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Review

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Performance ratio of photovoltaic installations in France

Comparison between inverters and micro-inverters

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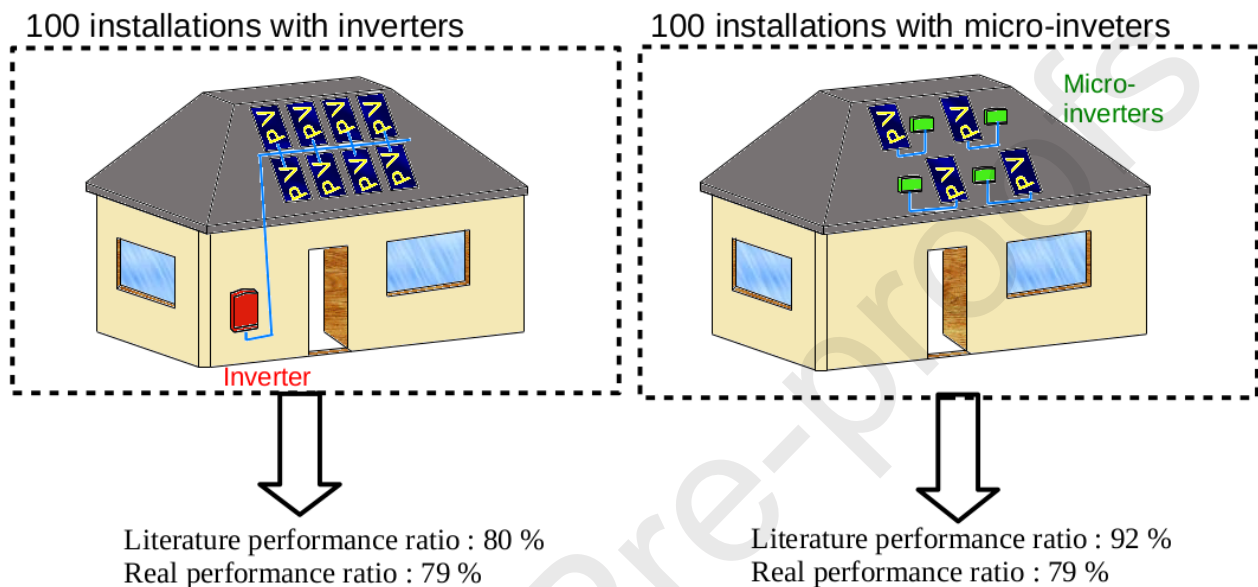
Performance ratio of photovoltaic installations in France

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Abstract : The **efficiency** of a **photovoltaic installation** is determined by its **performance ratio PR**. This ratio depends on many parameters including orientation, inclination, shading, losses in cables, number and performance of panels,.... The topology of the installation is also of great importance. Indeed, the number and location of the converter(s) can also have a significant impact on the PR. This is why choices between a **central inverter**, **string inverters** or **micro-inverters** must be made in order not to degrade the PR. In the scientific literature, it is stated that a photovoltaic installation equipped with a central inverter has a PR of between 70 and 80%. For micro-inverters in theory, it should be higher. The objective of this publication is to compare the

PK of installations equipped with a central inverter and string inverters with those using micro-inverters based on a statistical study grouping together 200 private installations spread throughout metropolitan France. For a better comparison, 100 installations will use a central inverter or string inverters and 100 other installations will use micro-inverters. For each installation, the data will be averaged over the longest possible periods.

Graphical abstract



Highlights :

- The performance ratio quantifies the losses induced by solar installations
- Microinverters have the same performance ratio as inverters
- The size of an installation has no influence on the performance ratio
- An installation with a strong irradiance will decrease the performance ratio

Keywords : *converter – inverter – micro-inverter – performance ratio – photovoltaic panels*

List of abbreviations:

°C: degrees Celsius
 Ω : Ohm
 C : Coulon
 eV : electronvolt
 J : Joule
 K : Kelvin
 kW : kilowatt
 kWh : kilowatt hours
 kWp : kilowatt peak
 m: meters
 PR : Performance Ratio
 W: Watt

I. Introduction

To transform the direct current generated by photovoltaic panels into an alternating power, allowing to power household appliances or to be resold, a set of energy converters is necessary.

When the illumination remains uniform over the entire installation, all panels can be connected to a central inverter.

If the illumination varies from one location to another, it is recommended to use string inverters, that is, to break down the installation into different zones with identical illumination conditions. The panels in the same zone are connected to an inverter and the installation therefore requires as many inverters as there are zones.

It is also possible to associate each panel with its own converter. Using micro-inverters can greatly reduce the problems of shading or failure of a panel, which for a central inverter causes production losses.

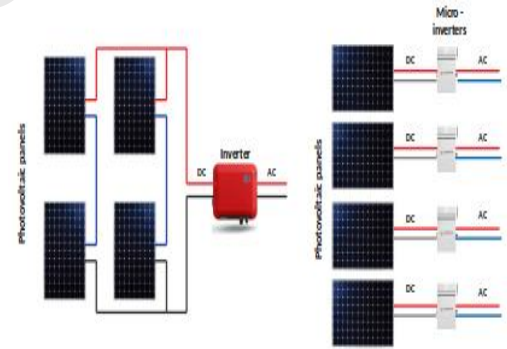


Figure 1 describes the difference in connection for a photovoltaic installation with an inverter or micro-inverters. The operation of inverters and micro-inverters is explained in more detail respectively in (Adouane et al., 2009) and (Scholten et al., 2013).

With each installation are associated losses between the theoretical production and the real production. They will cause a loss of efficiency of the installation, quantified by its performance ratio PR.

Figure 1: Explanatory diagram of a possible connection of four panels with an inverter on the left and micro-inverters on the right.

II. Theoretical estimate of PR

The PR depends on the various losses associated with the systems.

A first cause of losses is related to the electrical resistance of cables according to Equation 1.

$$R = \rho \frac{L}{S} \quad (1)$$

With:

R : Electrical resistance of cables in Ω

ρ : Resistivity of the material in $\Omega.m$ (generally copper)

L: Cable length in m
S: Cable section in m²

The greater the resistance, the higher the associated losses, corresponding to the power lost (Equation 2).

$$P = RI^2 \quad (2)$$

The cables have the same characteristics for an installation with an inverter or micro-inverter. Thus, the resistivity of the cable is identical. However, the length and section of the cables will be different depending on the installation. In fact, the micro-inverters are placed under the panels, at the level of the roofs (L is therefore small) and receive low currents that do not require a large cable (S small). On the contrary, the inverters are rather positioned inside the home (L large) and must withstand higher intensity (S large). In the end, the L / S ratio is approximately the same, in both cases. Losses in cables are estimated at 1 to 2% (Ekici and Kopru, 2017) for inverters and micro-inverters.

A second cause of losses is directly linked to converters. According to the instructions of the manufacturers of inverters and micro-inverters, the efficiency is between 95% and 98% depending on the brands and the quality of the equipment. Inverters and micro-inverters are subject to temperature ranges that must not be exceeded otherwise they will lose a little more efficiency. For inverters, the range is between -25 ° C and 60 ° C, that of micro-inverters between -40 ° C and 65 ° C. Since the inverters are often located in sheltered areas, the temperature impact on the inverter is low. Since micro-inverters are placed under roofs, the temperature variation is greater. Because micro-inverters are shaded by panels, it is very rare to go outside the expected temperature range. The study (Enphase Energy, 2013) on the temperature of micro-inverters demonstrates this.

The third cause of loss is related to the location of the panels. It can come from the temperature and irradiance modifying the operation of the modules, from the tolerance on the peak power of the installation. The losses due to temperature and irradiance for a panel with N_s cells in series and N_p cells in parallel follow the mathematical expression of Equation 3 (Acakpovi and Hagan, 2013).

An increase in the temperature of the modules causes a loss of efficiency of 0.3 to 0.4% / ° C depending on the panels (Tripathi et al., 2017). A decrease in irradiance causes a decrease in the intensity of the photovoltaic modules of approximately 0.12 W / (W / m²).

Shading also causes other losses. An important difference is present between inverters and micro-inverters. Indeed, the impact of shading on the efficiency of the installation will depend on the connection between panels. All the panels connected in series with each other will influence each other. As shown Figure 2, shading on part of a panel will cause a loss on the panel connected in series with it. However, panels connected in parallel are not impacted.

In the example of Figure 2, with a connection to an inverter, 50% of the installation is impacted by shading. In the case of micro-inverters, since the panels are not interconnected, only the shaded panel will be impacted.

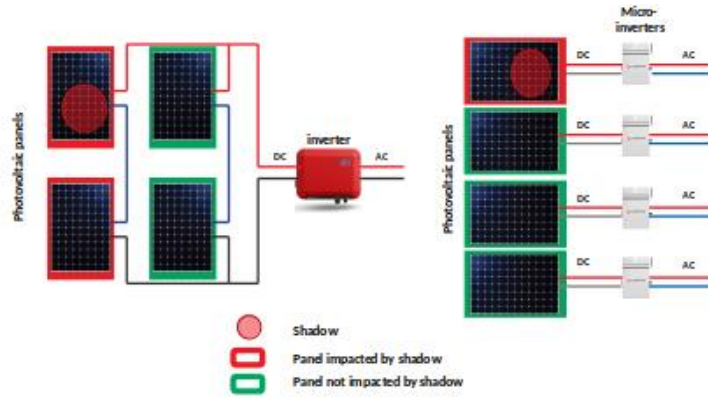


Figure 2: Explanatory diagram of the influence of shading on the PR, with a connection with an inverter on the left and a connection with micro-inverters on the right

$$I = N_P I_{PH} - N_P I_S \left[\exp \left(\frac{q}{k T_c A N_S} \cdot \left(V + I R_S \cdot \frac{N_S}{N_P} \right) \right) - 1 \right] - \frac{1}{R_{SH} \cdot \frac{N_S}{N_P}} \cdot \left(V + I R_S \cdot \frac{N_S}{N_P} \right) \quad (3)$$

With :

$$I_{PH} = [I_{SC} + K_I (T_c - T_{Ref})] \cdot G \quad (4)$$

$$I_S = I_{RS} \left(\frac{T_c}{T_{Ref}} \right)^3 \cdot \exp \left[\frac{q E_G}{k A} \left(\frac{1}{T_{Ref}} - \frac{1}{T_c} \right) \right] \quad (5)$$

$$I_{RS} = \frac{I_{SC}}{\exp \left(\frac{q V_{oc}}{N_S k A T_c} \right) - 1} \quad (6)$$

N_P : Number of cells in parallel

N_S : Number of cells in series

I_{PH} : Photo-current

I_S : Cell saturation current

I_{RS} : Reverse saturation current of the cell

q : Electron charge $q = 1.6 \cdot 10^{-19} \text{ C}$

k : Boltzmann constant $k = 1.38 \cdot 10^{-23} \text{ J / K}$

T_c : Cell operating temperature

R_{sh} : shunt resistance, Internal losses by parasitic currents (leaks) which pass through the cell at the junction

R_s : RS series resistance, Internal losses of a cell by Joule effect

I_{SC} : Short-circuit current of a cell at 25°C , 1 kW/m^2

V_{oc} : Open circuit voltage

K_I : Temperature coefficient of the short-circuit current

T_{ref} : Reference cell temperature

G : Solar irradiance in kW / m^2

E_G : Gap energy for crystalline silicon = 1.1 eV

A : ideality factor, equal to 1 for an ideal diode, but can go up to 2, when taking into account the generation - recombination current. For a mono-crystalline panel, A is generally equal to 1.2

Table 1 lists the advantages and disadvantages of an installation with an inverter and micro-inverters. Micro-inverters seem to be more advantageous on many points including price. Figure 3 shows the difference in the average price of an inverter and micro-inverters depending on the number of panels installed.

For example, for an installation of 25 panels of 355 Wp, i.e. an installation of 8.875 kWp, 25 IQ7+ micro-inverters be needed (a panel is equivalent to the purchase of a micro-inverter) for a total cost of $25 \times 119 \text{ €} = 2,975 \text{ €}$, to which must be added the connection cables between micro-inverters and panels (22 € per panel), solar protection boxes with Enphase decoupling relays (1 every 12 panels at 265 €) i.e. $3 \times 265 \text{ €} = 795 \text{ €}$ for 25 panels and a Enphase communication gateway of 325 €, i.e. a total of 4,095 € (blue curve). For the inverter, it is purchased according to the installed power. Its price is therefore not proportional to the installed capacity. In fact, the higher it is, the lower the price per kWp of the inverter. By taking a latest generation SMA® SunnyBoy brand inverter for installations between 1 kWp and 9 kWp, the price is 769 € to 1,530 €, to which it is necessary to add also cables of connections between inverters and panels (82 €), multi-contact connectors ($24 \times 4 \text{ €} = 96 \text{ €}$) and a solar protection box (279 €), a total of 1,987 € (grey curve).

We must also consider the lifespans of this equipment, which is a little less than 10 years for a central inverter and can reach 30 years for a micro-inverter. Thus, over 25 years (duration of the self-consumption contract with surplus sale), it will be necessary to change between 2 times, which is the minimum, (dotted end orange curve) and 3 times, which is very likely, (continuous curve orange) the inverter. Micro-inverters have a 25-years manufacturer's warranty and will not be replaced.

	Inverters	Micro-inverters
Power	 From 2 kW to 200 kW It is not possible to have a small installation	 From 100 W to 500 W It is possible to have any size of installation
Guarantee	 From 5 to 8 years	 From 10 to 25 years
Lifetime	 From 8 to 12 years	 About 30 years
Price	 See Figure 3 Requiring only one inverter, the initial outlet is less important. But having to change it 2-3 times during the 25 years, the inverter installation becomes less advantageous.	 See Figure 3 Since micro-inverters have a lifespan of 30 years, they will not need to be replaced, which gives them a price advantage
Shading and failure	 Shading or failure on a panel impacts all panels connected in series	 Shading or failure only impacts the affected panel because the panels are not linked together
Heterogeneous configurations in terms of orientation and inclination	 An installation with different orientations and inclinations is not possible with a single inverter because the MPTT is different	 It is possible to have different orientation and inclination of the panels without impacting the MPTT of the inverter
Variability of the number of panels in the grid and Scalability		 With one micro-inverter per panel, installing additional panels does not pose any particular problem

		It is complicated to add 2 panels to an initial installation if the inverter is already at its maximum power	
Panel variability		Even panels of identical brands have different characteristics. Panels wired in series are all going to have the characteristics of the worst panel	 A poorer quality panel will not have an influence on the other panels
Maintenance		Easy access inverter if default	 Micro-inverter under the panels, difficult to access area
Security		The intensity is higher because of the parallel connection of the panels	 The received intensity is the intensity of a panel

Table 1: Table listing the advantages and disadvantages of an installation with an inverter and micro-inverters

Micro-inverters also appear to be better suited to reducing the impact of losses that can occur in solar panels whether due to shading or panel malfunction.

Our statistical study must verify whether the PR of an installation equipped with micro-inverters is better than that of a similar installation with an inverter. A study in Belgium on installations equipped only with inverters made it possible to obtain a PR framework of between 70% and 80% (Leloux et al., 2012). Our study makes it possible to compare the results obtained in Belgium on French installations and to extend it for installations equipped with micro-inverters.

III. Methods of obtaining actual results

The PR is obtained by dividing the actual solar production by the theoretical solar production (Equation 7).

$$PR = \frac{E_{preal}}{G_{average}(i, o) \times Pp} \quad (7)$$

With:

E_{preal} : Solar energy actually produced from the installation listed on the BDPV site in kWh

$G_{average}$: Annual irradiance according to the PVGIS site, by averaging the four available irradiance data and according to the characteristics of the listed installations, in kWh / m² / year

i : Inclination of the panels on the roof ranging from 0 ° (horizontal) to 90 ° (vertical)

o : Orientation of the panels on the roof, ranging from -90 ° (East) to 90 ° (West) via 0 ° (South)

Pp : Total peak power installed in kWp

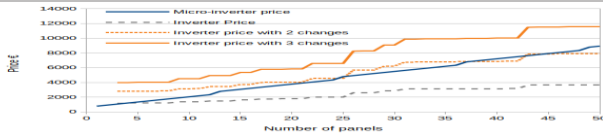


Figure 3: Price of IQ7+ micro-inverters and inverters SMA SunnyBoy 1.5 to 6.0, considering the cost of cables which differs from one installation to another, based on the number of panels over 25 years. Since inverters have a lifespan of 8-12 years, the gray curve for an inverter investment is unrealistic. It will certainly be necessary to change them 2 or 3 times, which will increase the cost of an installation with an inverter.

The actual production is given from installations coming from individuals, listed on the BDPV site (“BDPV - Page accueil - Base de données d’installations Photovoltaïque - BDPV,” n.d.). For each installation, the actual production of solar energy, as well as the orientation, the inclination, the peak power, the geographical area are transmitted. In order to carry out a statistical study on the PR, 200 data sets were recovered: 100 for installations with Enphase® M210, M215, M250 and IQ7 microinverters and 100 with installations using SMA® SunnyBoy 3000, SunnyBoy 5000 inverters and Sunny Tripower STP 8000. For the micro-inverters, the data was collected for Enphases® because the brand holds almost the entire French market. Their distributions (M210, M215, M250, IQ7) were chosen arbitrarily in rooftop installations with a minimum of one year of operation. SMA® inverters also hold a large part of the market. More than 40% of the installations listed in BDPV have an inverter of this brand while the second brand, Sputnik®, is only approaching 8%. Of the 100 systems, 50 are SunnyBoy 3000 (input power 3.2 kW), 25 are SunnyBoy 5000 (input power 5.2 kW) and 25 are Sunny Tripower STP 8000 (input power 8, 2 kW). This distribution does not, however, correspond to that recorded for all installations on BDPV. In fact, this is 46% for SunnyBoy 3000 inverters, 5% of SunnyBoy 5000 and 2% of Sunny Tripower 8000, the rest corresponds to other brands of SMA® inverters, most of which are 3kWp. The production data for micro-inverters and

inverters are averaged to obtain annual production. As inverters have been around for many years, the averages are taken over 7.6 years. Since micro-inverters are a newer technology, the averages are for shorter duration, on average 2.8 years. The distribution of the number of years of production of the 200 installations is given in Figure 4.

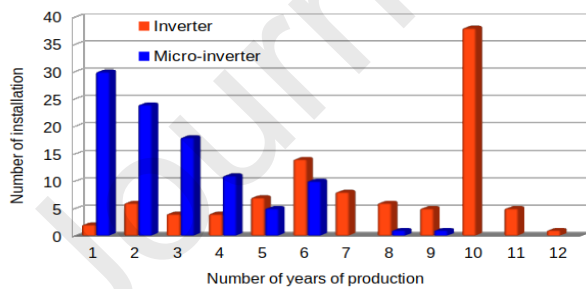


Figure 4: Histogram of the number of years of production of the 200 photovoltaic installations: in orange the installations with inverters, from 2008 to 2019; in blue, installations with micro-inverters, from 2011 to 2019.

Theoretical solar production is the production of a photovoltaic installation without the associated losses. Theoretical production is calculated using the average irradiance over one-year $G_{average}$ arriving at the solar panels with the associated inclination and orientation, multiplied by the total peak power of the installation. Through PVGIS (“JRC Photovoltaic Geographical Information System (PVGIS) - European Commission,” n.d.), the irradiance is recoverable for any location, inclination and orientation in Europe and North Africa following the calculation methods detailed in (Amillo et al., 2014; Huld et al., 2012; IEEE Photovoltaic Specialists Conference 40 2014 Denver et al., n.d.; Urraca et al., 2018b). In France, irradiance varies from 1,253 kWh / m² / year in the North to 1,937 kWh / m² / year in the South. The data from SARAH (Müller et al., 2015), CMSAF (Mueller et al., 2009), ERA5 and COSMO (Urraca et al., 2018a)

and from 2005 to 2015 for COSMO. From the 4 data series, an annual average of the irradiance is calculated over the 200 data sets of the BDPV installations.

IV. Results and discussions

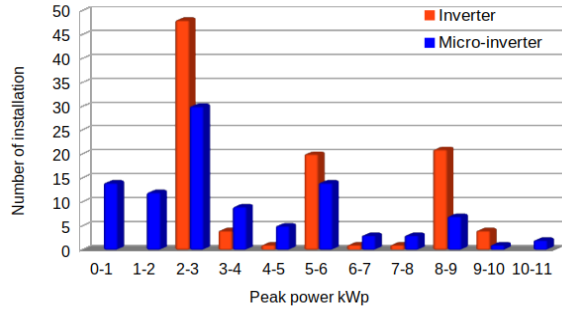


Figure 5: Histogram of the peak installed power; in orange peak power per inverter; in blue peak power of installations with micro-inverters

The peak power of the 200 installations follows the distribution of the histogram Figure 5. Installations equipped with inverters require sufficient power generated by the panels, of 2 kWp minimum. Micro-inverters do not have this limit. There are also many installations of less than 1 kWp, as well as larger scale installations, greater than 10 kWp. On the 100 installations considered with micro-inverters, the average peak power is 3.8 kWp.

On the 100 installations with inverters, the average power of panels installed is 5 kWp.

Figure 6 and Figure 7 show the distribution of the PR of installations with inverters and micro-inverters. It is between 0.6 and 0.94 for inverters with an average of 0.79. For micro-inverters, the PR ranges from 0.58 to 0.97 depending on the installation. It is within the range of what was suggested in article (Chub et al., n.d.). The average PR is also 0.79. However, depending on the photovoltaic panels, the yield decreases by 10 to 15% over 25 years. This loss of efficiency of the panels is considered in the PR. As the data with inverters is over a longer period than for micro-inverters, the PR can even be considered slightly lower for micro-inverters.

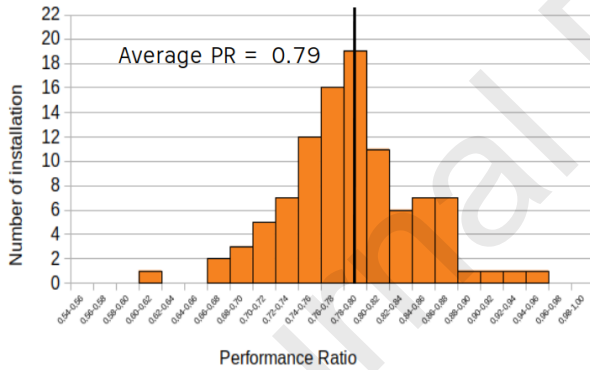


Figure 6: Performance ratio distribution histogram for the 100 installations with inverters

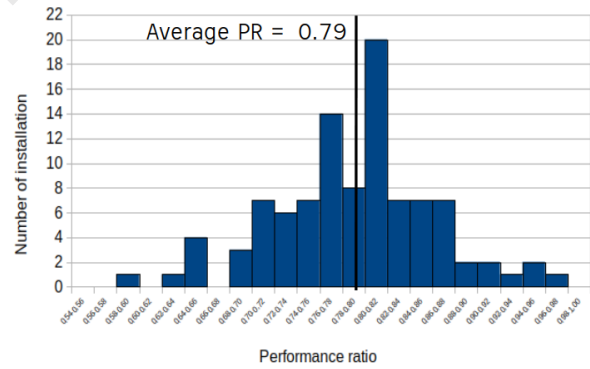


Figure 7: Performance ratio distribution histogram for the 100 installations with micro-inverters

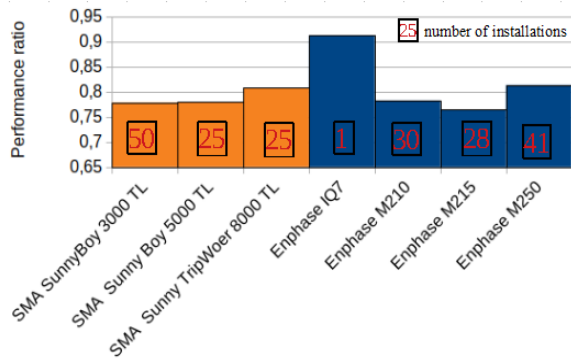


Figure 8: Histogram of the performance ratio distributed according to the type of inverter, in orange the inverters and in blue the micro-inverters

Figure 8 shows the average PR for the 7 inverters families used in the statistical analysis. The PR is substantially the same from one type of inverter to another except for the Enphase® IQ7 where the performance ratio is greater than 90%. Having only one data for this micro-inverter due to its novelty, it is difficult to say that it is better than the others.

On the other hand, the standard deviation of the SMA® is between 0.053 for the SunnyBoy 3000 to 0.059 for the Sunny Tripower 8000, while that of the Enphase® is between 0.064 for the M215 to 0.074 for the M210. For the same converter, installations with micro-inverters therefore have a more disparate PR than installations with inverters, showing that they are more sensitive to the environment around them.

Figure 9 shows the performance ratio of installations with inverters and with micro-inverters, according to peak power and their geographical distribution. The 200 data are distributed over the whole of France. For each data, a PR is calculated and compared with the peak power installed. The size of an installation does not seem to have an influence on either micro-inverters or inverters. This is not surprising for installations with micro-inverters because the power received on the micro-inverters is independent of the installed power. On the other hand, an inverter will receive a power, at its terminals, different according to the installed power. So, the power received by the inverter is linked to the installed power. But as shown in Figure 9, the power of the installations does not seem to influence the PR of installations with inverters either.

On the other hand, the geographic zone seems to influence the performance ratio. Indeed, irradiance and temperature play an important role in the performance of photovoltaic modules as explained by equation (3). In the south of France, the temperature is higher causing a drop in cell performance, thus influencing the performance ratio. A more detailed explanation can be found in article (Huld and Gracia Amillo, 2015). It is visible on the maps in Figure 9 that the performance ratios in the North of France are generally better than in the South.

The inclination and orientation of the panels have a significant influence on the irradiance received by an installation (National Committee for Lighting in Bulgaria et al., n.d.), making it possible to verify the impact of illumination on the converters.

The distribution of the number of installations according to inclination and orientation is shown in Figure 10. In most cases, individuals place their installations as close as possible to optimum irradiance, i.e. the maximum average irradiance over the year. In France, the optimal irradiance is 35° South. For inverters, more than 50% of installations are placed so as to be less than 5% of the optimum compared to 45% of installations with micro-inverters. And 80% of installations with inverters are less than 10% optimal irradiance against 87% with micro-inverters.

Figure 11 shows the impact that varying the tilt and orientation of the panels can have on the performance ratio. Whether for installations with inverters or with micro-inverters, it seems that the greater the loss compared to the optimum, the better the performance ratio and vice versa. Having very little data in cases deviating from the optimum, it is difficult to come up with any certainty about an explanation. But the possibility that a decrease in irradiance affects the temperature of the modules and by feedback influences the performance ratio, is possible.

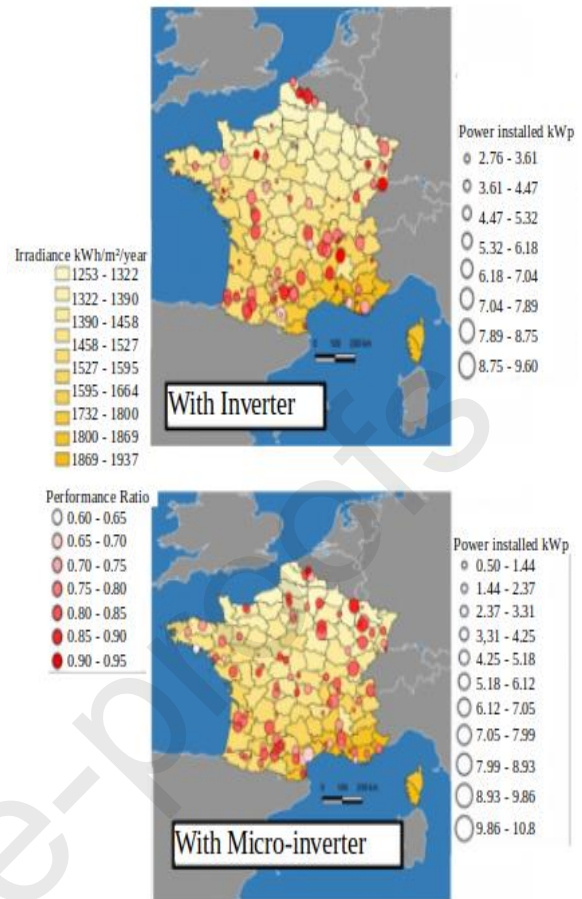


Figure 9: Cards for installations with an inverter for the top card and micro-inverter for the bottom card, depending on the optimal irradiance variation from one department to another. The size of the bubbles shows the peak power installed: the smaller the size, the lower the peak power of the installation. Please note, the legend for the installed power is different between the 2 maps. The color gradient corresponds to the performance ratio: the lighter the color, the lower the performance ratio.

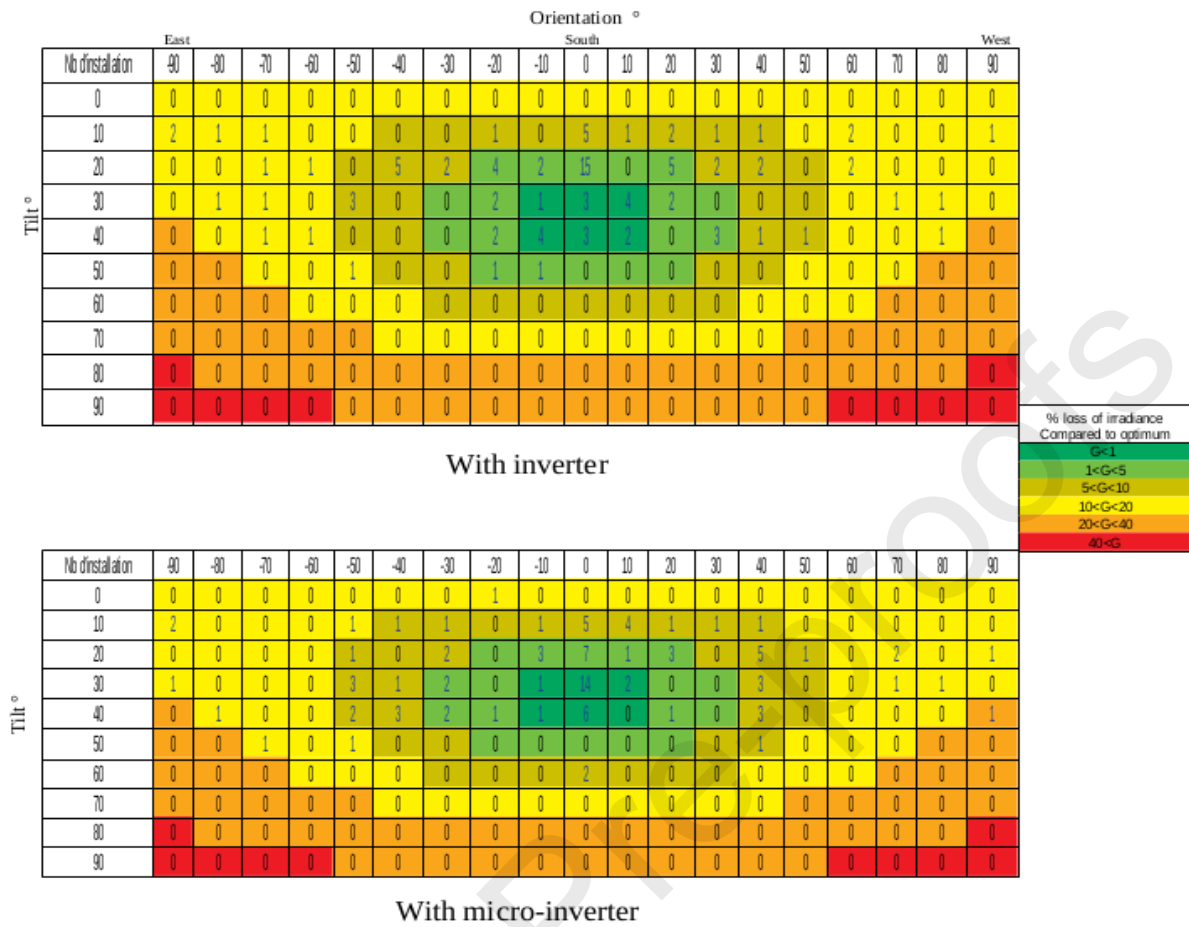


Figure 10: Number of installations used to depend on the inclination and orientation of the panels, with inverter shown at the top and micro-inverter at the bottom. The more the color is in the green, the closer the received irradiance is to the optimum, the more the color is red, the greater the loss of received irradiance compared to the optimum.

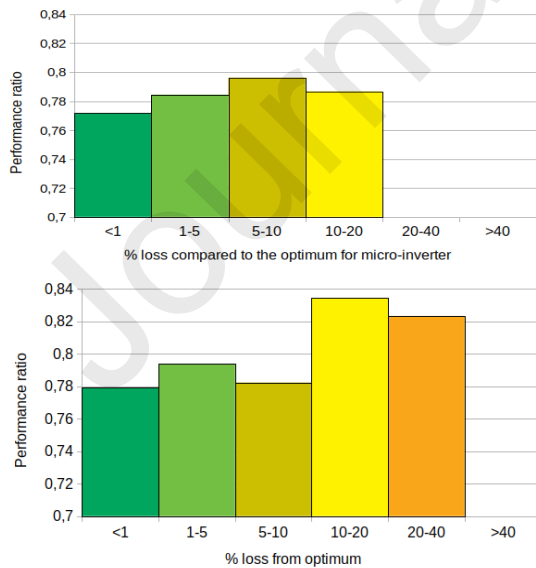


Figure 11: Histogram of performance ratios with inverters at the top and micro-inverters at the bottom versus the percentage of irradiance loss due to the tilt and orientation of the panels

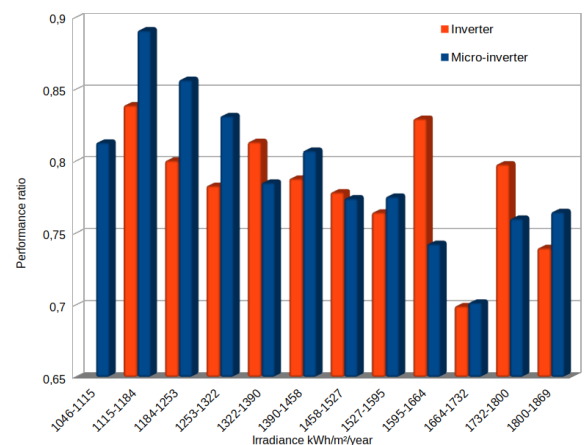


Figure 12: Histogram of performance ratio versus irradiance, related to geographic area and loss due to tilt and orientation, arriving at panel level for inverters in orange and micro-inverters in blue.

This appears to be confirmed by Figure 12 which shows the PR as a function of irradiance, linked to the geographical area and the orientation-inclination of the installations. The trend for all installations is a decrease in the performance ratio as the irradiance increases.

But beware, a loss of PR due to irradiance does not mean that you should install your panels in areas where the irradiance is lowest. The energy produced will still be higher with better irradiation.

V. Conclusion

The PR performance ratios of photovoltaic installations equipped with an inverter and micro-inverters were compared. It has thus been shown that, contrary to our initial intuition, installations equipped with micro-inverters do not have a higher PR than those equipped with an inverter.

This result may be surprising given the difference in panel connection for installations using a single inverter and those using as many micro-inverters as there are panels. Indeed, if a failure (failure or shading) of a panel can have consequences distributed over the production of all the panels associated in series with the failed one for an installation using an inverter, this is not the case for installations with micro-inverters where the failure remains localized to the only offending panel.

According to the 200 real production data, the performance ratio is ultimately almost identical for installations with inverters or micro-inverters. The PR is around 79% for both the average facility equipped with micro-inverters and the average for other facilities.

In addition, in both cases, there is no significant change in the performance ratio depending on the installed power. On the other hand, there seems to appear a slight increase in the performance ratio when the irradiance decreases, either due to the inclination and orientation of the panels or to the geographical area and this for installations with inverter and micro-inverters.

Finally, the results show a homogeneity of the performance ratio between the two technologies despite different operations. Losses due to shading must therefore be minimal compared to other losses. On the one hand, because the panels are equipped with bypass diodes, which allow the shaded cells to be bypassed. On the other hand, because when deploying the installation, it is recommended to cut or move any objects that may cast shadows on the panels.

However, even if the performance ratio is identical between inverters and micro-inverters, micro-inverters are still to be favored because of their lifespans and their prices, which make it possible to consider not need to replace them for 25 years of operation and on the other hand they allow to better guarantee the safety of the installation even in the event of fire.

The results of the PR obtained through this publication will make it possible to calculate the yields of more realistic photovoltaic installations. Thus, the profitability estimates for future photovoltaic installations will have to be more in line with the actual operating results.

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Declaration of interests

We declare the following financial interests/personal relationships which may be considered as potential competing interests: Region Nouvelle-Aquitaine (France), European Union with FEDER-FSE 2014-2020, ECOGELEC, ENEDIS

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	Inverters	Micro-inverters
Power	 From 2 kW to 200 kW It is not possible to have a small installation	 From 100 W to 500 W It is possible to have any size of installation
Guarantee	 From 5 to 8 years	 From 10 to 25 years
Lifetime	 From 8 to 12 years	 About 30 years
Price	 See Figure 3 Requiring only one inverter, the initial outlet is less important. But having to change it 2-3 times during the 25 years, the inverter installation becomes less advantageous.	 See Figure 3 Since micro-inverters have a lifespan of 30 years, they will not need to be replaced, which gives them a price advantage
Shading and failure	 Shading or failure on a panel impacts all panels connected in series	 Shading or failure only impacts the affected panel because the panels are not linked together
Heterogeneous configurations in terms of orientation and inclination	 An installation with different orientations and inclinations is not possible with a single inverter because the MPTT is different	 It is possible to have different orientation and inclination of the panels without impacting the MPTT of the inverter
Variability of the number of panels in the grid and Scalability	 It is complicated to add 2 panels to an initial installation if the inverter is already at its maximum power	

		with one micro-inverter per panel, installing additional panels does not pose any particular problem
Panel variability	 Even panels of identical brands have different characteristics. Panels wired in series are all going to have the characteristics of the worst panel	 A poorer quality panel will not have an influence on the other panels
Maintenance	 Easy access inverter if default	 Micro-inverter under the panels, difficult to access area
Security	 The intensity is higher because of the parallel connection of the panels	 The received intensity is the intensity of a panel

Table 1: Table listing the advantages and disadvantages of an installation with an inverter and micro-inverters

Declaration of interests

☐ 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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