cases, the capture and system losses to be considered. They may be used together with the PR defined in the standard. If the analysed case is considered, the system operates properly as an annual PR 0.83 is obtained. In order to provide a better system performance analysis, PR_{SC} and PR_{TG} are estimated, 0,16 and 0,67. It must be highlighted that the latter may be substituted for non self-consumption losses, L_{NSC}, when the Rooftop PV cannot inject the energy surplus to the grid. In this scenario, the net Performance Ratio of the system is given by PR_{SC}.

In addition, a normalized way is provided to estimate the self-consumption and self-sufficiency indices according to the corresponding IEC standard. In this paper the self-sufficiency and self-consumption indices are considered as ratios, SCR and SSR, respectively, so as to keep the terminology used in the standard. Moreover, they are calculated through the new self-consumption yield. Regarding the analyzed case, SCR and SSR of 0.19 and 0.49 are achieved showing a poor matching capability between generation and load profiles although half the load consumption is covered by the Rooftop PV system.

These new calculated parameters and performance ratios may provide a proper performance analysis of Rooftop PVs and may help not only to assess the potential of this technology but may help to keep the desired performance and improve the sizing of this type of facilities which are key issues for the deployment of PV solar rooftop facilities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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