

A new approach to analyse from monitored data the performance, matching capability and grid usage of large Rooftop Photovoltaic systems. Case of study: Photovoltaic system of 1.05 MW installed at the campus of University of Jaén

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ABSTRACT

Rooftop photovoltaic installations highlight their potential to meet a significant portion of urban electricity demand. These systems range from a few kW in residential areas to hundreds of kW in large Rooftop PV systems in commercial and industrial settings. The latter, which may include several inverters or arrays with different orientations and inclinations, require a proper analysis to assess the potential of this technology and to ensure the design objectives. This paper presents a methodology for analysing from monitored data large Rooftop PV systems, focusing on performance, self-consumption and grid usage. The approach is scalable, applicable at the inverter, individual Rooftop PV and global system levels. New key parameters defined include weighted system irradiation ($H_{t,weighted}$) and weighted system reference yield ($Y_{r,weighted}$), which account for different array orientations and inclinations. The methodology is validated using a 1.05 MW system at the University of Jaén with monitored data over a year. Results indicate subsystem and system PR values above 0.83 and a system Capacity Factor of 0.19, confirming a proper performance. Annual self-consumption and self-sufficiency indices of 97.5 % and 17.7 %, respectively, and a solar hour self-sufficiency of 27.7 % reveal minimal energy export and substantial potential to meet the university's electricity demand.

1. Introduction and background

Electricity generation through renewable energy sources reached 30 % globally in 2022, which provides a potential to cover 50 % of electrical demand by 2030. Moreover, it must be highlighted that in 2022, 83 % of the additional electricity generation capacity installed worldwide came from renewable sources, amounting to an installation of an additional 295 GW [1]. Out of this total, 220 GW were accounted for by solar photovoltaic (PV) systems, including both Rooftop PV and utility-scale installations [2]. This technology experienced the greatest growth, with a twenty-six-fold increase from 2010 to 2022, reaching a global installed capacity of 1047 GW in the last year [1]. Moreover, in 2023, the European Union had an installed photovoltaic capacity of 263

GW [3].

Regarding photovoltaics, special attention may be paid to Rooftop PV systems which implies decentralized renewable energy production which is self-consumed *in situ*. This type of systems may play a critical role in the transition towards clean energy in the building sector thanks to its competitiveness in electricity generation [4,5]. Moreover, this technology offer several advantages on the overall building performance, particularly in moderate and warm climates and its deployment has the potential to cover a considerable fraction of a city's electricity consumption [6]. Roofs are often unobstructed for solar radiation and freely available. In this sense, Rooftop PV undoubtedly represents an appealing solution to provide significant renewable energy generation and fulfil the building electricity needs for both new and existing

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buildings [7]. Rooftop PV annual installations, and according to IEA, has experienced a considerable increase, going from 9.2 GW in 2010 to 76 GW in 2021 [8]. It must be highlighted that this type of facilities provide a remarkable potential of share in the final electricity consumption. Although it depends on the considered country, it can range between 20 % and 30 % in France, Spain, and Germany and between 30 % and 40 % in Italy and Greece while in Malta, Cyprus, and Portugal may be over 40 % [9].

Due to its modularity, the size of these systems may range from a few kW in the residential sector to Rooftops PV in industries, offices and shopping centres which may reach hundreds of kW [10–12]. In this case, a large Rooftop PV, even having more than one inverter or several Rooftops PV may be considered. Moreover, in some university campus, as the case here analysed, it may be found different Rooftops PV with different orientation and inclination spread across several buildings [13–15].

Furthermore, when considering different Rooftops PV, and in a broader context, it can be also defined a renewable energy community (REC) where a group of end-users connected to the same Medium-Low Voltage (MV-LV) transformer substation take advantage of community self-consumption. In this sense, REC introduces the new concept of ‘virtual’ self-consumption where the photovoltaic energy generated by the different Rooftops PV or plants that constitutes the REC is not directly self-consumed but it is firstly fed into the grid and then self-consumed by the different end-users within the same portion of the distribution grid. This approach provides collective advantages together with several benefits for the local distribution grid as it can be developed through different business model looking for a better profitability [16]. In a Techno-economic analysis of self-consumption schemes and energy communities in Italy and Portugal it was concluded that, in general, individual self-consumption schemes may be provide lesser profitability than energy communities, as within these communities, individual self-consumption is still prioritised for members while simultaneously offering prosumers the opportunity to sell their excess energy at a higher value to their peers [17]. It must be taken into account that it is estimated that RECs may have installed more than 50 GW of solar power by 2030, which may show a distribution of 21 % of total installed capacity [18].

To assess the potential of Rooftop PV technology and to ensure that design objectives have been achieved, which constitute key issues for the deployment of this type of facilities, it is necessary to provide a proper analysis of these systems from monitored data. As aforementioned, and due to photovoltaic modularity, a Rooftop PV may have one or more inverters. Moreover, it may be found systems composed of various Rooftops PV which may have PV arrays with different array inclination and orientation. This association may constitute or not a REC. Nevertheless, and in any case, it is necessary to achieve a joint analysis when performing a global analysis of the different Rooftops PV and plants involved that takes into account inverter, each Rooftop PV considered and the global system composed of several Rooftops PV. Moreover, this analysis must consider both the performance and self-consumption analysis together with grid usage. Therefore, in the next section it will be reviewed different indicators that may be found in the literature to analyse Rooftops PV in order to provide the aforementioned methodology.

1.1. Performance, matching and grid usage indicators in Rooftops PV

As it is known, the performance analysis manages to detect possible failures, evaluate the efficiency of the system and its performance in the corresponding reporting period, τ , which may be daily, weekly, monthly or annual, 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 the photovoltaic system. In order to analyse the 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. In this sense, the standard IEC 61724-1 [19], IEC 61724-2 [20] and IEC 61724-3 [21] define common criteria regarding the parameters to monitor, the format of the data collected and the analytical method to be followed to manage a performance and energy evaluation, Table 1.

On the other hand, and regarding self-consumption analysis, many different parameters may be found in the literature to analyse Rooftops PV, considering the matching capability and the grid usage [22–24], Table 1. The most widely used ones to assess the matching capability in order to face the load consumption are the self-consumption, φ_{SC} , and self-sufficiency, φ_{SS} , indices [25]. Self-consumption index can be expressed as the ratio between the self-consumed energy, $E_{out,SC}$, and the energy generated by the Rooftop PV, E_{out} , during a given reporting period, Equation (1). On the other hand, the self-sufficiency index can be defined as the ratio between $E_{out,SC}$ and the load consumption, E_L , during the same reporting period, equation (2).

$$\varphi_{SC} = \frac{\int_{t_1}^{t_2} P_{out,SC}(t) dt}{\int_{t_1}^{t_2} P_{out}(t) dt} = \frac{E_{out,SC}}{E_{out}} \quad (1)$$

$$\varphi_{SS} = \frac{\int_{t_1}^{t_2} P_{out,SC}(t) dt}{\int_{t_1}^{t_2} P_L(t) dt} = \frac{E_{out,SC}}{E_L} \quad (2)$$

where $P_{out}(t)$ corresponds to the instantaneous onsite PV power generation obtained at the inverter output and $P_L(t)$ the instantaneous power load consumption. Moreover, $P_{out,SC}(t)$ provides the photovoltaic self-consumed power which may be obtained as:

$$P_{out,SC} = \min(P_L(t), P_{out}(t)) \quad (3)$$

The self-consumption and self-sufficiency indices may be found in the literature in different although similar ways, usually defined as supply cover factor (self-consumption) and load cover factor (self-sufficiency) [23,24]. Moreover, and as aforementioned, they can be also found as a self-sufficiency and self-consumption ratios, SCR and SSR, respectively [27], adapted to the IEC 61724 standard, Table 1. Apart from the self-consumption and self-sufficiency indices or ratios, it is also possible to estimate the self-sufficiency index in solar hours, $\varphi_{SS,SH}$, which may be estimated as the ratio between $E_{out,SC}$ and the load consumption during solar hours, $E_{L,SH}$ [26,29], Table 1. The self-sufficiency index in solar hours indicates the level of energy coverage considering exclusively the load consumption during these hours (i.e. in the period of time in which the photovoltaic energy source may be active). Therefore, and used together with the global self-sufficiency index, it can allow a better energy and matching analysis of Rooftops PV with direct self-consumption where no battery energy storage system (BESS) is used and if a load profile with a remarkable consumption during the night is considered.

As mentioned above, when analysing Rooftop PV systems, the literature focuses on the matching capability between the load and the generation profiles together with the interaction with the utility grid. In this sense, and in order to manage a proper analysis of PV Rooftop systems and to provide a better assessment about the performance analysis of self-consumption systems, a final self-consumption and a to grid yields, $Y_{f,SC}$ and $Y_{f,TG}$, respectively, are provided to combine both the matching capability together with the grid interaction and the Rooftop PV system performance [27], Table 1. Moreover, these new parameters manage to provide comparisons between installations with different rated array power and they may be used together with the ones stated by the International Electrotechnical Commission (IEC) 61724-1 and 61724-3.

Moreover, and regarding grid usage, the load duration curve for normalized net exported electricity may provide important information related to the time the system is injecting, exporting energy and the time the building is self-sufficient. Moreover, values of the normalized peak power generation and the normalized peak power load are shown in this

Table 1

Calculated parameters for the performance and self-consumption together with grid usage analysis of Rooftop PV systems [19,26–28] in a given recording period, τ (daily, monthly or annual). τ_k indicates the recording interval. Self-consumption and self-sufficiency indices have not been included in the table as they are already defined in equations (1) and (2).

Parameter	Symbol	Equation	Units	Performance	Self-consumption & grid usage	Reference
In-plane irradiation	H_I	$\sum_k G_{I,k} \times \tau_k$	(4) Wh/m ²	*		[19]
Array energy	E_A	$\sum_k P_{A,k} \times \tau_k$	(5) kWh	*		[19]
Output energy	E_{out}	$\sum_k P_{out,k} \times \tau_k$	(6) kWh	*		[19]
PV array energy yield	Y_A	E_A/P_0	(7) kWh·kW ⁻¹	*		[19]
Final system yield	Y_f	E_{out}/P_0	(8) kWh·kW ⁻¹	*		[19]
Reference yield	Y_r	$H_I/G_{I,ref}$	(9) kWh·kW ⁻¹	*		[19]
Array capture loss	L_c	$Y_r - Y_A$	(10) kWh·kW ⁻¹	*		[19]
Balance of system loss	L_{BOS}	$Y_A - Y_f$	(11) kWh·kW ⁻¹	*		[19]
BOS efficiency	η_{BOS}	E_{out}/E_A	(12) –	*		[19]
Performance ratio	PR	Y_f/Y_r	(13) –	*		[19]
Capacity Factor	CF	$\frac{E_{out}}{P_{0,AC} \cdot (24 \cdot \text{days})}$	(14)	*		[21]
Photovoltaic self-consumed energy	$E_{out,SC}$	$\sum_k P_{out,SC,k} \times \tau_k$	(15) kWh		*	
Load energy	E_L	$\sum_k P_{Load,k} \times \tau_k$	(16) kWh		*	
Load energy in solar hours	$E_{L,SH}$	$\sum_k P_{Load,SH,k} \times \tau_k$	(17) kWh		*	[26]
Energy to grid	E_{TG}	$\sum_k P_{TG,k} \times \tau_k$	(18) kWh	*	*	[19]
Energy from grid	E_{FG}	$(Y_f - Y_{JSC}) \cdot P_0 = (1 - SCR) \cdot P_0$	(19) kWh	*	*	[19,27]
Final self-consumption yield	Y_{JSC}	$\frac{E_{out,SC}}{P_0}$	(20) kWh·kW ⁻¹	*	*	[27]
Final to grid yield	$Y_{f,TG}$	$\frac{E_{TG}}{P_0} = Y_f - Y_{JSC}$	(21) kWh·kW ⁻¹	*	*	[27]
Self-sufficiency in solar Hours	$\varphi_{SS,SH}$	$\frac{E_{out,SC}}{E_{L,SH}}$	(22) –		*	[26]
Load duration curve for normalized net exported electricity	–	–			*	[23]

curve [23] where the design connection capacity is used as normalizing quantity.

Finally, 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 Ref. [22].

The main objective of the paper is to show a methodology to manage an integral performance, self-consumption and grid usage analysis from monitored data either if a single Rooftop PV or a system composed of different Rooftops PV are considered and a joint analysis is needed. Moreover, this approach may be extrapolated to renewable energy communities which is made up of several Rooftops PV and/or plants in order to provide a global performance and self-consumption analysis. The set of all Rooftops PV whether or not they are part of a REC will be considered as a system while each Rooftop PV will be seen as a subsystem. Moreover, it will be taken into account the different inverters each Rooftop PV may have. It will be used the aforementioned calculated parameters but taking into account that there may be Rooftops PV and/or plants with arrays with different power, inclination and orientation. In this sense, it will be provided a methodology to manage the performance analysis of the different inverters which may define the subsystem performance through weighted parameters. Finally, the whole system performance will be also estimated as a function of the subsystems performance. In this case, new weighted parameters will be defined due to the different array orientation and inclination of the Rooftops PV involved: a new weighted system irradiation, $H_{I,weighted}$, and a weighted system reference yield, $Y_{r,weighted}$, will be considered in order to manage the performance analysis of the whole photovoltaic system. This approach will be very useful when analysing the role of each Rooftop PV in the system together with the whole system performance.

In order to show this methodology, it will be analysed from monitored data obtained throughout a year the photovoltaic system of 1.050 MW installed at the University of Jaen. This system consists of five

facilities or Rooftops PV installed in various buildings and parking lots with different nominal power and different array inclination and orientation. The output energy provided by the system is not directly self-consumed but it is firstly fed into the grid and then self-consumed by the different end-users within the same portion of the distribution grid as it may be the case of a REC. Although this PV system may not be considered *strictu sensu* an energy community the methodology here developed may be also extrapolated when analysing this type of systems where not only an individual but a global performance and self-consumption analysis must be managed. The assessment provided will be based in a first stage on a performance analysis of the different Rooftops PV at three levels: inverter, subsystem (i.e. the Rooftop PV installed in each building or parking lot) and system, and may help to better detect anomalies and malfunctions. In a second stage, self-consumption analysis and grid usage of the system will be provided. Analysis will be managed considering both monthly and annual reporting periods.

The outline of the document is as follows: the UJA Rooftop PV system together with the monitoring system will be described in Section 2 while the performance, self-consumption and grid usage analysis methodology will be shown in Section 3. Then, the results obtained when analysing the photovoltaic system installed at the University of Jaén are shown in section 4. Finally, in Section 5 conclusions are drawn.

2. UJA Rooftop PV system & monitoring system

2.1. UJA Rooftop PV system

UJA photovoltaic system of 1.05 Mwp is composed of five Rooftops PV subsystems or facilities installed at the roofs of three buildings (B4, C3 and D3) and the canopies of two parking lots (P3 and P4), Figs. 1 and 2. Each subsystem consists of a PV array with a given nominal power, P_0 , and different multistring inverters, Table 2. As can be seen, P3 and P4



Fig. 1. Rooftop PV system installed at University of Jaén which is composed of five Rooftops PV or *subsystems* installed on the Rooftops of buildings B4, C3, D3 and parking lots P4 and P3.

arrays have an inclination of 7° due to canopies profile while Rooftop PV subsystems B4, C3 and D3 have an array inclination of 10° in order to maximize the number of PV modules on the roof minimising the effect of shadows, Fig. 3. Moreover, the PV arrays have different azimuth. All the inverters, Fig. 4, of each subsystem or Rooftop PV are connected to an AC box, which, in turn, is connected to the general box of the Transformation Centre (TC) where the energy produced is transformed from low to high voltage to be distributed through the ring formed by the different transformation centres of the Campus, Fig. 5. The energy produced by the whole photovoltaic system will be self-consumed on the Campus in the different buildings and the non self-consumed energy will be exported to the grid.

2.2. UJA Rooftop PV monitoring system

The monitoring system, Fig. 5, may be divided into two types: the one that manages the performance monitoring (1) and the one that monitors self-consumption and grid usage monitoring (2–4). Performance monitoring follows IEC 61724 recommendations and is based on dataloggers connected to the inverters via RS485 through a Modbus link, Fig. 6. There is one datalogger for each inverter which is connected to the internet network of the UJA. These data loggers monitor the parameters stated by the standard with a recording interval, τ_k , of 1 min, Table 3. Moreover, minimum, maximum and average values for each parameter are also recorded. In plane irradiance, G_t , in each subsystem and ambient temperature, T_{amb} , are also monitored through a calibrated cell. Cell temperature, T_c , is also provided by this calibrated cell. DC array voltage (V_A) and current (I_A) per string are also monitored; therefore, array power (P_A) at different levels: per string, per MPPT, per inverter and per subsystem may be estimated. Furthermore, AC voltage (V_{out}), current (I_{out}) and power (P_{out}) of each of the phases at the output of the inverters are also monitored, Table 3. The outputs of the 12 inverters are connected to the TC input. In the case here considered, the inverters monitored data will be used to define the subsystem (i.e each Rooftop PV) performance and the global system performance before the TC input.

On the other hand, the TC output is monitored by a legal distribution company counter (2). This counter considers a recording interval of 15

min. The TC output data may be used to manage the global system analysis performance at this point which may include the wire losses from the inverters to the input of the TC together with its efficiency.

Regarding the self-consumption monitoring, it may be provided by the legal distribution company counters (2) and (3) ($\tau_k = 15$ min) together with energy analyzers (4) ($\tau_k = 1$ min) that have been installed in each of the 16 buildings of the Campus to monitor the load consumption. AC load voltage (V_L), current (I_L) and power (P_L) of each building are monitored. These energy analyzers are connected to the UJA internet network via Modbus TCP protocol to a Gateway module with an integrated automation server. A recording interval of 15 min to achieve a self-consumption and grid usage analysis may be acceptable as indicated in Refs. [30–32].

Finally, in order to control, monitor, collect and analyse the aforementioned data a *scada* system has been developed *ad hoc*, Fig. 7.

Once the monitored data have been collected, it has been followed the recommendations given by IEC 61724 [19] for data validation. Monitored data has been verified and filtered according to the recommendations indicated by the standards [19–21] in order to detect and avoid possible invalid data, such as negative electricity generation, as well as possible data gaps. In the latter case, the intervals detected with absence of data have been filled in using a linear interpolation. The data filtering and processing, which have been developed through MATLAB, manage to complete the data series corresponding to photovoltaic generation. These data can now be used to manage the performance analysis at different levels: inverter, subsystem and system as it will be described in the next section.

3. Methodology for the performance, self-consumption and grid usage analysis of UJA PV system

3.1. Performance analysis of UJA PV system

In order to provide the performance analysis of the UJA Rooftop PV system it has been managed the performance analysis of each inverter, each subsystem (each Rooftop PV) and the global system. It must be taken into account that each PV subsystem array has their own azimuth and inclination. In this sense, to provide a proper assessment of the

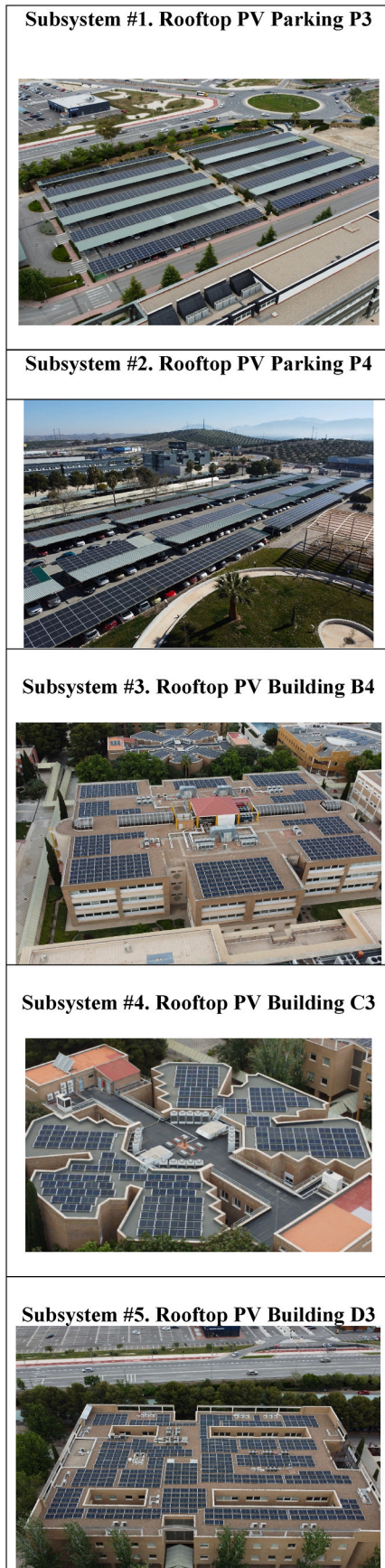


Fig. 2. Aerial photographs corresponding to the Rooftops PV subsystems installed at University of Jaén.

whole system it has been defined new weighted in-plane irradiation and a weighted reference yield.

The performance analysis will be managed at different stages: inverter, subsystem (each array with a given orientation and inclination: building and parking lot) and system. Moreover, the different calculated parameters that define the system performance will be expressed as a function of the corresponding subsystem or Rooftop PV calculated parameters and the latter will be estimated as a function of the inverter/s performance. This approach may provide not only a proper analysis from monitored data in order to better detect malfunctions or anomalies but it will be shown the role of each element in the system.

$$X_{\text{system}} = f(X_{\text{subsystem}}) = f(X_{\text{inverter}})$$

where X corresponds to the calculated parameter under analysis.

In order to provide the inverter performance it may be used Equations (4)–(13), Table 1, for each inverter. Where P_0 is the nominal array power of each inverter. It must be highlighted that all the strings in each multistring inverter have the same orientation and inclination.

If the analysis performance is focused now on the subsystem performance (Rooftop PV with a single or several inverters), H_I and Y_r for each subsystem are the same that the ones corresponding to their associated inverters. This is true when all the strings in the different inverters of the considered Rooftop PV have the same orientation and inclination. If it not were the case, weighted parameters for H_I and Y_r should be also considered as it will be later discussed.

As aforementioned, the subsystem performance may be estimated as a function of the inverter performance. Therefore, the subsystem array energy, $E_{A,\text{subsystem}}$, may be defined as follows:

$$E_{A,\text{subsystem}} = \sum_{i=1}^m E_{A,i} \quad (23)$$

where i indicates the inverter (in this case, $i = 1, \dots, 12$) and $m-l$ provide the inverters associated to each subsystem, Table 2. $E_{A,i}$ indicates the array energy given by the array connected to the corresponding inverter in each subsystem.

In this way, the array yield of the considered subsystem may be defined as:

$$Y_{A,\text{subsystem}} = \frac{E_{A,\text{subsystem}}}{P_{0,\text{subsystem}}} = \sum_{i=1}^m \frac{(Y_{A,i} \cdot P_{0,i})}{P_{0,\text{subsystem}}} \quad (24)$$

$P_{0,\text{subsystem}}$ is the nominal array power of each Rooftop PV subsystem. Moreover, $Y_{A,\text{subsystem}}$ may be defined by $E_{A,\text{subsystem}}$, or may even be expressed as a weighted array yield as a function of the inverters array yields, $Y_{A,i}$, associated to each subsystem. This approach may be very interesting as it may provide the role of each inverter in the subsystem analysis.

The subsystem capture loss, $L_{C,\text{subsystem}}$, may be estimated as a function of the subsystem reference and array yields. Moreover, it may be calculated as a weighted capture loss which depends on the capture loss of each inverter in the subsystem:

$$L_{C,\text{subsystem}} = Y_{r,\text{subsystem}} - Y_{A,\text{subsystem}} = \sum_{i=1}^m \frac{(L_{C,i} \cdot P_{0,i})}{P_{0,\text{subsystem}}} \quad (25)$$

where $L_{C,i}$ indicates the array capture loss associated to each inverter in the subsystem. It must be remembered that in the case here studied, $Y_{r,\text{subsystem}}$ has the same value as the reference yield used to manage the performance analysis of the inverters associated to each subsystem.

Finally, the output energy provided by each subsystem, $E_{\text{out},\text{subsystem}}$, may be estimated as:

$$E_{\text{out},\text{subsystem}} = \sum_{i=1}^m E_{\text{out},i} \quad (26)$$

$E_{\text{out},i}$ indicates the output energy provided by each inverter.

Table 2

Photovoltaic system at the University of Jaén: subsystems and inverters. The power module has 325 W and there are 20 modules per string connected in series.

Rooftop PV Subsystems	N° Mod.	Strings	Array Power, $P_{0,i}$, per subsystem (kW)	N° Strings per Inverter	Array Power, $P_{0,i}$, per inverter (kW)	Inverter	Inverter Power AC (kW)	β	α
P3	1400	70	455	18	117	inv1	100	7°	42
				17	110.5	inv2	100		
				18	117	inv3	100		
				17	110.5	inv4	100		
P4	680	34	221	17	110.5	inv5	100	7°	36
				17	110.5	inv6	100		
B4	520	26	169	9	58.5	inv7	50	10°	36
				17	110.5	inv8	100		
C3	180	9	58.5	9	58.5	inv9	50	10°	0
D3	460	23	149.5	8	52	inv10	40	10°	36
				8	52	inv11	40		
				7	45.5	inv12	40		
Total	3240	162	1053				920		



Fig. 3. PV array corresponding to Rooftop PV subsystem at building D3.



Fig. 4. The three inverters corresponding to Rooftop PV subsystem installed at D3 Building.

The final subsystem yield, $Y_{f,subsystem}$, and the subsystem BOS loss, $L_{BOS,subsystem}$, and $PR_{subsystem}$ may be expressed as follow:

$$Y_{f,subsystem} = \frac{E_{out,subsystem}}{P_{0,subsystem}} = \sum_{i=1}^m \frac{(Y_{f,i} \bullet P_{0,i})}{P_{0,subsystem}} \quad (27)$$

$$L_{BOS,subsystem} = Y_{A,subsystem} - Y_{f,subsystem} = \sum_{i=1}^m \frac{(L_{BOS,i} \bullet P_{0,i})}{P_{0,subsystem}} \quad (28)$$

$$PR_{subsystem} = \frac{Y_{f,subsystem}}{Y_{r,subsystem}} = \sum_{i=1}^m \frac{(PR_i \bullet P_{0,i})}{P_{0,subsystem}} \quad (29)$$

when facing the global system analysis performance, it must be considered that there are photovoltaic arrays corresponding to each subsystem or Rooftop PV with different inclination and orientation. In order to provide a proper analysis, new weighted system in plane irradiation and system reference yield, $H_{I,weighted}$ and $Y_{r,weighted}$, respectively, must be considered:

$$H_{I,weighted} = \sum_{j=1}^p \frac{(H_{I,j} \bullet P_{0,subsystem,j})}{P_{0,system}} \quad (30)$$

$$Y_{r,weighted} = \frac{H_{I,weighted}}{G_{t,ref}} = \sum_{j=1}^p \frac{(Y_{r,j} \bullet P_{0,subsystem,j})}{P_{0,system}} \quad (31)$$

$H_{I,j}$ corresponds to in-plane irradiation of subsystem j while p provides the total number of subsystems (in the case here analysed $p = 5$). $P_{0,system}$ is the nominal array power of the whole PV system (1.05 MW). $P_{0,subsystem,j}$ represents the array peak power of subsystem j .

Fig. 8 shows the monthly and annual in-plane irradiation monitored by the five calibrated cells associated to each Rooftop PV or subsystem together with the weighted in-plane irradiation that will be used in a performance analysis of the whole system.

Finally, and considering these new calculated parameters, the system array energy $E_{A,system}$, the array yield, $Y_{A,system}$, and the system capture loss, $L_{C,system}$ may be defined as follows:

$$E_{A,system} = \sum_{j=1}^p E_{A,subsystem,j} \quad (32)$$

$$Y_{A,system} = \frac{E_{A,system}}{P_{0,system}} = \sum_{j=1}^p \frac{(Y_{A,subsystem,j} \bullet P_{0,subsystem,j})}{P_{0,system}} \quad (33)$$

$$L_{C,system} = Y_{r,weighted} - Y_{A,system} = \sum_{j=1}^p \frac{(L_{C,subsystem,j} \bullet P_{0,subsystem,j})}{P_{0,system}} \quad (34)$$

where $E_{A,subsystem,j}$ indicates the array energy given by subsystem j . $Y_{A,subsystem,j}$ and $L_{C,subsystem,j}$ indicates, respectively, the array yield and the array capture loss associated to each subsystem. Here again, the system yields together with the different losses may be expressed both considering the system calculated parameters or may be defined as weighted values depending on the subsystem yields and losses, which, in turn, may be also expressed as weighted values considering the inverters yields and losses. As aforementioned, this approach manages to provide

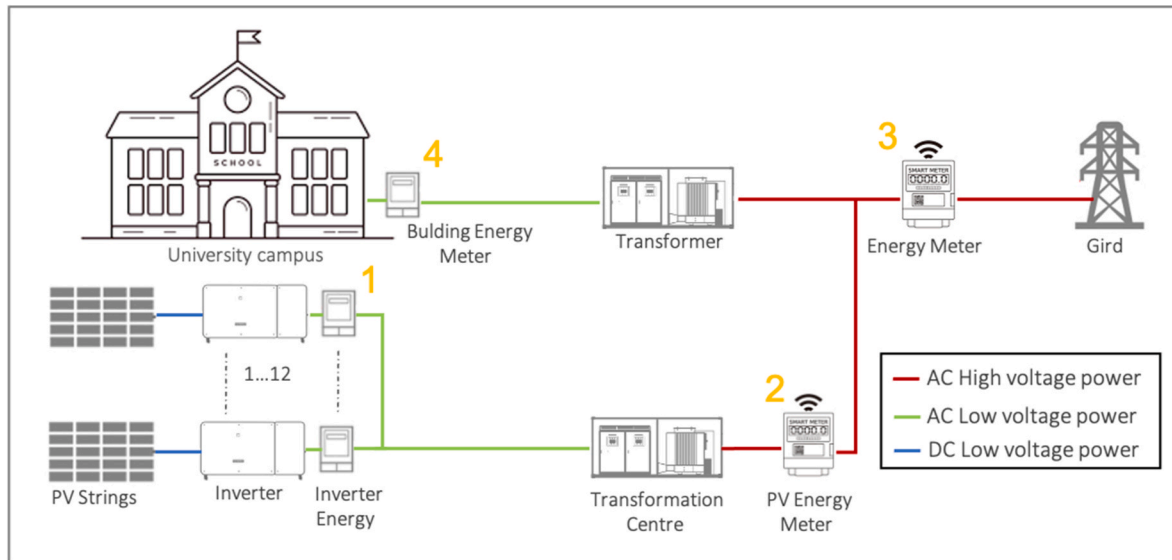


Fig. 5. Schematic Diagram of energy metering at the University of Jaén. Monitoring points (MP).

ARCHITECTURE OF THE MONITORING SYSTEM

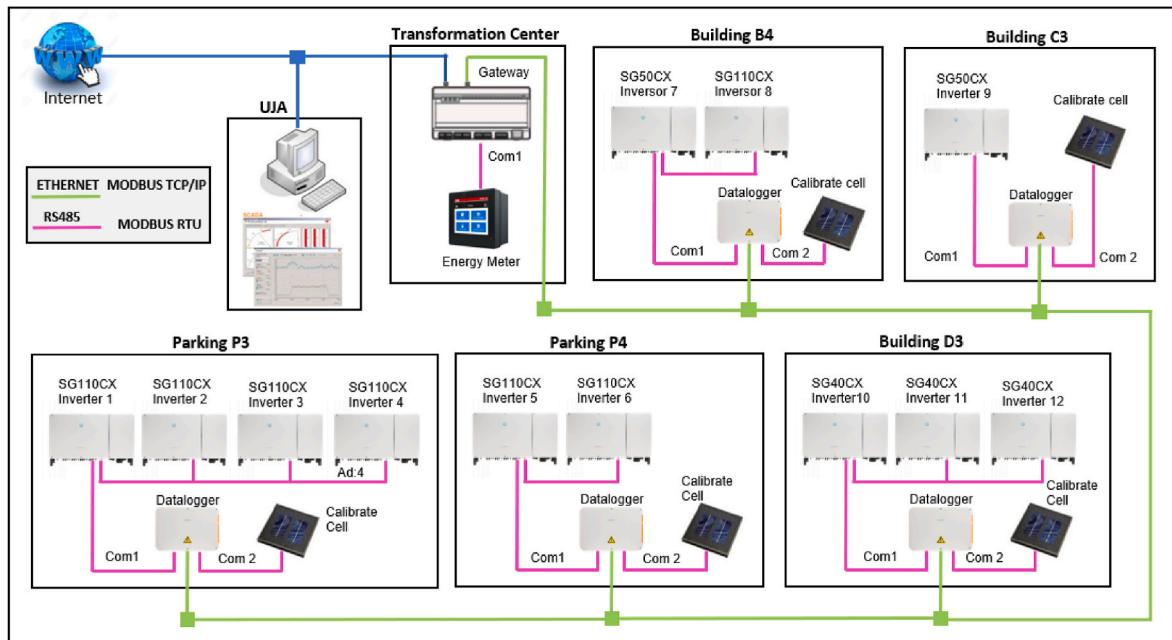


Fig. 6. Performance monitoring system architecture.

the role of each inverter and subsystem in the whole system performance.

Finally, the output energy provided by the system, $E_{out, system}$, the final system yield, $Y_{f, system}$, together with the system BOS loss, $LBOS, system$, may be estimated as:

$$E_{out, system} = \sum_{j=1}^p E_{out, subsystem, j} \quad (35)$$

$$Y_{f, system} = \frac{E_{out, system}}{P_{0, system}} = \sum_{j=1}^p \frac{(Y_{f, subsystem, j} \cdot P_{0, subsystem, j})}{P_{0, system}} \quad (36)$$

$$LBOS, system = Y_{A, system} - Y_{f, system} = \sum_{j=1}^p \frac{(L_{C, subsystem, j} \cdot P_{0, subsystem, j})}{P_{0, system}} \quad (37)$$

$$PR_{system} = \frac{Y_{f, system}}{Y_{r, weighted}} = \sum_{j=1}^p \frac{(PR_{subsystem, j} \cdot P_{0, subsystem, j})}{P_{0, subsystem}} \quad (38)$$

where $E_{out, subsystem, j}$, $Y_{f, subsystem, j}$ and $LBOS, subsystem, j$ indicates, respectively, the output energy, the final yield and the BOS losses provided by each Rooftop PV subsystem.

In order to evaluate the amount of energy generated by each subsystem or Rooftop PV at it can be defined the following parameter, *Role Level*, *RL*:

Table 3

Monitored parameters to achieve the UJA Rooftop PV performance [19], self-consumption and grid usage analysis.

Monitored Parameter	Symbol	Units	MP	Performance monitoring	Self-consumption and grid usage analysis
In-plane irradiance	G_I	W/m ²	(1)		
Ambient temperature	T_{amb}	°C	(1)		
Cell temperature	T_C	°C	(1)	*	
Inverter Array voltage ^a	$V_{A,inverter}$	V	(1)	*	
Inverter Array current ^a	$I_{A,inverter}$	A	(1)	*	
Inverter Array power ^a	$P_{A,inverter}$	W	(1)	*	
Inverter Output Voltage	$V_{out,inverter}$	V	(1)	*	
Inverter Output Current	$I_{out,inverter}$	A	(1)	*	
Inverter Output Power	$P_{out,inverter}$	W	(1)	*	
System Output Power (output TC)	$P_{out,system,TC}$	W	(2)	*	*
Power from grid ^b	P_{FG}	W	(3)		*
Power to grid ^b	P_{TG}	W	(3)		*
Load power	P_L	W	(4)		*

^a Array current and voltage per string are monitored. In this sense, array power per string, per MPPT and per inverter can be considered.

^b These parameters are being monitored by legal energy meters (2) and (3) with a recording interval of 15 min.

$$RL_{subsystem,j} = \frac{E_{out,subsystem,j}}{E_{out,system}} \quad (39)$$

If now the output system is considered at the output of the TC (monitoring point 2), $Y_{f,system,TC}$ may be defined as:

$$Y_{f,system,TC} = \frac{E_{out,system,TC}}{P_{0,system}} \quad (40)$$

where $E_{out,system,TC}$ provides the output energy at the TC output. Moreover, and following the IEC 61724 recommendations in order to define derate factors (Annex D), it has been provided the wire distribution losses between the inverters outputs and the TC input together with the TC efficiency, $L_{TC,system}$:

$$L_{TC,system} = Y_{f,system} - Y_{f,system,TC} \quad (41)$$

$Y_{f,system}$ provides the system final yield at the subsystems output (1) and $Y_{f,system,TC}$ provides the system total final yield at the TC output (2), Fig. 5.

So, it can be said that:

$$Y_{r,weighted} = L_{C,system} + L_{BOS,system} + L_{TC,system} + Y_{f,system,TC} \quad (42)$$

And the performance ratio at TC output may be expressed as follows:

$$PR_{system,TC} = \frac{Y_{f,system,TC}}{Y_{r,weighted}} \quad (43)$$

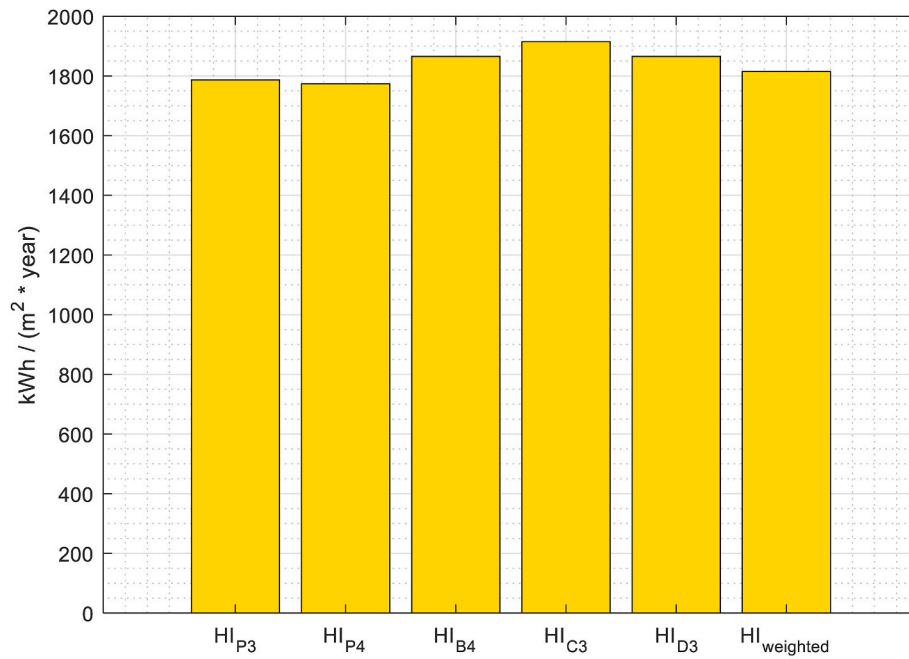
Moreover, the capacity factor (CF) obtained as the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period can be expressed as:

$$CF = \frac{E_{out,system,TC}}{P_{0,AC} \cdot (24 \cdot \text{days})} \quad (44)$$

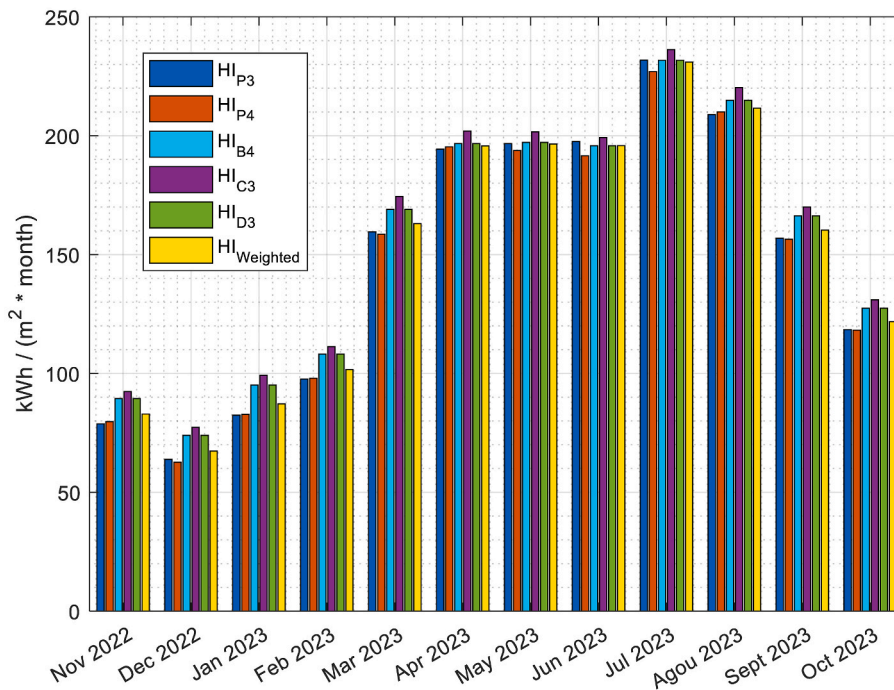
where $P_{0,AC}$ is the AC rating in kW as calculated from the sum of the inverters rating. days corresponds to the number of days of the considered reporting period. CF is a metric that allows comparisons not only between PV plants but also between different energy source plants.



Fig. 7. Scada system used to monitor the UJA PV system.



(a)



(b)

Fig. 8. Annual (a) and monthly (b) in-plane irradiation corresponding to the five calibrated cells associated to each Rooftop PV subsystem. Weighted system in-plane irradiation has been included.

3.2. Self-consumption and grid usage analysis of UJA Rooftop PV

Regarding the self-consumption analysis, and at a first glance, it will be characterized the daily load profiles together with the generation profiles obtained at the TC output. Moreover, monthly and annual load consumptions will be estimated. It will be also considered the load consumption during solar hours. This calculated parameter may be of

interest as it may provide the energy consumption that may be covered by the Rooftop PV system without battery energy storage system (BESS). Moreover, calculated parameters that may provide better assessment about the joint performance and self-consumption analysis of Rooftop PV systems have been considered: final self-consumption and a to grid yields, Y_{pvsc} and Y_{Tg} , respectively [27]. These yields may be used to make comparisons between other Rooftops PV with different array

nominal power. Moreover, apart from the self-consumption and self-sufficiency indices or ratios [25,27], the self-sufficiency index in solar hours has been estimated [26], $\varphi_{SS,SH}$, which together with the global self-sufficiency index can allow a better characterization of Rooftops PV with a remarkable load consumption during the night and no BEES is considered. Moreover, and regarding grid usage, the load duration curve for normalized net exported electricity will be considered [23].

4. Results

The analysis results will be divided into two categories: performance and self-consumption together with grid usage analysis. Performance analysis will follow IEC 61724 recommendations and the aforementioned methodology in order to provide a proper assessment. In this sense, calculated parameters, yields and losses together with PR will be estimated. Moreover, this performance analysis will be considered at three levels: inverter, subsystem (i.e. the Rooftop PV system installed in each building or parking lot) and system. Inverter and subsystem analysis will be considered at the output of the inverters (1) while system performance will be managed either at the inverters output and at the TC output (2), Fig. 5. On the other hand, self-consumption and grid usage analysis will be focused on the assessment of matching capability, self-sufficiency and grid usage. Therefore, self-consumption and self-sufficiency ratios or indices will be estimated. Moreover, calculated parameters that combine performance with matching capability will be considered: self-consumption and to grid final yields and global self-consumption and self-sufficiency. The load duration curve for normalized net exported electricity will be also plotted. Analysis will be managed considering both a monthly and an annual reporting periods.

4.1. UJA Rooftop PV performance analysis

4.1.1. Performance inverter analysis

In this section it will be given the performance analysis of each inveter considering an annual reporting period, Tables 4 and 5 and Fig. 9.

Inverters #2, #4, #5, #6 and #8 have the same array power (110.5 kWp), Table 2, and provide similar annual output energies although there are slightly differences between them. Among them, inverter #4 provides the lowest energy as parking lot P3 suffers from a higher shadowing. In this sense, inverters #1 and #3 which belong to subsystem P3 provide the same amount of energy than 110.5 kWp arrays, even little less energy although they have a higher array power (117 kWp). Regarding inverters #7 and #9 which have an array power of 58.5 kWp they provide considerably less annual output energy. Inverter #9 provides a slightly higher output energy compared to inverter #7 as although they have the same inclination, inverter #9 is oriented to south. Finally, inverters #10, #11 and #12 provide the lowest E_{out} as they have the lowest array power. Inverter #8 gives the maximum E_{out} .

Table 4

Annual yields and losses per inverter and per subsystem corresponding to the UJA Rooftop PV system.

Rooftop PV UJA	$Y_{r,inverter}$ subsystem	Y_r	L_C inverter (kWh/kW)	L_C Subsystem (kWh/kW)	Y_A inverter (kWh/kW)	Y_A Subsystem (kWh/kW)	L_{BOS} inverter (kWh/kW)	L_{BOS} Subsystem ((kWh/kW)	Y_f inverter (kWh/kW)	Y_f subsystem ((kWh/kW)
Parking lot P3	1786.7	236.3	226.9	1550.3	1559.8	31.6	39.64	1518.7	1520.1	
		229		1557.7		61.3		1496.4		
		190.4		1596.3		34.5		1561.7		
		251.2		1535.5		30.3		1505.2		
Parking lot P4	1773.9	188.8	159.79	1585.1	1614.1	31.1	38.3	1554.0	1575.8	
		130.8		1643.1		45.4		1597.7		
B4	1865.6	253.3	227.0	1612.3	1638.5	27.9	36.6	1584.4	1602.0	
		213.1		1652.5		41.2		1611.3		
C3	1914.9	228.5	228.5	1686.4	1686.4	29.3	29.3	1657.1	1657.1	
D3	1865.6	258.4	272.0	1607.1	1593.6	36.3	30.5	1570.8	1563.1	
		318.0		1547.5		26.4		1521		
		234.9		1630.7		28.4		1602.3		

Table 5

Annual E_{out} per inverter and per subsystem. Role Level (R_L) has been included.

UJA Rooftop PV	inverter	$E_{out, inverter}$ (kWh/year)	R_L inverter (%)	$E_{out, subsystem}$ (kWh/year)	R_L subsystem (%)
Parking lot P3	inv1	177687.92	10.8	691662.80	42.1
	inv2	175078.44	10.7		
	inv3	172573.89	10.5		
	inv4	166322.54	10.1		
Parking lot P4	inv5	171718.38	10.5	348261.15	21.2
	inv6	176542.78	10.8		
	inv7	92687.25	5.6		
B4	inv8	178045.68	10.8	270732.93	16.5
C3	inv9	96940.73	5.9		
D3	inv10	81680.97	5.0	233680.68	14.2
	inv11	79096.75	4.8		
	inv12	72902.97	4.4		

Regarding annual yields and losses, it can be seen that inverters associated to same subsystem as their arrays have the same orientation and inclination, they have the same reference yield ($Y_{fi} + L_{C,i} + L_{BOS,i}$). Moreover, it must be highlighted that reference yield corresponding to inverter #8 is the highest as it is oriented to south (0°). As can be seen, the highest capture losses, mainly due to shadowing, are provided by the D3 Rooftop PV inverters while the lowest values correspond to P4 Rooftop PV.

4.1.2. Performance subsystem analysis

Fig. 10 together with Table 4 and 5 show the performance analysis of each subsystem. As expected P3 subsystem is the one which provides more output energy while C3 provides the lowest value, Fig. 10(a). Regarding performance analysis, Fig. 10(b), capture loss are quite similar in P3, B4 and C3 while P4 and D3 provides the lowest and highest value, respectively. On the other hand, regarding BOS loss they are similar in all subsystems, being building C3 which shows the minimum value. The achieved PR subsystem values, Fig. 10(c), are all above 0.80 showing a proper performance [10,12,27]. It must be highlighted the role of the Rooftop PV corresponding to parking lot P3 which shows a R_L of 42.1 % providing near the half of the AC energy generated by the whole PV system.

4.1.3. Performance system analysis

In Fig. 11 it can be found the yields and losses (a) together with system PR, PR_{system} , (b) considering either a monthly and annual reporting periods. As expected, and due to in-plane irradiation values, higher final yields corresponding to spring and summer months are considerably higher than those corresponding to winter and autumn: the highest final yield is reached in July which quadruple the lowest one on December, Table 6. Regarding the capture and BOS losses, they are also lower in autumn and winter months as lower cell and inverter

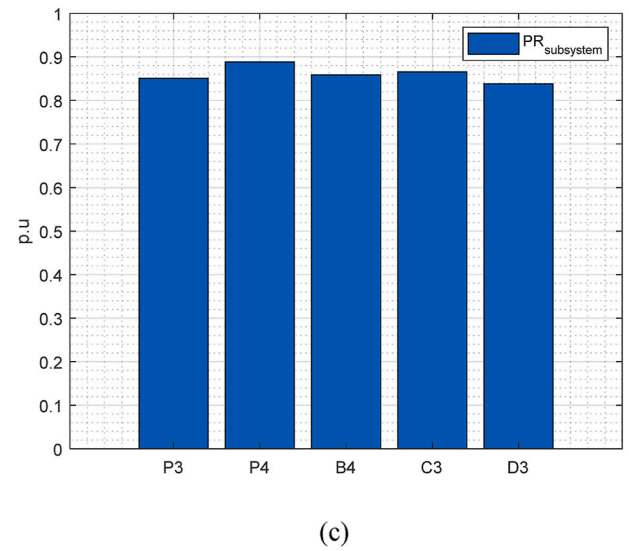
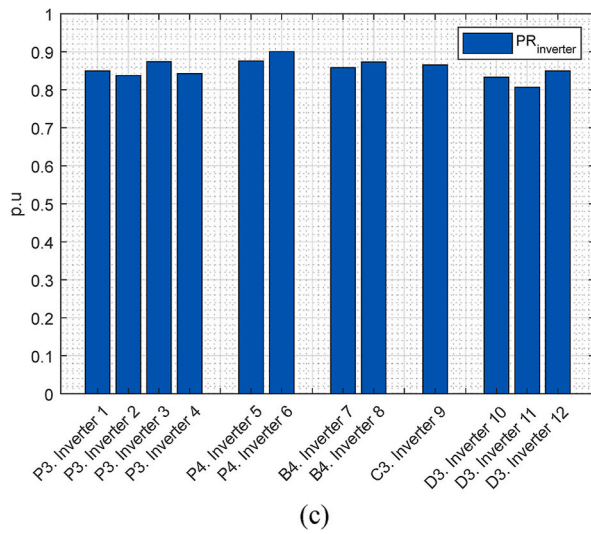
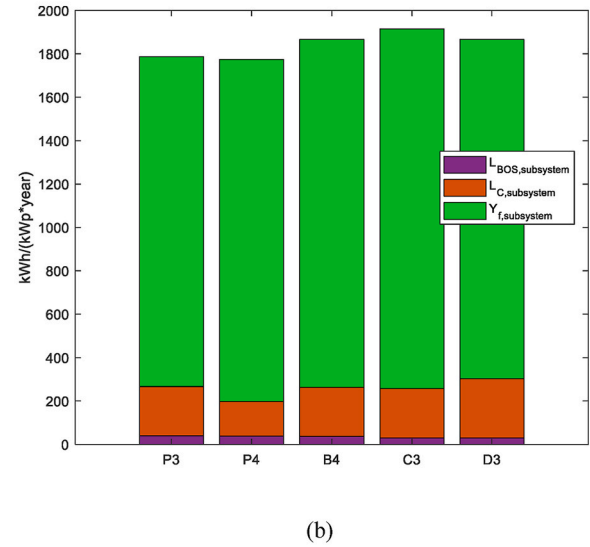
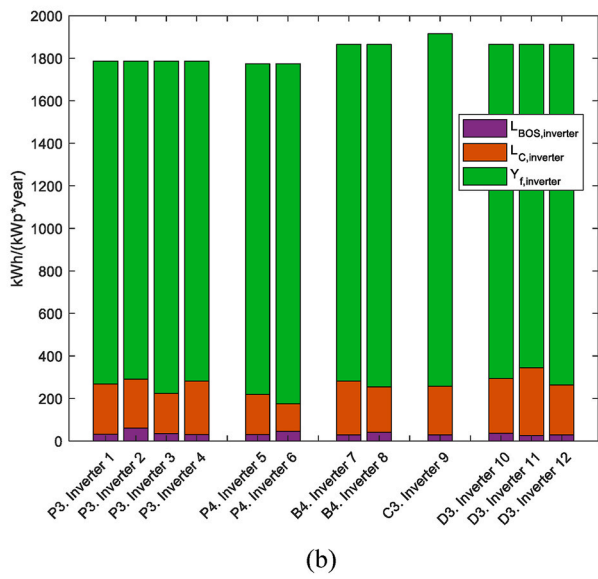
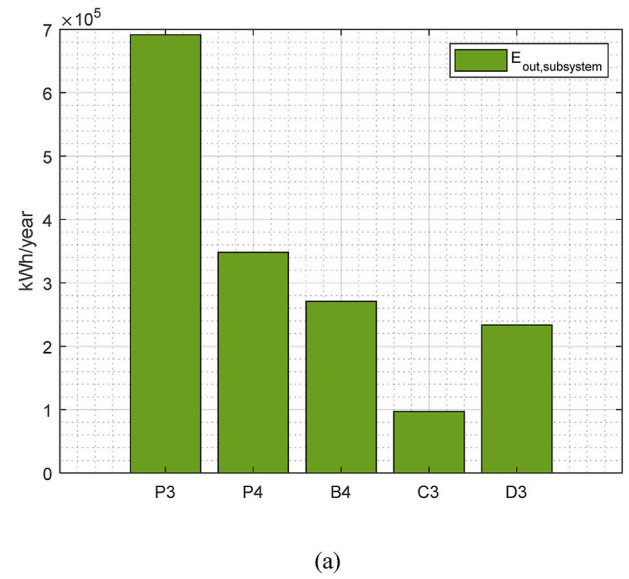
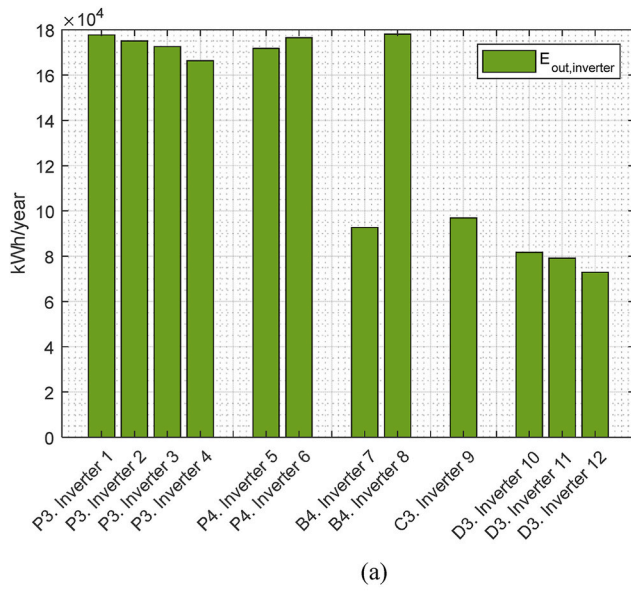


Fig. 9. Annual performance analysis per inverter. (a) Output energy, $E_{out,inverter}$ (b) final yields and losses (c) $PR_{inverter}$.

Fig. 10. Annual performance analysis per subsystem (a) $E_{out, subsystem}$ (b) Sub-system yields and losses (c) $PR_{subsystem}$.

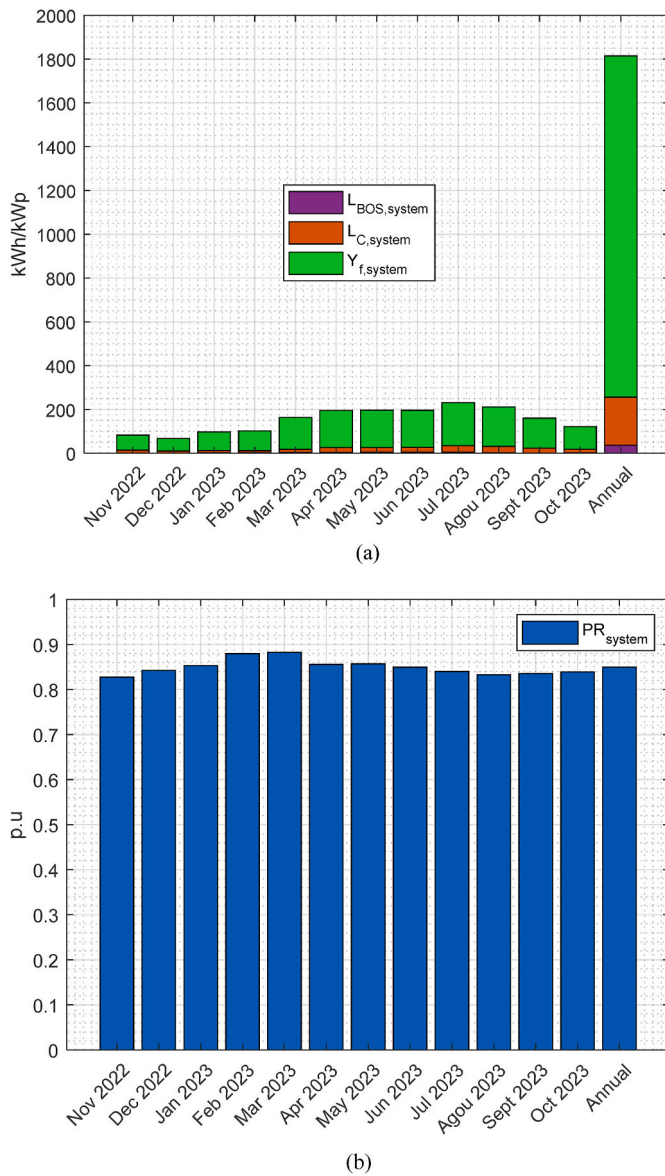


Fig. 11. Monthly and annual system performance (a) yields and losses (b) PR.

temperatures are got. It can be said that capture loss, as expected, are higher during summer months due to the high cell temperatures: 29.67 and 28.65 kWh/kWp in July and August, respectively. In December $L_{C,system}$ shows a minimum value, 9.05 kWh/kWp where lower cell temperatures are got. Moreover, $L_{BOS,system}$ also reaches the highest values

during these months due to the high ambient temperatures in the rooms containing the inverters: 4.89 and 4.30 kWh/kWp in July and August, respectively, while in December 1.08 kWh/kWp are got. Highest PR_{system} are reached in february and march. Anyway, even considering the TC efficiency these values show a proper performance. In Table 6 are also shown the indices and losses together with $PR_{system,TC}$ considering an annual reporting period.

Moreover, monthly and annual CF values are shown in Table 6. This indicator, which is very used in the literature, manages to make comparisons not only between photovoltaic facilities but between different energy production technologies. The obtained annual value perfectly matches with the ones obtained in the analysis of different PV facilities [10,12,14,33].

4.2. Self-consumption and grid usage analysis

The load power profile during several weeks is plotted in Fig. 12 in order to illustrate the UJA daily power consumption profile. *Grosso modo* it can be found two determined consumption periods: *academic* and *non academic* periods. In academic days and from 8:00 a.m. the load consumption increases reaching a maximum; from that point on the load consumption decreases until a minimum which may be placed near high noon. Then, it increases a little again to start decreasing until reaching the night load consumption. This type of daily load profile is got for any academic day, Fig. 12 (a) and (b). The only difference may be found in the maximum load power consumption achieved (i.e. in summer, specially in July, it is got the highest maximum and, therefore, the highest load consumption). Moreover, during non academic days such as the weekends or vacations (e.g. spring break holidays), Fig. 12 (c), it is obtained a load profile where there is very little variability.

Regarding self-consumption and if the daily power profiles at the TC output obtained by the UJA PV system are considered, Fig. 12, it can be seen that during an academic day the whole output profile is under the load consumption one: the whole daily output energy may be self-consumed and no energy will be exported to the grid. On the other hand, on a non academic day, the self-consumption performance depends on the power consumption magnitude. As can be seen, in Fig. 12 (b) during the weekends all the output energy is self-consumed while in Fig. 12(c) which correspond to the spring break vacations, there is output energy that it is not self-consumed and it is exported to the grid.

Fig. 13 shows the daily load consumption, $E_{L,day}$, throughout the analysed year. In order to characterize the energy load consumption, it may be considered not only the monthly and annual consumption but the energy consumption in solar hours, E_{LSH} , which takes place during sunshine hours (from sunrise to sunset) [26], Table 7 and Fig. 14. Moreover, an E_{LSH} to E_L ratio, either monthly and annual, has been defined in order to highlight the diurnal consumption versus the nocturnal one:

Table 6

Monthly and annual yields and losses expressed in kWh/kW concerning the whole UJA Rooftop PV system. PR and CF are also included

Month	$Y_{f,system}$	$L_{C,system}$	$Y_{A,system}$	$L_{BOS,system}$	$Y_{I,system}$	PR_{system}	$L_{TC,system}$	$Y_{I,system,TC}$	$PR_{system,TC}$	CF
Nov_22	82.9	12.4	70.6	1.7	68.9	0.83	0.0	68.9	0.83	0.103
Dec_22	67.4	9.1	58.3	1.5	57.0	0.84	0.0	57.0	0.85	0.082
Jan_23	87.3	10.7	87.3	1.8	74.8	0.86	0.2	74.6	0.86	0.108
Feb_23	101.7	9.6	92.0	2.0	90.0	0.89	0.4	89.7	0.88	0.138
Mar_23	163.0	14.3	148.7	3.2	145.5	0.89	1.4	144.2	0.88	0.208
Apr_23	195.7	22.3	173.4	3.8	169.6	0.87	1.9	167.7	0.86	0.250
May_23	196.5	21.9	174.5	4.0	170.6	0.87	1.9	168.7	0.86	0.244
Jun_23	195.9	23.1	172.7	4.2	168.5	0.86	2.0	166.6	0.85	0.249
Jul_23	231.0	29.7	201.3	4.9	196.4	0.85	2.2	194.2	0.84	0.280
Ago_23	211.6	28.7	182.9	2.4	178.6	0.84	2.2	176.4	0.83	0.255
Sep_23	160.3	21.5	138.8	1.6	135.5	0.85	1.4	134.2	0.84	0.200
Oct_23	121.8	16.2	105.6	2.5	103.1	0.85	0.7	102.4	0.84	0.148
Annual	1814.6	219.0	1595.7	37.0	1558.7	0.86	14.1	1544.5	0.85	0.189

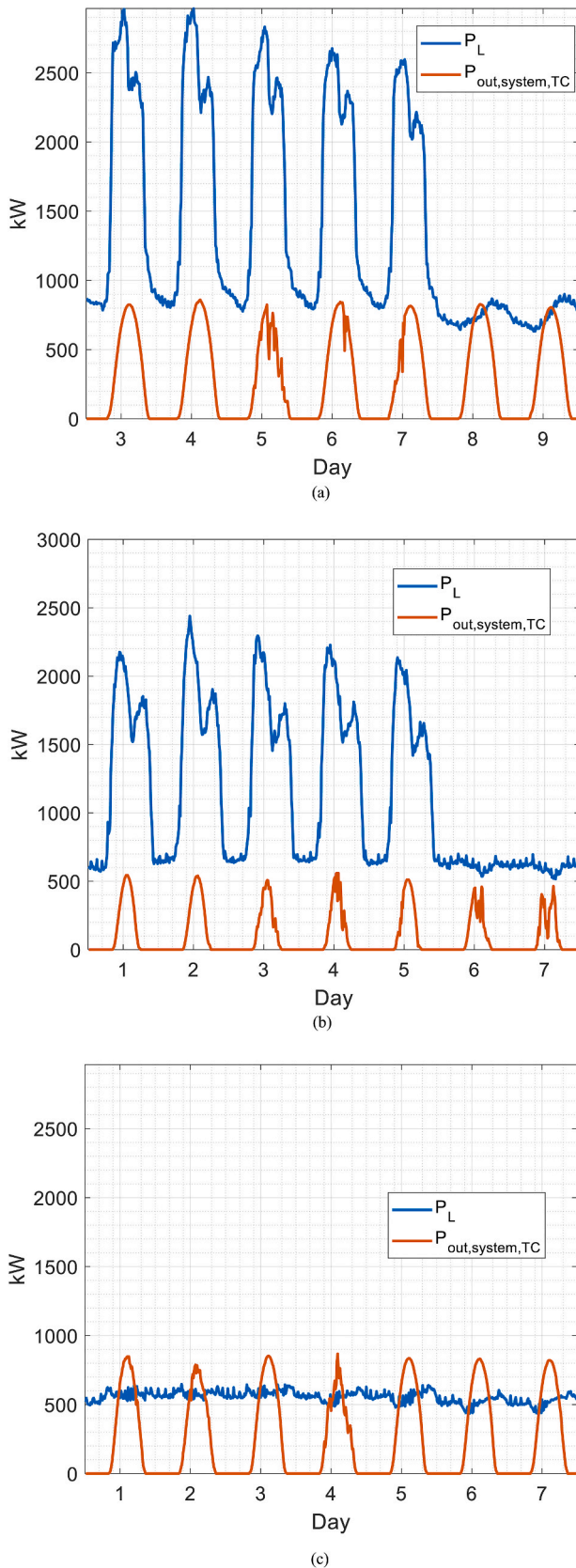


Fig. 12. Power load profile, P_L , and TC output power, $P_{out, system, TC}$, for determined weeks. (a) Academic summer week (b) academic winter week (c) Spring break holidays.

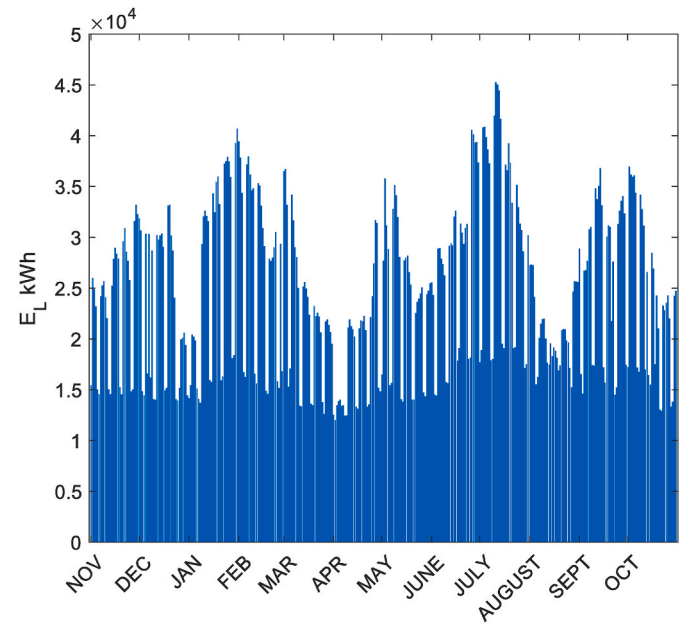


Fig. 13. Daily Load consumption, $E_{L, day}$, throughout a year.

Table 7

Monthly and annual load consumption. Total versus solar hours.

Month	E_L (kWh/month)	$E_{L, monthly}/E_{L, annual}$	E_{LSH} (kWh/month)	$E_{LSH, monthly}/E_{LSH, annual}$	LSHR (E_{LSH}/E_L)
Nov_22	707,657	0.079	383,005	0.067	0.541
Dec_22	708,705	0.079	356,871	0.062	0.504
Jan_23	828,558	0.092	449,103	0.078	0.542
Feb_23	770,788	0.086	454,064	0.079	0.589
Mar_23	705,223	0.078	442,910	0.077	0.628
Apr_23	551,050	0.061	357,866	0.062	0.649
May_23	748,302	0.083	552,797	0.096	0.739
Jun_23	825,185	0.092	628,380	0.110	0.762
Jul_23	972,582	0.108	727,338	0.127	0.748
Ago_23	642,972	0.071	400,919	0.070	0.624
Sep_23	796,956	0.089	532,609	0.093	0.668
Oct_23	740,580	0.082	444,179	0.078	0.600
Annual	8,998,558		5,730,041		0.637

$$LSHR = \frac{E_{LSH}}{E_L} \quad (45)$$

The monthly load consumption varies between 972,582 (July) and 551,050 (April) kWh/month. Moreover, as expected, the monthly and annual energy consumption in solar hours which take place during sun hours (from sunrise to sunset) is always higher than the load consumption outside this time frame. An annual LSHR of 0.637 is achieved while monthly LSHR values ranges between 0.504 (December) and 0.762 (June). These values, together with the daily load consumption profiles show the high potential of Rooftop PV systems without BESS to face the UJA consumption.

Next, a self-consumption analysis as stated in section 3 will be managed using not only the self-consumption and self-sufficiency indices but the calculated parameters and yields defined in Ref. [27], Table 1. Fig. 15 and Tables 8 and 9 show these calculated parameters considering either a monthly and an annual reporting period: load consumption, E_L ; TC output energy, $E_{out, system, TC}$; photovoltaic self-consumed energy, $E_{out, SC}$; energy to grid, E_{TG} and energy from grid, E_{FG} . $E_{out, system, TC}$ reaches maximum values during summer months due to the high irradiation levels. As can be seen, most the output energy is self-consumed and the energy exported to the grid is negligible. E_{TG} reaches a maximum in April due to the low consumption during the

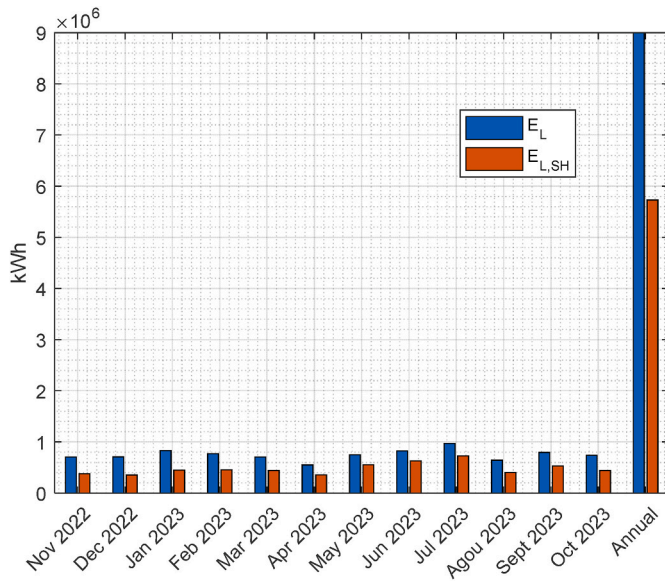


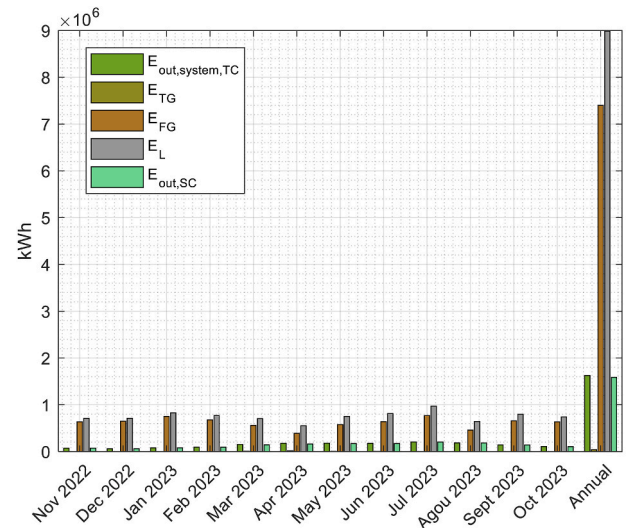
Fig. 14. Monthly and annual load consumption: E_L versus $E_{L,SH}$ (load consumption during solar hours).

weekends and the spring break vacations. In this sense, self-consumption indices, except March and April, are higher than 97 %. Regarding self-sufficiency, the higher values are reached in April and August and are very close to 30 %. The rest of the months this index ranges between 8.5 % (December) and 28 % (August). Furthermore, self-sufficiency index in solar hours may reach 45 % in August and April. Almost half the load consumption in solar hours in these months is faced by the UJA PV system. Apart from these months, this index varies between 16.8 (December) and 32.7 % (March). As indicated in Ref. [27] the final yield can be divided into two new final yields: self-consumption and a to grid final yield. In this case, $Y_{f,SC}$ varies between 193.1 and 56.9 kWh/kWp in July and December, respectively, while $Y_{f,TG}$ ranges between 15.28 and 0.03 kWh/kWp in April and December, respectively.

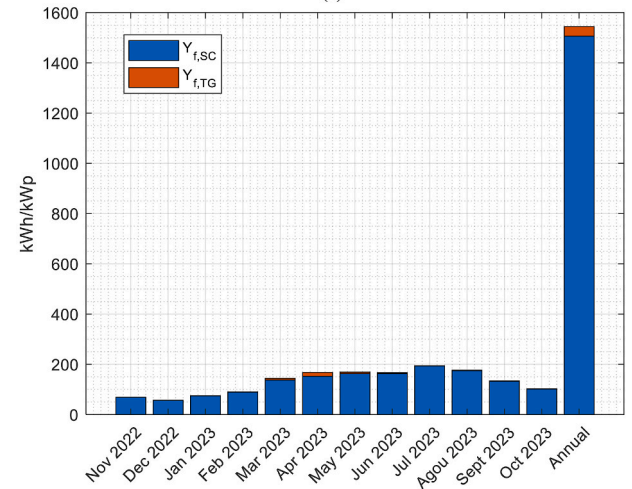
If now an annual reporting period is considered, the final yield is divided into an annual self-consumed yield and a to grid yield of 1506.33 and 38.21 kWh/kWp, respectively, providing an annual self-sufficiency index of 17.65 % where most the output energy is self-consumed: self-consumption index is higher than 97 %. The self-sufficiency index in solar hours may reach 27 %.

It must be highlighted that the high self-consumption index achieved shows that the UJA PV system may be enlarged keeping cost competitiveness and even profitability considering the corresponding self-consumption and self-sufficiency curves together with economic analysis [5,34].

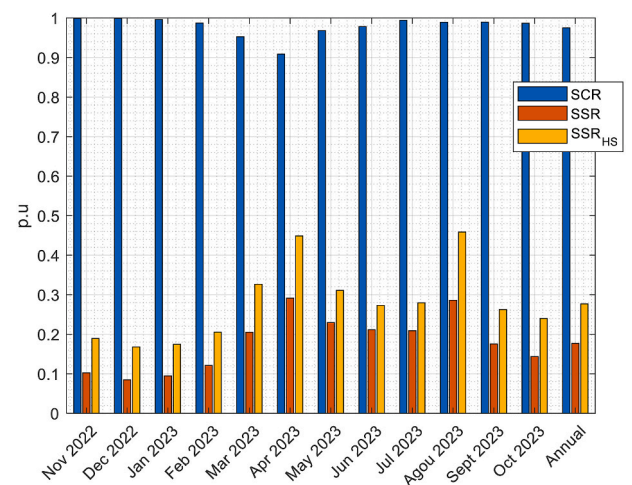
Finally, the Load duration curve for normalized net export electricity [23] corresponding to UJA PV system will be analysed, Fig. 16. Both the peak power on site generation and the peak power load are normalized to the design connection capacity which for University of Jaén is 2400 kW. As can be seen, and as expected, the University of Jaén imports energy 85 % of the time. Moreover, normalized peak power load is greater than one and there is a negligible amount of time where the load power exceeds the design capacity. In this sense, penalties are applied; although, due to the short duration interval when the power load is higher than the design capacity, they are lower than the cost of increasing the design capacity. Anyway, and as aforementioned regarding self-sufficiency, increasing the array power may not only cover a higher fraction of load consumption but it may reduce normalized peak generation, especially below unity.



(a)



(b)



(c)

Fig. 15. Monthly and annual self-consumption analysis (a) energy calculated parameters (b) final self-consumption and final to grid yield (c) Self-consumption and self-sufficiency indices or ratios.

Table 8

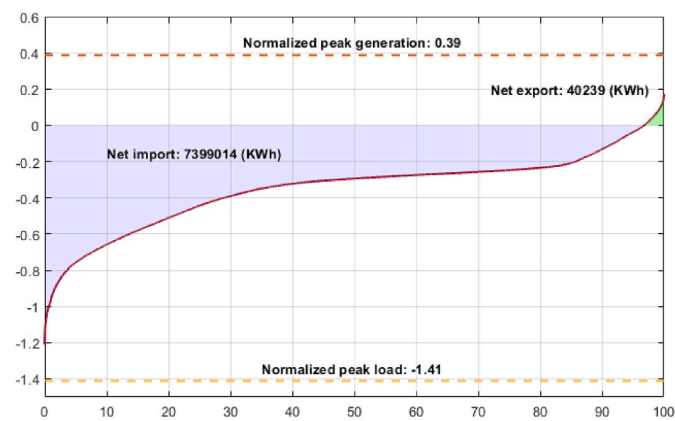
Monthly and annual calculated parameters for the self-consumption analysis of UJA PV system.

Month	$E_{out, \text{system, TC}}$ (kWh)	E_{TG} (kWh)	E_{FG} (kWh)	E_L (kWh)	E_{LSH} (kWh)	$E_{out, SC}$ (kWh)
Nov_22	72,525	52	635,184	707,657	383,005	72,473
Dec_22	59,981	31	648,755	708,705	356,871	59,950
Jan_23	78,588	264	750,234	828,558	449,103	78,324
Feb_23	94,433	1201	677,556	770,788	454,064	93,232
Mar_23	151,808	7166	560,581	705,223	442,910	144,642
Apr_23	176,622	16,095	390,523	551,050	357,866	160,527
May_23	177,623	5655	576,821	748,789	552,797	171,968
Jun_23	175,413	3803	639,708	811,318	628,380	171,610
Jul_23	204,482	1143	769,243	972,582	727,338	203,339
Ago_23	185,763	1972	459,181	642,972	400,919	183,791
Sep_23	141,304	1453	657,105	796,956	532,609	139,851
Oct_23	107,861	1404	634,123	740,580	444,179	106,457
Annual	1,626,403	40,239	7,399,014	8,985,178,00	5,730,041,00	1,586,164

Table 9

Monthly and annual yields, self-consumption and self-sufficiency indices for the self-consumption analysis of the UJA Rooftop PV system.

Month	$Y_{f, SC}$ (kWh/kWp)	$Y_{f, TG}$ (kWh/kWp)	SCR	SSR	SSRHS
Nov_22	68.83	0.05	99.93 %	10.2 %	18.9 %
Dec_22	56.93	0.03	99.95 %	8.5 %	16.8 %
Jan_23	74.38	0.25	99.66 %	9.5 %	17.4 %
Feb_23	88.54	1.14	98.73 %	12.1 %	20.5 %
Mar_23	137.36	6.81	95.28 %	20.5 %	32.7 %
Apr_23	152.45	15.28	90.89 %	29.1 %	44.9 %
May_23	163.31	5.37	96.82 %	23.0 %	31.1 %
Jun_23	162.97	3.61	97.83 %	21.2 %	27.3 %
Jul_23	193.10	1.09	99.44 %	20.9 %	28.0 %
Ago_23	174.54	1.87	98.94 %	28.6 %	45.8 %
Sep_23	132.81	1.38	98.97 %	17.5 %	26.3 %
Oct_23	101.10	1.33	98.70 %	14.4 %	24.0 %
Annual	1506.33	38.21	97.53 %	17.7 %	27.7 %

**Fig. 16.** Load duration curve for normalized net export electricity [23] corresponding to UJA Rooftop PV system.

5. Conclusions

Rooftop PV represents an appealing solution to provide renewable energy generation. In this sense, this type of facilities has experienced a considerable increase and its deployment has the potential to cover a considerable fraction of a city's electricity consumption. Moreover, they can fulfil the building electricity needs for both new and existing buildings not only in the residential sector but in industries, offices and large shopping centres where large Rooftops PV are needed.

This paper shows a methodology to manage a performance, self-consumption and grid usage analysis from monitored data of large Rooftop PV either if a single Rooftop PV or a system composed of

different Rooftops PV are considered and a joint analysis is needed. The set of all Rooftops PV is considered as a system while each Rooftop PV may be seen as a subsystem. Moreover, it has been taken into account the different inverters each Rooftop PV may have. As it has been shown, this approach will be very useful when analysing the role of each inverter and Rooftop PV together with the whole system performance.

This approach firstly provides the performance analysis of the different inverters which, in turn, may define the subsystem performance through weighted parameters obtained from the inverters yields and losses. Finally, the whole system performance will be also estimated as a function of the subsystems performance through weighted parameters. Moreover, this approach may be considered in renewable energy communities where the photovoltaic energy is harvested by several generation plants or Rooftops PV that are spread throughout the energy community and a global analysis is needed.

New weighted parameters have been defined: a new weighted system in-plane irradiation, $H_{I, weighted}$, and a weighted system reference yield, $Y_{r, weighted}$, in order to achieve the global PV system performance due to the different array orientation and inclination of the Rooftops PV involved.

In order to show this methodology, it has been analysed from monitored data obtained throughout a year the photovoltaic system of 1.050 MW installed at the University of Jaén. Analysis have been managed considering both monthly and annual reporting periods. This system consists of five facilities or Rooftops PV installed in several buildings and parking lots with different nominal array power and different array inclination and orientation. Results show PR subsystem and system values above 0.83 and a global CF value of 0.19 has been reached, showing a proper performance. It must be highlighted the role of the Rooftop PV corresponding to parking lot P3 which shows a role level of 41.2 % providing almost the half of the AC energy generated. Regarding self-consumption and grid usage, annual self-consumption and self-sufficiency indices of 97.5 % and 17.7 %, respectively, are achieved. Moreover, a self-sufficiency in solar hours of 27.7 % is obtained. These values show not only the high matching between generation and consumption profiles where little energy is exported to the grid but the potential to fulfil the electricity demand in the different buildings of the University of Jaén. Moreover, as it has been shown, and considering the high self-consumption index together with the shape of the consumption and generation profiles and the high load solar hours ratio achieved, 0.64, the array power of the system may be considerably increased, maintaining high self-consumption ratios but at the same time providing higher self-sufficiency indices.

The methodology here shown not only provide an analysis of large Rooftops PV at different levels: inverter, subsystem (i.e. each PV Rooftop system) and the whole system but it may help to better detect anomalies and malfunctions.

CRediT authorship contribution statement

F.J. Muñoz-Rodríguez: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **P. Gómez:** Validation, Supervision, Project administration, Investigation. **J.I. Fernández-Carrasco:** Software, Data curation. **G.M. Tina:** Writing – review & editing, Visualization, Investigation, Formal analysis. **G. Jiménez-Castillo:** Software, Investigation, Formal analysis, Data curation.

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.

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