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Performance comparison between micro-inverter and string-inverter Photovoltaic Systems

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Abstract

This paper focuses on the analysis of the energy production of building integrated photovoltaic systems. All the PV systems are located in the south part of Italy - Sicily. A comparison has been made between two different conversion technologies: string-inverter versus micro-inverter.

The two string-inverter systems analyzed have different azimuth angle, no shadowing, different peak power and different types of photovoltaic modules (monocrystalline and polycrystalline silicon). The four micro-inverter systems have different shadowing percentage, different azimuth. All systems have fixed tilt angle and fixed azimuth angle. The experimental data were treated for almost one year. In order to analyze the performance of the systems, the most common Indexes (the Energy Yield Y_f, the Reference Yield Y_R, the Performance Ratio PR and Efficiency η) have been used. This allowed to obtain a correct comparison even with different Irradiance values and different Peak Powers.

The main goal of the analysis has been to evaluate the performances of the micro-inverter systems at different shadowing conditions. The results of the comparison have confirmed that micro-inverter systems present better performances both at shadowed and “not-shadowed” conditions.

By comparing not-shadowed systems with the two different conversion technologies and similar azimuth and tilt angle it has been shown how, with almost the same values of Irradiance, micro-inverter systems maximize the energy production.

Furthermore, the highest percentage of produced energy could justify the more expensive cost of this new conversion technology.

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Keywords: microinverter, photovoltaics, string inverter, performance ratio, shading;

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1. Introduction

The debate about the ways to generate electrical energy has taken a main dispute: distributed versus centralized generation. The opportunity to relieve the electricity grids by the on-site production of energy may help to reduce the losses due to transmission. Moreover smart grids will be freer to redistribute the energy generated by renewable systems in order to replace the traditional power plants with distributed renewable energy power plants [1].

This idea leads to a growth in the installation of small power plants in order to generate on-site the necessary energy. The improvements in energy storage, such as Li-batteries, or in energy conversion systems should lead to the same direction [2]. Therefore, the aim should be at relieving the grids and letting the old fossil fuels power plants be dismissed for a cleaner energy production era.

This virtuous scenario would also help to make changes in mobility systems with an increasing diffusion of electrical, hybrid or hydrogen vehicles [3]. The change could also help in building heating and cooling systems, by the use of heat pumps more than traditional boilers. All these changes lead to a less polluting electrical [4-5] and thermal generation of energy with a slighter use of combustion systems. The use of building integrated photovoltaic systems is one of the ways to make these changes possible. It has seen an enormous growth during the last years, after the Kyoto protocol application, thanks also to the environmental policies applied by many countries.

In this paper it has been analyzed the energy production of different building integrated PV systems with two different conversion technologies: micro-inverter conversion (using each single module to generate AC electricity) versus string-inverter conversion (allowing the conversion from DC to AC only after a certain number of modules in order to have a minimum of potential difference to power the inverter up). The energy extraction characteristics of a solar PV system for different converter schemes, including central, string and micro-converter configurations has been studied in [6]. In order to understand the utility of microinverter an experimental setup of One system with a standard string inverter and another with microinverters on each solar panel is described in [7]. Partial shade is applied to both systems in a comprehensive range of shading conditions, simulating one of three shade extents. A study about the economic viewpoint has been carry out in [8]. A low cost single stage micro-inverter with MPPT for grid connected applications has been studied in [9]. The literature survey also notes that most micro-inverters are designed in the power range of 100–250 W with power conversion efficiencies above 90% [10].

In this paper the analysis have been made on two string-inverter (SIS) and four micro-inverter (MIS) systems with different tilt angle, azimuth angle, peak power, latitude and longitude, shadowing percentage and panel materials.

In order to have a correct way to compare systems with all these differences it has been necessary to calculate many performance indexes to elude all the dissimilarities and to have comparable results.

2. Performance indexes

The performances of different PhotoVoltaic systems could be analyzed with an index named Performance Ratio (PR). The PR evaluates the performance of the system by rationing the value of “energy produced per peak power installed” with the value of the “radiation received per Irradiance of the site”.

The ratio between the energy production E [kWh] and the system peak power P_0 [kW_p] is known as Array Yield (Y_f). The Y_f can be evaluated before or after the inverter, in order to have a Y_{f_DC} or Y_{f_AC}. The Array Yield is measured in hours [h] and helps to compare system of different sizes.

The value of the Solar Radiation Received E_{GNI} [kWh/m^2] divided per the Global Normal Irradiance of the site GNI (1000 [W/m^2] for fixed tilt angle PV systems) is known as Reference Yield (Y_R).

The Reference Yield is measured in hours [h] and normalizes the energy received for different sites (location, weather condition), azimuth and tilt angle.

By the ratio of these two indexes the Performance Ratio index is defined as follow:

$$PR = \frac{Y_f}{Y_R} = \frac{E_{GNI}}{GNI} \quad (1)$$

The PR is an index of the efficiency independent of the Peak Power and the Irradiation of the site. With these indexes is possible to evaluate the energy losses:

$$L_C = Y_R - Y_{f\_DC} \tag{2}$$

It includes the thermal losses due to temperature higher than 25 °C , the transmission of the cables, the bypass diodes, the MPPT, mismatch, spectral losses.

Using the Y_{f_AC} the losses of energy conversion are calculated as follow:

$$L_S = Y_R - Y_{f\_AC} \tag{3}$$

The efficiency of the system (η) is the ratio between the produced energy (E_{PROD}) and the Irradiation received:

$$\eta = \left(\frac{E_{PROD}}{E_{DNI} \cdot A}\right) \cdot A \tag{4}$$

It is possible then to relate PR with η:

$$PR = \left(\eta \cdot \frac{A}{100} \cdot \frac{DNI}{P_0}\right) \cdot 100 \tag{5}$$

By using the efficiency it is possible to compare systems with the same peak power, same conversion technology and same irradiation received. It is more accurate if we consider the conversion of the module, but it is more restrictive for a study of various systems, as in this case.

3. Systems description

All the systems analyzed are installed in Sicily – Italy. They are six photovoltaic systems grid connected and are located in six different municipalities of Sicily: four MIS and two SIS. The medium EGNI is about 1900 $[kWh/m^2]_{year}$. All of them are building integrated systems installed on roofs, the tilt and azimuth angles are fixed.

The difference in received irradiation is not high, as it is possible to notice by comparing the values of the Reference Yield (in a range from 4.9 to 5.6 h); the comparison among the system could have been done just by using the Array Yield values. However by using the Y_R values it is possible to compare the best azimuth/tilt/location conditions (that are quite dissimilar in the different installations).

For all of these systems the total Energy production in a year has been estimated by a simulating software (E_{est}) and compared with the real measured energy (E_{real}). In order to have a more accurate comparison it has been considered in the simulation the estimation of different energy conversion losses such as:

- Losses due to temperature and low irradiance
- Losses due to angular reflectance effects
- Other losses (cables, inverter etc.)

The thermal losses are related with the cell temperature or the ambient temperature as follows:

$$P_{tpv} = \frac{(T_{cell} - 25) \cdot \beta}{100} \tag{6}$$

$$P_{tpv} = \frac{\left[T_{atm} - 25 + \frac{(NOCT - 20) \cdot I}{800}\right] \cdot \beta}{100} \tag{7}$$

where:

- β: power temperature coefficient (for silicon modules is 0.4-0.5 %/°C).
- NOCT: Nominal operating cell temperature (usually 40-50 °C).
- T_{atm}: atmospheric temperature
- T_{cell}: is the temperature of the PV module.

The E_{est} of the system at STC is given by the relation from the UNI 8477-1:

$$E_{est} = \frac{P \cdot Irr_{est}}{1000} \cdot (1 - Disp) \qquad [\text{kWh/year}] \tag{8}$$

where:

- P is the peak power of the system [kW].
- Irr_{est} is the average year global irradiation per square meter received by the modules [kWh/m^2] calculated by the UNI.
- Disp is the percentage of energy losses determined by the sum of those losses cited before.

3.1. String-Inverter System (S1)

The SIS-S1 analyzed has a peak power of about 2.86 kW (Fig. 1).

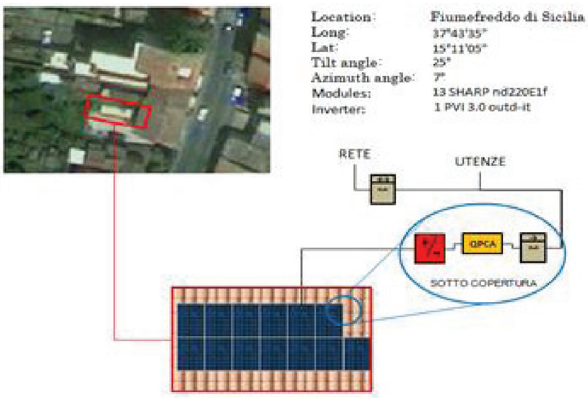

Fig. 1. The String-Inverter System S1

The system is orientated almost perfectly South with a tilt angle of 25 degrees. There are no obstacles that shadow the area. The system technical characteristics are shown in Table 1:

Table 1. Datasheet of the system S1.

SYSTEM		INVERTER	
P_{max}	2860 W	N° of inverters	1
Azimuth	7° (South-West)	P_o	3.12 kW
Tilt	25°	P_{max}	3.43 kW
Shadowing	0%	V_0	360 V
Location	Fiumefreddo (CT)	V_{max}	600 V
MODULES		V_1	231 V
Material	SI-polycrystalline SHARP nd220E1f	I_0	20 A
η	13.4 %	I_{max}	20 A
P_{max}	220 W	η	96 %
V_n	29.2 W	Total Area	20.8 m^2
V_0	36.5 V		
I_n	7.5 A		
I_0	8.2 A		
N° of modules	13		

The losses and total energy production are shown in Table 2:

Table 2. Losses and Energy production of S1.

System S1	
Losses due to Temperature and low irradiance	15.5 %
Losses due to angular reflectance effects	2.6 %
Other losses	7.0%
Total losses	25.1 %
E_{est}	4281.74 kWh/y
E_{real}	4263.81 Wh/y

3.2 String-Inverter System (S2)

The SIS-S2 has a peak power of about 5.98 kW (Fig. 2). The system is orientated East and West (two orientations for the two strings) with a tilt angle of 22 degrees. There are no obstacles that shadow the area.

The losses and total energy production are shown in Table 4:

Table 4. Losses and Energy production of S2.

System S2	
Losses due to Temperature and low irradiance	14.9 %
Losses due to angular reflectance effects	3.3 %
Other losses	0.0%
Total losses	18.2 %
E_{est}	8758.16 kWh/y
E_{real}	8713.49 kWh/y

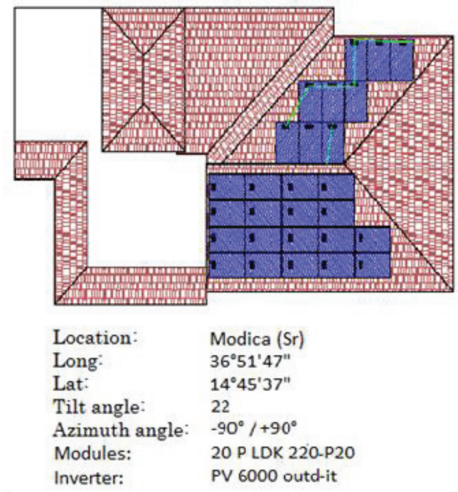

Fig. 2. The String-Inverter System S2

The system technical characteristics are shown in Table 3:

Table 3. Datasheet of the system S2.

SYSTEM		INVERTER	
P_{max}	5940 W	N° of inverters	1
Azimuth	-90°/+90° (East –West)	P_o	6.2 kW
Tilt	22°	P_{max}	6.9 kW
Shadowing	0%	V_0	360 V
Location	Modica (RG)	V_{max}	600 V
MODULES		V_1	231 V
Material	Si – polycrystalline (ldk p20)	I_0	36 A
η	13.5 %	I_{max}	36 A
P_{max}	220 W	η	96 %
V_n	29.8 V	Total Area	43.1 m^2
V_0	36.5 V		
I_n	7.4 A		
I_0	8.1 A		
N° of modules	27		

3.2. Micro-Inverter System M1

The MIS-M1 has a peak power of about 3.00 kW (Fig. 3). The system is orientated South-East with a tilt angle of 15 degrees. There are some obstacles that shadow the area. The average shadow percentage is given by the value of 9.4%.

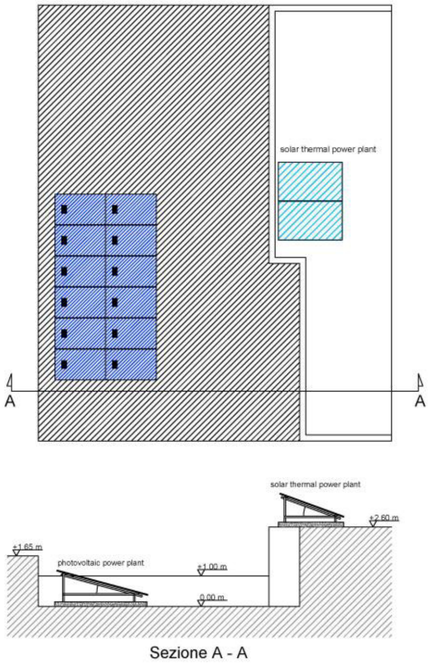

Fig. 3. The Micro-Inverter System M1

The system technical characteristics are shown in Table 5:

Table 5. Datasheet of the system M1.

SYSTEM		INVERTER	
P_{max}	3000 W	N° of inverters	12
Azimuth	-16°(South-East)	P_o	200 W
Tilt	15°	P_{max}	215 W
Shadowing	9.4%	V_0	29 V
Location	Assoro (EN)	V_{max}	45 V
MODULES		V_1	230 V
Material	Si – polycrystalline	I_0	7.4 A
η	14.8 %	I_{max}	10.5 A
P_{max}	250 W	η	95.4 %
V_n	29.8 V	Total Area	19.48 m^2
V_0	37.1 V		
I_n	8.4 A		
I_0	8.9 A		
N° of modules	12		

The losses and total energy production are shown in Table 6:

Table 6. Losses and Energy production of M1.

System M1	
Losses due to Temperature and low irradiance	14.8 %
Losses due to angular reflectance effects	2.7 %
Other losses	12.0%
Total losses	29.5 %
E_{est}	4251.21 kWh/y
E_{real}	4231.87 kWh/y

3.3. Micro-Inverter System M2

The MIS-M2 has a peak power of about 3.00 kW (Fig. 4). The system is orientated South-East with a tilt angle of 17 degrees. There are some obstacles that can shadow the area. An evaluation of the average shadow percentage during the year has given a value of 12%.

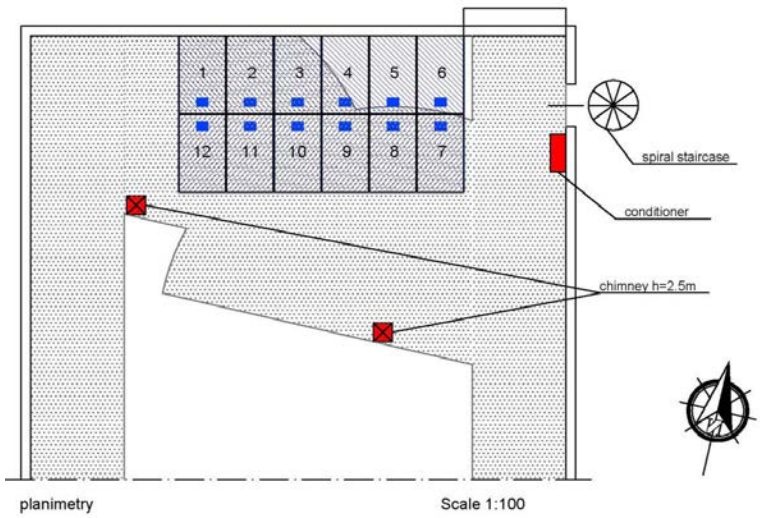

Fig. 4. The Micro-Inverter System M2

The system technical characteristics are shown in Table 7:

Table 7. Datasheet of the system M2.

SYSTEM		INVERTER	
P_{max}	3000 W	N° of inverters	12
Azimuth	-13°(South-East)	P_o	200 W
Tilt	17°	P_{max}	215 W
Shadowing	12%	V_0	29 V
Location	Noto (SR)	V_{max}	45 V

MODULES			
Material	Si – polycrystalline	V_1	230 V
η	14.8 %	I_0	7.4 A
P_{max}	250 W	I_{max}	10.5 A
V_n	29.8 V	η	95.4 %
V_0	37.1 V	Total Area	19.48 m^2
I_n	8.4 A		
I_0	8.9 A		
N° of modules	12		

The losses and total energy production are shown in Table 8:

Table 8. Losses and Energy production of M2.

System M2	
Losses due to Temperature and low irradiance	15.5 %
Losses due to angular reflectance effects	2.8 %
Other losses	7.0%
Total losses	25.3 %
E_{est}	4697.39 kWh/y
E_{real}	4673.83 kWh/y

3.4. Micro-Inverter System M3

The MIS-M3 has a peak power of about 2.88 kW (Fig. 5). The system is orientated South-East with a tilt angle of 51 degrees. There are no obstacles that shadow the area.

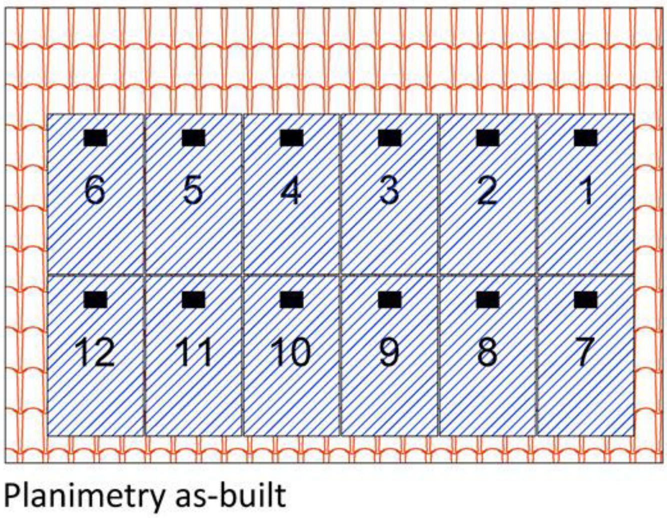

Fig. 5. The Micro-Inverter System M3

The system technical characteristics are shown in Table 9:

Table 9. Datasheet of the system M3.

SYSTEM		INVERTER	
P_{max}	2880W	N° of inverters	12
Azimuth	-51°(South-East)	P_o	200 W
Tilt	12°	P_{max}	215 W
Shadowing	0%	V_0	29 V
Location	Calascibetta (EN)	V_{max}	45 V
MODULES		V_1	230 V
Material	Si – polycrystalline	I_0	7.4 A
η	14.0 %	I_{max}	10.5 A
P_{max}	240 W	η	95.4 %
V_n	30.7 V	Total Area	19.48 m^2
V_0	37.4 V		
I_n	7.9 A		
I_0	8.6 A		
N° of modules	12		

The losses and total energy production are shown in Table 10:

Table 10. Losses and Energy production of M3.

System M3	
Losses due to Temperature and low irradiance	15.5 %
Losses due to angular reflectance effects	2.8 %
Other losses	7.0%
Total losses	25.3 %
E_{est}	4090.50 kWh/y
E_{real}	4291.73 kWh/y

3.5. Micro-Inverter System M4

The MIS-M4 has a peak power of about 2.94 kW (Fig. 6). The system is orientated South-East with a tilt angle of 37 degrees. There are some obstacles that shadow the area. The average shadow percentage is given by a value of 5.4%.

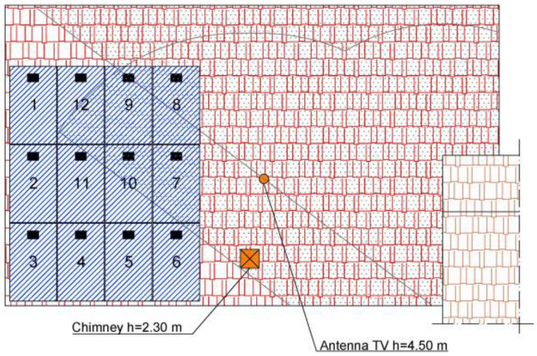

Fig. 6. The Micro-Inverter System M3

The system technical characteristics are shown in Table 11:

Table 11. Datasheet of the system M4.

SYSTEM		INVERTER	
P_{max}	2940 W	N° of inverters	12
Azimuth	-37°(South-East)	P_o	200 W
Tilt	17°	P_{max}	215 W
Shadowing	5.4%	V_0	29 V
Location	Valverde (CT)	V_{max}	45 V
MODULES		V_1	230 V
Material	Si – polycrystalline	I_0	7.4 A
η	14.9 %	I_{max}	10.5 A
P_{max}	240 W	η	95.4 %
V_n	30.7 V	Total Area	19.48 m^2
V_0	37.4 V		
I_n	7.9 A		
I_0	8.6 A		
N° of modules	12		

The losses and total energy production are shown in Table 12:

Table 12. Losses and Energy production of M4.

System M4	
Losses due to Temperature and low irradiance	10.0 %
Losses due to angular reflectance effects	3.0 %
Other losses	8.0%
Total losses	21.0 %
E_{est}	4681.98 kWh/y
E_{real}	4452.17 kWh/y

4. Data Analysis

A whole year analysis (2013) has been developed for all the six systems. The values of irradiation received by the systems have been evaluated by using a simulation software at the different latitudes of the sites (H_real). Each MIS has a peak power of 215 W: this means that connected to a 250 W module, the maximum power cannot overcome the value of 215 W. In order to avoid this limitation of evaluating the performances an "enhanced" approach for the micro-inverter systems has been used: the Energy Yield Y_f has been evaluated on a maximum power of 2.58 kW (215 W x 12 modules), that is the maximum power reachable by the micro-inverters.

Three different values have been found for the calculation of the PR:

- PR estimated (PR_e) by using the values of energy production estimated by the simulation software;
- PR real (PR_r) by using the real values of energy production from the systems measured on site;
- PR enhanced (PR_{en}) by using for the MIS an enhanced value of energy yield Y_f with a peak power of 2.58 kW, the maximum that can be used by the 12 microinverter of the systems.

The mean values of all PR calculated are shown in the table 13 and Fig. 7:

Table 13. PR mean values comparison for all systems.

System	PR_e	PR_r	PR_{en}
S1	0.77	0.70	-
S2	0.83	0.84	-
M1	0.74	0.73	0.85
M2	0.77	0.77	0.90
M3	0.81	0.77	0.86
M4	0.77	0.79	0.90

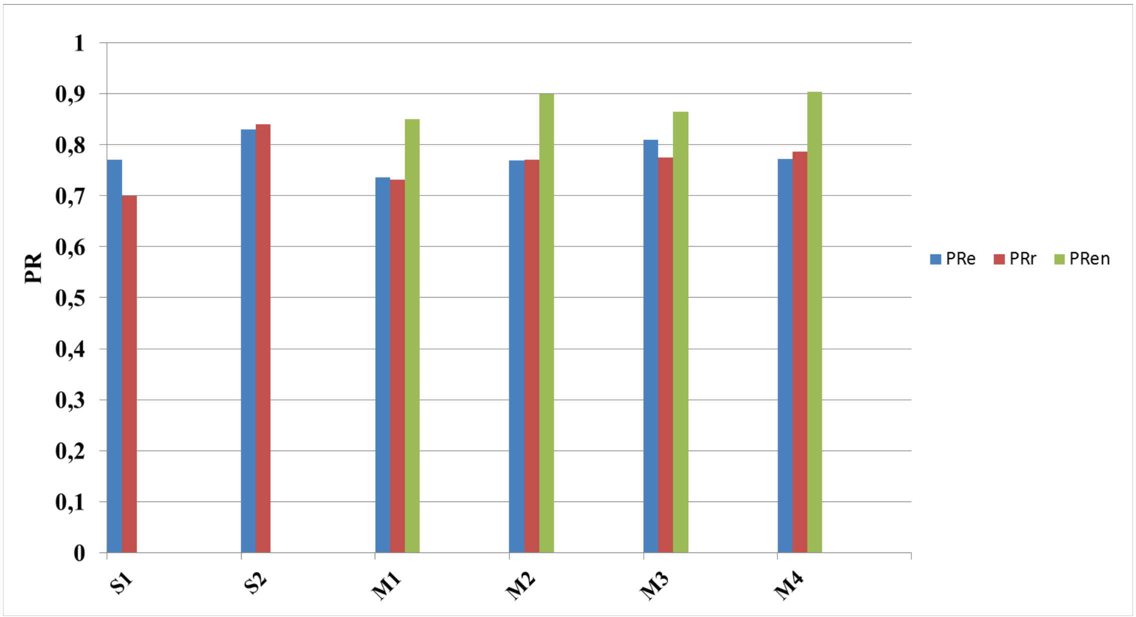

Fig. 7. PR indexes for all systems.

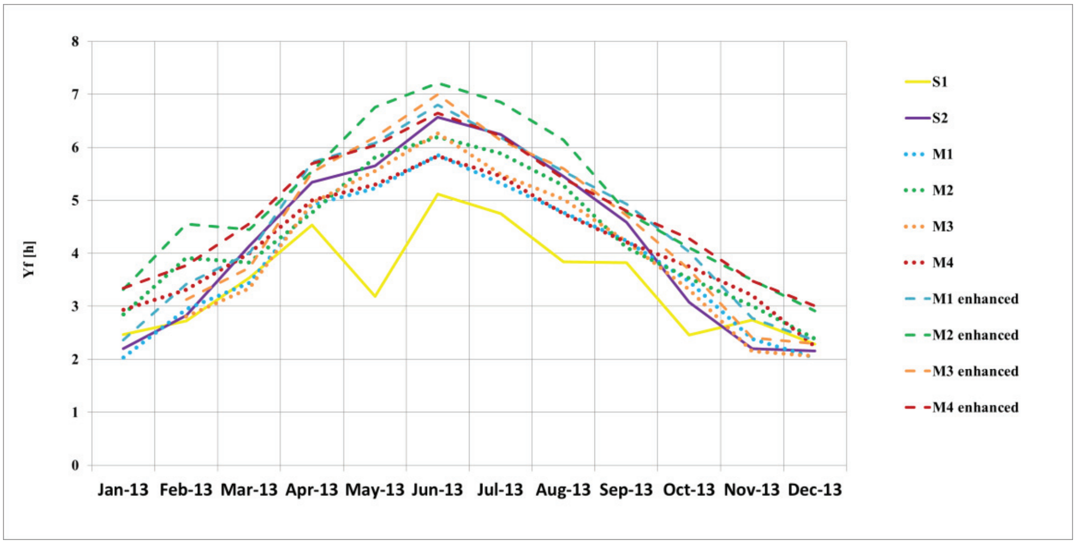

Fig. 8. Yf indexes for all systems.

By taking the mean value of Y_f of the string inverter systems as the reference, a comparison has been made among all the systems to understand the performances showed during the evaluation time (Fig. 8). The enhanced performances of the MIS have showed clearly that the energy produced per peak power has been higher than the SIS. Studying the real production only one MIS worked worse (98.8% the energy production of the SIS even if more than 9% of the surface was shadowed during the year). With a mean shadowing percentage on MIS of 6.7%, the energy production per peak power Y_f has been higher than 4.8% on real analysis, than 20.17% on enhanced analysis.

5. Conclusions

A comparison between MIS and SIS has been developed. This has highlighted the great potentialities of MIS. Although the four MIS were partially shaded their performances were better. Moreover, the SIS need a roof of a certain area to contain at least 5 or 6 modules (990 mm * 1640 mm * 6 modules is almost 10 m^2) in order to reach the V_0 of the inverter to start the conversion DC/AC. Instead, the MIS can be installed module by module, giving much more options on utilizable roofs and size of the systems The results showed the great potentiality of MIS to raise the energy production by using the same area on the roofs. This would demonstrate the enormous potentiality of micro-inverters in roof integrated PV systems to reduce traditional power plants loads. For future work another scenario could be the calculation of the roof area not usable with the traditional SIS in order to evaluate the amount of lost energy production in comparison with MIS.

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