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Analysis and Energetic Characterization of Low-Power Grid-Connected Photovoltaic Systems

António P. Martins[1] and Domingos M. Carvalho[2]

[1,2] Department of Electrical and Computer Engineering
Faculty of Engineering, University of Porto
Rua Dr Roberto Frias, s/n, 4200-465 Porto (Portugal)
Phone/Fax number: +351 225081816, e-mail: ajm@fe.up.pt

Abstract. This paper discusses some of the most important Photovoltaic (PV) systems characteristics related to its global efficiency like MPP tracking efficiency, static efficiency, conversion efficiency as well as the Euro efficiency. The losses models of the power semiconductors constituting the Power Electronics (PE) subsystems as well as the models of transformers and DC and AC cables are reviewed. Three topologies are selected, representing the PV market and simulation results are discussed. Given the importance of the global efficiency of an installation for the owner, recorded field results with the same systems are presented. The main conclusion is that the global efficiency of a PV installation depends not only on the PE subsystem, with or without isolation transformer in the low or high-frequency stages, but also on the DC and AC conduction losses, and on the distance of the installation to the coupling point to the electric grid.

Keywords

Cabling, Efficiency, Losses, PV inverters

1. Introduction

The highest efficiency reached until now in PV inverters is 98.8%, and was obtained at the Fraunhofer Institute for Solar Energy Systems using silicon carbide transistors. The dissipated power in conventional inverters using silicon transistors was reduced between 30 and 50%. This technology has been explored with success and the highest efficiencies have been obtained in the low power ranges, as demonstrated in [1]-[3].

However, the global efficiency of a PV system depends on other factors like DC and AC cable losses. Additionally, from the investment point of view, other aspects must be considered like the efficiency of the Maximum Power Point Tracking (MPPT) algorithm or the rating of the PE system compared to the installed PV power or the contracted power with the grid operator.

The system rating should be done in such a way that the PV inverter will be nor underutilized nor overloaded. Under-rating was identified in the beginning of the 90's as a possibility for reducing the costs of the generated kWh, [4]. In such a way, an inverter with less capacity for the same PV generator can be used, without a significant impact on the amount of energy injected in the grid; so, the generated energy tends to be less costly.

The Inverter Design Factor (IDF) represents the relation between the inverter nominal power and the maximum PV power. Analyzing the behaviour of a single inverter is was concluded that the productivity decayed more sharply for inverters with an IDF less than 0.6, according to the limiting power condition, occurring when the available PV is higher than the inverter rating. Independently of the geographic location of the PV system, the losses caused by the limited inverter power are less than 10% for an IDF of 0.5 and less than 3% for an IDF of 0.6, [4]. So, an under-rated inverter can be an interesting choice for PV systems.

2. Efficiency Parameters for PV Systems

Several parameters are used to characterize and determine the global efficiency of a PV system. It must be referred the DC/DC and the DC/AC conversion efficiency, and the MPP tracking efficiency. Additionally, the Euro efficiency allows classifying and comparing PV systems in different environment conditions.

A. DC/AC Conversion Efficiency

The efficiency of the DC/AC conversion characterizes losses originated by the conversion of the DC current into AC current. In PV systems, these losses include the losses originated in the transformer and in the PE switches. This efficiency can be represented by:

$$\eta_{Con} = \frac{P_{AC}}{P_{DC}} \quad (1)$$

where P_{AC} is the power delivered at the inverter output (fundamental component) and P_{DC} is the input power at inverter DC-bus.

B. Tracking Efficiency

PE converters for grid-connected PV systems assure an optimal adaptation to the PV panel I-V characteristic. The capability of a power converter for adjusting its operating point to the PV panel MPP point is described by the tracking efficiency

$$\eta_{Tr} = \frac{P_{DC}}{P_{PV}} \quad (2)$$

where P_{DC} is the active power supplied to a DC-bus and P_{PV} is the instantaneous maximum power available in the PV panel. In the calculation of η_{Tr} it can be included the DC cable losses.

The static efficiency of a PV system is then obtained by the product of the two described efficiencies, conversion and tracking:

$$\eta_{Inv} = \eta_{Con} \cdot \eta_{Tr} \quad (3)$$

This efficiency can be determined for different load conditions. The nominal efficiency, given by manufacturers, is obtained during inverter operation in nominal conditions (V_n and I_n). The nominal scenario, and also the maximum efficiency, is only reached with certain conditions of irradiance and temperature; irradiance variations are responsible for the inverter frequent operation in partial load.

C. Euro Efficiency

In order to facilitate the comparison between different PV systems based on their efficiency, it was created the Euro efficiency, η_{Euro}, calculated to the European climate. To consider different load scenarios, Euro efficiency is calculated using a weighted average of different static efficiencies, defined for six load conditions (nominal and five different partial loads), according to:

$$\begin{aligned}\eta_{Euro} = \; & 0{,}03\eta_{5\%} + 0{,}06\eta_{10\%} + 0{,}13\eta_{20\%} + 0{,}1\eta_{30\%} \\ & + 0{,}48\eta_{50\%} + 0{,}2\eta_{100\%}\end{aligned} \quad (4)$$

As can be verified in (4), the $\eta_{100\%}$ value corresponds to the efficiency in the condition of nominal irradiance. The PV generator power corresponds then to the nominal inverter power ($P_{PV} = P_n$). In average, it is assumed that the inverter is operating with 100% load during 20% of the time along a year, and so on. The Euro efficiency allows for the comparison of different inverters.

Extensive comparisons between inverters efficiency curves are not justified. Depending on the power rating, DC voltage level and power circuit architecture, Euro efficiency varies between 86% and 95%. It is usually calculated only for the nominal voltage while PV panels operating in MPP points cover a wide voltage range. The IEC 61683 specifies three voltages for efficiency calculation: minimum input voltage, nominal, and 90% of the maximum input voltage. However, there is no standard method to calculate the weighted average of the Euro efficiency with different voltages, which turns difficult to obtain the best estimation of the real efficiency of a PV system and the establishing of comparative analysis between different systems.

D. Performance Ratio

Performance Ratio (PR), frequently referred as quality factor, is an important measure for evaluating the efficiency of a PV system. PR designates the relation (independent of the PV system alignment and irradiation) between the energy effectively produced and the possible theoretical one. In general, highly efficient PV systems reach a PR of nearly 80%, [5]. The ideal time interval for evaluating PR is a year; however, smaller time intervals can be used. To evaluate PR, the following simplified expression can be used:

$$PR = \frac{E_{\text{Real}}}{E_{Annual}\eta_{PV}} \quad (5)$$

where E_{Real} is the real energy produced in a year, E_{Annual} is the one-year irradiation energy in the PV panels surface and η_{PV} is the PV panels efficiency. The real energy produced in a year is measured, e.g. by an energy meter.

Environment factors like panels' temperature, solar irradiation and shadows and other factors like conduction losses, PV panels and inverter efficiency, all have influence in the PR value.

E. Methods to Increase the Converters Efficiency

The increasing of the converters power density is obtained increasing the converters switching frequency thus reducing the volume and weight of the reactive components. However, an increased switching frequency also increases semiconductor losses, mainly the switching ones, bringing the need of an increasing volume of the heat sinks. This fact reduces the possibility of reducing the converter volume. It is needed then to reduce the semiconductors voltage and current stress in order to reduce the losses. In this sense, techniques for the association of switches or converters can be used.

To reduce switching losses different resonant techniques can be used, thus achieving lossless switching. The most used ones are the Zero-Voltage Switching (ZVS) and the Zero-Current Switching (ZCS), [6].

Non-dissipative techniques minimize switching losses, enabling a higher switching frequency, but conduction losses remain. To reduce these losses a possible solution is the series or parallel association of semiconductors and converters. Also, multilevel current-source and voltage-source inverters are used in the high power range, [7].

3. Power Electronics Losses

The PE system efficiency is the factor that most influences the global efficiency of the PV system. In this section it is reviewed the model losses of power semiconductors, namely conduction and switching losses, in order to present simulation results related to three of the most used topologies in the low power PV market.

A. Conduction Losses

To evaluate losses in the DC/DC converter and in the inverter it is needed the conduction and switching models of the power semiconductors and the associated operating conditions: for the DC/DC converter, input and output DC voltage and input current and, for the inverter, DC-bus voltage and output voltage and current, magnitude and phase. In both cases the switching frequency is also needed. The typical I-V static relation of a power semiconductor (diode or transistor) is shown in Fig. 1.

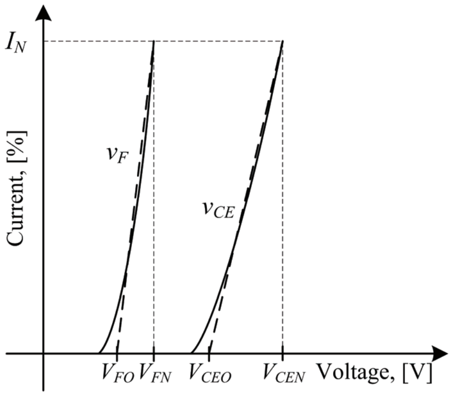

Fig. 1. Power semiconductor conduction model, transistor or diode.

For the transistor, its V-I model can be approximated by the following linear relation:

$$v_{CE} = \frac{V_{CEN} - V_{CEO}}{I_{CN}} i_C + V_{CEO} \tag{6}$$

where I_{CN} and V_{CEN} are the current and voltage nominal values in forward conduction and V_{CEO} is the threshold conduction voltage, which depends on the transistor type and the nominal DC voltage.

Generally, the diode voltage drop follows an exponential law. Inside the conduction zone the curve can be approximated by a linear relation starting at V_{FO} (Fig.1). This conduction threshold is variable; it depends on the particular diode technology but, typically, can be considered equal to 0.7 V. In the same figure, V_{FN} is the diode voltage drop at nominal current. So, the diode V-I relation is given by (7):

$$v_F = \frac{V_{FN} - V_{FO}}{I_{CN}} i_C + V_{FO} \tag{7}$$

If $F(\alpha)$ is the modulating function ($-1<F(\alpha)<1$), θ the angle between the inverter output current and the fundamental component of the inverter output voltage and m the modulation index then the duty-cycle, δ, of the switching pulses is given by (8):

$$\delta = \frac{1}{2}\left[1 + m \cdot F(\alpha + \theta)\right] \tag{8}$$

In the case of sinusoidal modulation it results:

$$F(\alpha + \theta) = \sin(\alpha + \theta) \tag{9}$$

The need of injecting a grid current with a very low THD implies the use of high switching frequencies and an adequate filtering inductance. So, for the analysis of inverter losses, the inverter current can be considered a sine wave:

$$i_C = I_{CM} \sin(\alpha) \tag{10}$$

Solving the equation for the dissipated energy in the semiconductors during the conduction intervals the following results are obtained for the losses in a transistor and in a diode, [8]-[9].

$$P_T = \left(\frac{1}{8} + \frac{m}{3\pi}\right)\frac{V_{CEN} - V_{CEO}}{I_{CN}} I_{CM}^2 + \left(\frac{1}{2\pi} + \frac{m}{8}\cos\theta\right) V_{CEO} I_{CM} \tag{11}$$

$$P_D = \left(\frac{1}{8} - \frac{m}{3\pi}\right)\frac{V_{FN} - V_{FO}}{I_{CN}} I_{CM}^2 + \left(\frac{1}{2\pi} - \frac{m}{8}\cos\theta\right) V_{FO} I_{CM} \tag{12}$$

These equations can be applied also to MOSFET transistors; their conduction model can be written in the same form, with V_{CEO}=0, $V_{CEN}=I_{CN}R_{DS}$.

B. Turn-on and Turn-off Switching Losses

Switching losses can be analyzed with the help of Fig. 2, where V_{DC} is the DC-bus voltage and L_s is the leakage inductance of the DC loop. It is verified that the *di/dt* during turn-on is approximately constant; it means that rise time is proportional to the switched current.

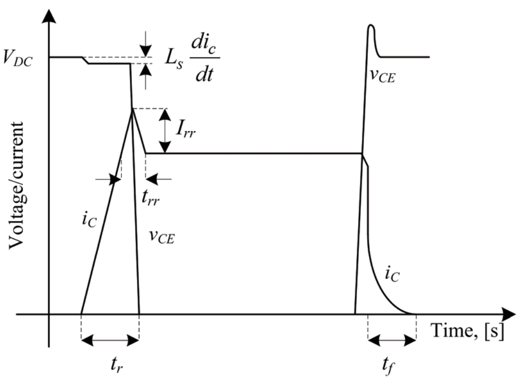

Fig. 2. Typical switching waveforms of a transistor-diode pair.

Being F_s the switching frequency and t_{rN} the nominal rise time under nominal current it can be obtained:

$$P_{on} = \frac{1}{8} V_{DC} t_{rN} \frac{I_{CM}^2}{I_{CN}} F_s \tag{13}$$

From manufacturers catalogues and experiments it can be concluded that the fall time of the current almost does not depend on the current to be commutated but on the time the semiconductor tail current reaches zero. Simple calculations allow concluding that losses due to turn-off switching are given by (14), [8]-[9]:

$$P_{off} = V_{DC} I_{CM} t_{fN} F_s \left(\frac{1}{3\pi} + \frac{1}{24}\frac{I_{CM}}{I_{CN}}\right) \tag{14}$$

C. Recovery Losses

The switching of an inductive circuit, as is the case of voltage-source inverters connected to the grid, contains an additional loss term due to the recovering of storage charges in the free-wheeling diodes (Fig. 2). In a first interval, the transistor is subjected to the DC-bus voltage and conducts the diode recovery current until it reaches its maximum value. In a second interval, when the current in the diode returns to zero, the diode is subjected to the DC voltage. During the two intervals losses occur in the transistor and in the diode and they can be combined in a single expression. Considering the current a sine wave, it results (15) for the losses in a transistor-diode pair, [9]:

$$P_{rr} = F_s V_{DC}\left[\left(0{,}28+\frac{0{,}38}{\pi}\frac{I_{CM}}{I_{CN}}+0{,}015\left(\frac{I_{CM}}{I_{CN}}\right)^2\right)\times Q_{rrN} + \left(\frac{0{,}8}{\pi}+0{,}05\frac{I_{CM}}{I_{CN}}\right)I_{CM}t_{rrN}\right] \quad (15)$$

where t_{rrN} and Q_{rrN} are the nominal recovery time and recovery charge, respectively.

The inverter total losses depend on the specific topology as well as the switching method. A similar procedure can be applied to other converters existing in the PV chain, namely a DC/DC converter.

D. Simulation Results

The PV chain is mainly constituted by PV panels, DC cables, step-up converter, PWM inverter and AC cables. The output transformer has been or not considered according to the specific topologies used in the experiments. In the results, losses in the DC and AC cables are not included in order to allow a better comparative analysis between the three PV installations. Table I lists the main characteristics of the analysed systems: topology, power rating, PV panels arrangement and Euro efficiency.

Table I. Main characteristics of the analysed PV systems.

	Syst. I	Syst. II	Syst. III
PV power (W)	4320	4140	4140
AC power (W)	3500	3680	3600
PV panels; strings	18; 3	18; 2	18; 2
PV voltage range (V)	150–400	200–400	350–600
DC/DC converter	Yes	No	No
HF transformer	Yes	No	No
Grid transformer	No	Yes	No
Euro efficiency (%)	93.5	94.7	95.8

The topologies of the three systems are shown in Fig. 3. It was considered the presence of a MPPT algorithm based on the open circuit voltage, thus allowing the establishing of the PV panels voltage according to the supplied power, [10]. It was also admitted an inverter with a constant DC-bus voltage for the topology with two conversion stages. In the others, the DC-bus voltage is variable and depends on the available PV power. So, it is established the duty-cycle of the existing DC/DC converter and the modulation index and phase of the fundamental component of the inverter output voltage.

Table II shows the main parameters used to evaluate the losses in the conversion chain and Fig. 4 the results for the three considered systems. From these results it can be concluded that System I, with a two-stage conversion chain and a HF transformer, is the one with the lowest efficiency.

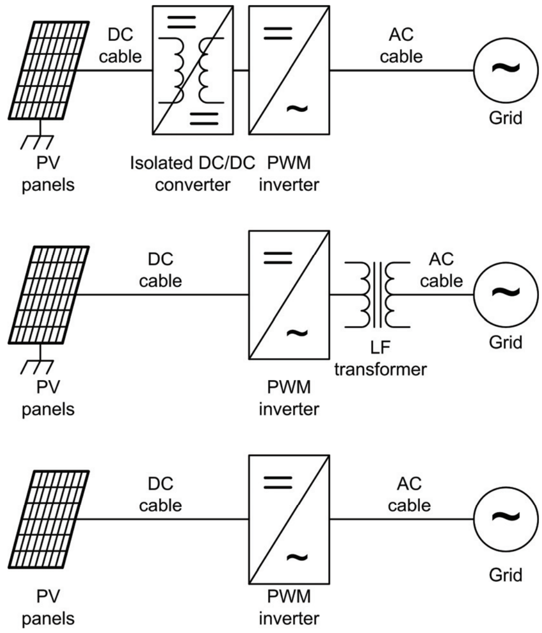

Fig. 3. Internal configuration of System I (top), System II (middle) and System III (bottom).

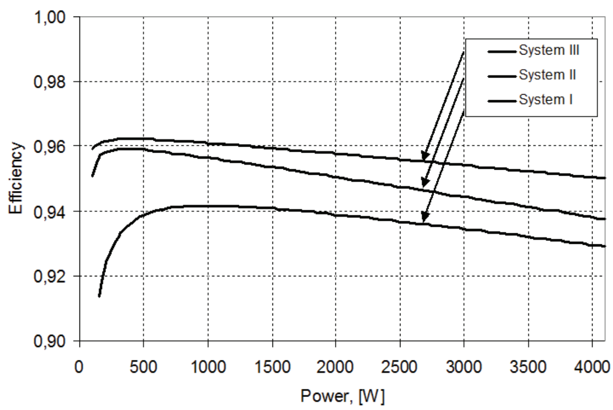

Fig. 4. Efficiency of System I, with DC/DC converter and HF transformer, System II, with grid transformer, and System III, with single stage conversion, without transformer.

System II although using a grid transformer and, consequently, isolation of the PV panels, is not particularly affected in terms of efficiency by that fact. Finally, the simplest in terms of configuration, System III is, in fact, the most efficient in what refers to energy. This fact makes that this kind of systems have gained importance in the PV market, namely where isolation is not mandatory.

However, the global efficiency of an installation does not depend exclusively on the PE system but also on the installation conditions, namely PV panels arrangement, DC cabling and connection to the electric grid. The next section will clearly demonstrate this.

4. Experimental Results

Besides the PE parameters already presented, the analysed PV systems were installed in different conditions, namely in DC and AC cabling from the solar panels to the point of grid coupling. Table III shows the cable arrangements in the three installations.

Table II. Parameters used for simulation.

	System I	System II	System III
MPP voltage	290–340 V	270–310 V	350–600 V
DC current: I_{CN}	22.5 A	23.4 A	13.2 A
MOSFET: R_{DS}	0,1 Ω	-	-
Diode: V_{FO}; V_{FN}	0.7 V; 1.3 V	-	-
Switching frequency: F_s	20 kHz	-	-
DC/DC transformer: R_{eq}	0.02 Ω	-	-
DC voltage: V_{CC}	400 V	260–330 V	350–540 V
AC current: I_{CN}	32 A	49 A	32 A
IGBT: V_{CEO}; V_{CEN}	1.5 V; 2.5 V	2.9 V; 3.2 V	1.8 V; 4.5 V
Diode: V_{FO}, V_{FN}	0.5 V; 1.0 V	0.7 V; 1.5 V	1.2 V; 2.5 V
Switching frequency: F_s	20 kHz	15 kHz	18 kHz
Switching times: t_{rN}; t_{fN}	300 ns; 300 ns	200 ns; 200 ns	400 ns; 400 ns
Recovering: t_{rrN}; Q_{rrN}	300 ns; 0.5 µC	200 ns; 0.5 µC	400 ns; 0.1 µC
Filter inductance: L_g; R_{eq}	20 mH; 0.1 Ω	10 mH; 0.1 Ω	25 mH; 0.1 Ω
Grid transformer: V_p/V_s; R_{eq}	-	150/230; 0.22 Ω	-

Table III. Cable parameters in different installations.

	Syst. I	Syst. II	Syst. III
DC cable length (m)	15	12	4
DC cable section (mm^2)	10	10	10
PV strings	3	2	2
DC cable resistance (Ω)	0.02 Ω	0.02 Ω	0.01 Ω
AC cable length (m)	25	15	120
AC cable section (mm^2)	16	16	16
AC cable resistance (Ω)	0.05 Ω	0.03 Ω	0.27 Ω

A. Systems I, II and III

The graphic in Fig. 5 shows the measured efficiency at the inverter output in function of the PV power delivered by the panels in System I, II, and III not considering the DC and AC cable losses.

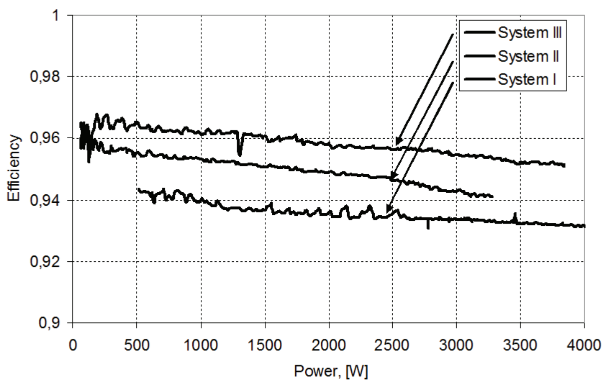

Fig. 5. Experimental recorded efficiency vs. output power for System I, System II and System III.

In the record from System I, it can be noticed that for higher powers the efficiency slightly decreases. According to the manufacturer, System I presents a maximum efficiency of 94.3% and a Euro efficiency of 93.5%. For the measured results and doing a weighted average it is obtained an efficiency of 93.72%, close to the manufacturer data. For the used DC and AC cabling it can be estimated losses of 0.07% and 0.37%, respectively, at nominal power.

For System II, as in System I, it can be noticed a decreasing efficiency for higher output powers. From the manufacturer, this inverter has a maximum efficiency of 95.6% and a Euro efficiency of 94.7%. For the measured results and doing a weighted average it is obtained 95.27%, close to the manufacturer data and higher than that of System I. The efficiency is higher despite having a LF transformer; it gives isolation but increases cost. For the used string arrangement and the DC and AC cabling it can be estimated losses of 0.10% and 0.27%, respectively, at nominal power.

Several measurements, in different irradiation and temperature conditions were recorded in System III. For higher powers the efficiency slightly decreases; however, the absolute values are higher. According to the manufacturer, the system has a maximum efficiency of 96.4% and a Euro efficiency of 95.8%; a weighted average of 95.82% was obtained. From all the analysed systems this is the one presenting the highest efficiency; it has a simple topology, with a single conversion stage and does not have a transformer. As shown in Table III, this microgeneration has a DC cable of 4 meters length and an AC cable of 120 meters; the PV installation is far from the grid. It is obtained very high AC losses, 79.39 W at nominal power and the total cable losses are 2.0%, an unsatisfactory value. Only a thicker cable, more expensive, or a close connection to the grid could improve the installation efficiency.

B. Comparative Results

In nominal conditions, and for the three microgenerations, the following THD values for the injected grid current were recorded (Table IV).

Table IV. THD of the injected current in nominal conditions.

	System I	System II	System III
THD (%)	3.9	2.2	2.8

From the table, it can be concluded that System I is the one presenting the highest THD value. This value is due, mainly, to the presence of harmonics of order 3, 7 and 9. These harmonics are hardly generated by the high frequency switching inverter; in principle they will be caused by the distortion of the grid voltage and a smaller AC inductance. In any case, however, any microgeneration presents THD values for the injected current smaller than the ones imposed by grid standards [11]-[12].

Table V summarizes the efficiency results, from manufacturers, measurements and estimations. The most efficient from the point of view of the PE conversion is System III, with an average efficiency of 95.8%. However, the specific installation where it is used makes it not to be the globally most efficient system, leaving that position for the installation incorporating System II.

Table V. Comparative analysis of the efficiency.

	System I	System II	System III
Maximum (catalogue)	94.3	95.6	96.4
Euro (catalogue)	93.5	94.7	95.8
Average of the converter, (measured)	93.7	95.3	95.8
Average of the installation, (estimat.)	93.3	94.8	93.8

5. Conclusion

This paper presented the main characteristics of three PV installations based on different panels' arrangements, PE systems and grid connection. The losses models of the PE subsystems were presented and the obtained simulation results allowed concluding that the simplest topology has the highest efficiency. The two-stage topology, with DC/DC converter and HF transformer, has the lowest efficiency, and System II, including a LF transformer, is in the middle.

From the three analysed installations and because there are various subsystems where losses occur, the one presenting the best overall efficiency is System II. From the point of view of the PE, System III has the best inverter but, due to a larger distance to the grid, is the one presenting the highest conduction losses and therefore is not the best system. The factor "inverter efficiency" is one of the most important ones in a PV installation but the overall energetic efficiency depends on other factors also.

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