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BROADER PERSPECTIVES

Technical and economic performance analysis of large-scale ground-mounted PV plants in Italian context

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ABSTRACT

During the last decade, the market penetration of photovoltaic (PV) technology has been increased tremendously worldwide. In the EU context, following the quick development in German and Spanish PV sector, Italy is currently one of the most interesting market. In view of these facts, it is strategic to perform detailed technical and economic analyses to establish energy performances and profitability of the PV plants, depending on their configurations. In particular, in addition to the selection of main components, such as inverters and modules, which are now characterized, on average, by good performance levels, the debate on the support structures is still open. In detail, the choice may fall, for example, on traditional fixed structures or on one/two axis tracking systems, that could ensure best productivity per unit of power, but also are typically characterized by higher complexity and land-occupation factors than the first ones. The purpose of this work is to carry out performance analyses on the most widespread plant configurations, taking into account different Italian climatic contexts, considering technical, energetic, and economic points of view. With this aim, different types of components (modules and inverters) and ground-mounting structures (fixed, one-axis, two-axis) have been evaluated. Subsequently, their obtainable performances have been estimated in three different locations (Milano, Roma, Palermo) that have been considered representative of average irradiation levels available in Italy. Analyses have been carried out by computer simulations, through two consequent levels of detail, highlighting the main performance influence-factors. In conclusion, the final profitability of each analyzed configuration has been evaluated, giving a reliable indication on their effective economic advantages. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS

ground-mounted PV plants; fixed and tracking mounting systems; energy performance analysis; economic analysis

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1. INTRODUCTION

Currently, worldwide, the market of the PV sector is supporting the predictions made in recent years by some experts of the energy sector [1]. This trend is driven not only by the associated environmental benefits that characterize this technology, but also by the incentive mechanisms developed in various Countries [2].

Recent market surveys confirm that the production of solar photovoltaic technology has grown, since 2003, 40% every year on average, with a peak of 60% in 2007. Germany was a clear leader in the European market, with sales totaling 5.7 billion euros and more than 100 000 homes equipped with a photovoltaic system. Overall, worldwide, half of the total production of PV electricity, which amounts to 10 billion kWh, is generated by EU countries [3].

To achieve these results, a key contribution is due to the introduction of specific incentive policies, aimed to enhance the development of this sector. In particular, at EU level, the 2001/77/EC-Electricity production from RES directive defined the basic principles to apply feed-in tariff to the electricity production by photovoltaic systems connected to the electricity grid. This mechanism provides remuneration to the whole energy produced by the plants for a given number of years starting to their first grid connection, according to rates expressed in €/kWh. This incentive program was implemented in Italy with the Decree ''D.M. 19/08/2005'', then modified by the ''D.M.

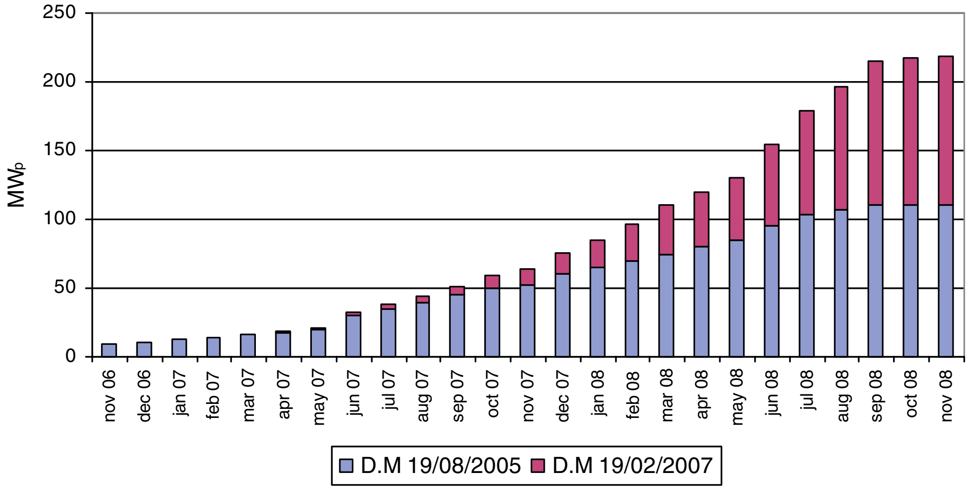

Figure 1. Italy, installed power under Feed-in tariff program.

del 19/02/2007'', that introduced the feed-in tariff mechanism for PV electricity production.

Figure 1 shows the evolution of installed PV power in Italy under the feed-in tariff program [4].

This kind of financing mechanism has significantly increased the interest of national and international market on systems and design solutions that allow to increase energy production for equal surfaces and installed powers [5].

In this situation, a significant part of the plants under construction belongs to the medium and large size ground-mounted installations. Despite the lower national feed-in tariff rates for non-BIPV (Building Integrated PV) plants, large ground mounted PV centrals represent economically feasible solution, considering cost reductions achieved through huge sizes .

It must also be considered that southern Europe is characterized by interesting irradiation levels and, in particular, southern Italy, like some areas in the south of Spain, combines abundant availability of agricultural grounds at low cost and very favorable weather conditions. In fact, as can be observed in Figure 2, the annual irradiation value on an optimal-tilted and oriented plane for the mentioned areas, is on average over 1700 kWh/m^2 [6].

Since 2003 in Spain and recently in the Italian context, the above-mentioned opportunities allowed the development of several large-size PV installations. These projects are usually shared by many investors, frequently belonging to financial groups responsible for project and plant management. Nowadays, in Spain, about 2200 investors have joined these kind of projects, who bought shares for a total amount of 177 million euros [7]. Likewise, in Italy, under the motion of the current financial market difficulties, several projects are being developed, potentially able to guarantee attractive economic benefits.

Therefore, it is particularly important to analyze in detail the various configurations that can be adopted for the PV plants, carefully evaluating the economic viability in relation with current-market materials costs and required works for their implementation, management, and maintenance.

2. METODOLOGY

Energy productivity of PV systems depends on many factors, as climate, technological components, and tracking strategies.

In the present work, the first part is related to the detailed specific analysis of different influence-factors, listing the performance reference-parameters used in the various assessments. Then, a 6.3 kW$_p$ sample plant configuration has been chosen by selecting high quality technological components. Further, energy performance simulation has been carried out for the sample PV plant in different climatic contexts, evaluating differences due to available ground-placing layouts and tracking strategies.

In consideration of the emerged results in the preliminary analysis, in this second part of the work more detailed energetic assessments have been carried out, concerning a large PV plant, with a peak power close to 1 MW$_p$. For this case-study, further elements have been taken into account, like shadow effects generated on the field and analyzing different typologies of PV modules and inverter available on the market.

Subsequently, different hypotheses were analyzed from an economic point of view, referring to the real costs of realization, derived from market surveys on prices associated to turnkey plants with similar size to that under study.

The final outcome is a detailed performance and profitability analysis on different plant configurations, allowing to determine the best choice in response to the installation context.

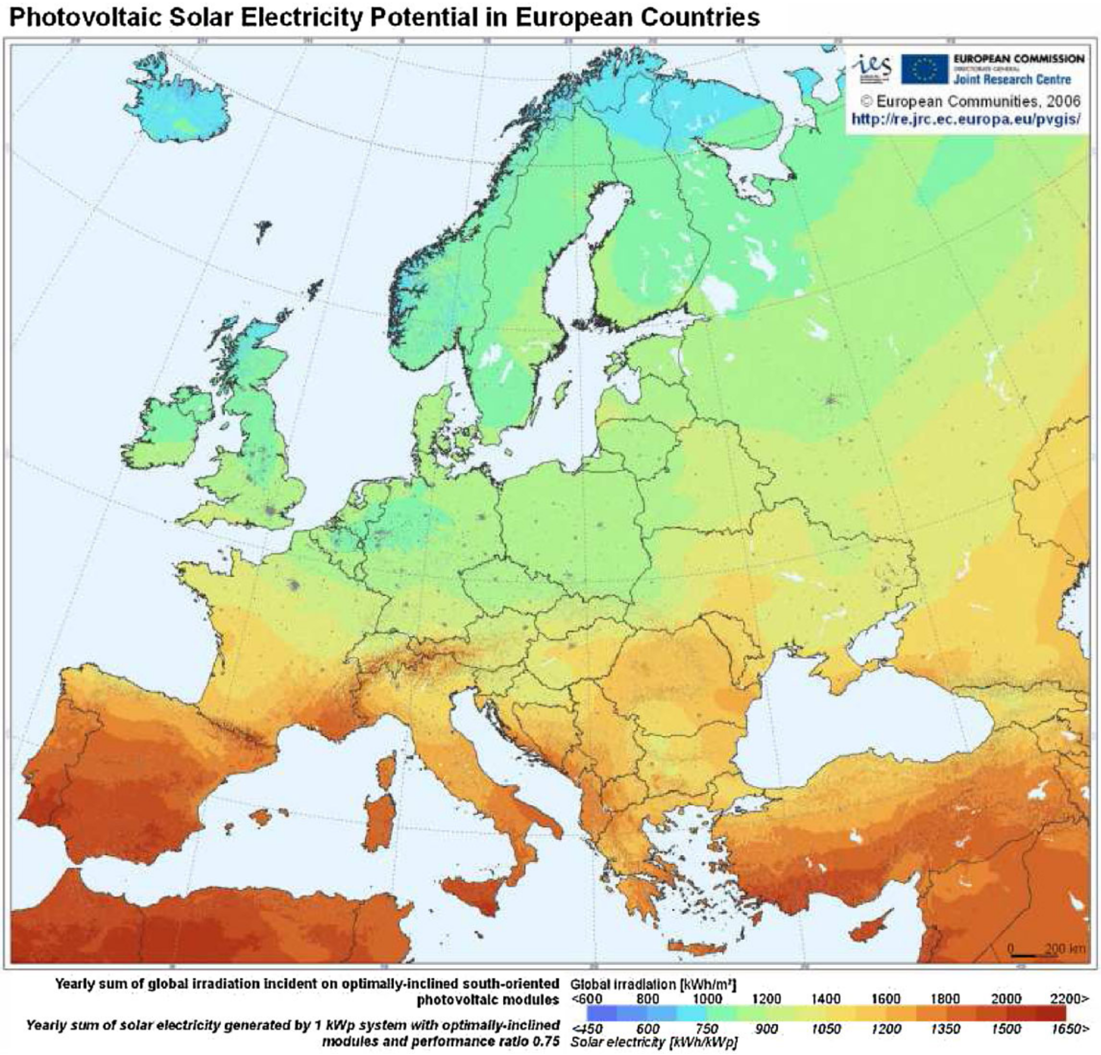

Figure 2. Europe, annual average irradiation value on an optimal-tilted and oriented plane.

3. ENERGY PERFORMANCE OF PV PLANTS

Energy productivity of PV systems depends mainly on the following factors:

- technical components;
- climatic reference context;
- ground-placing layout and tracking strategies.

Below are then analyzed in detail the peculiarities of each of the above-mentioned categories, listing the performance reference-parameters used in the present work.

3.1. Technological components

The main technological components of a PV plant can be divided into the followings subcategories.

3.1.1. PV modules.

The main parameters that characterize the energy performance of a photovoltaic module are:

- The nominal conversion efficiency, which indicates the amount of electricity supplied by the module as a function of incident solar radiation, determined in standard test conditions (STC). This efficiency depends on the peak power rating of the module and its total area, and allows also to determine the module power density, expressed in W/m^2.
- The temperature coefficient, which indicates the deviation percentage of the nominal efficiency of the modules, depending on the temperature variation in relation to STC.
- The performance-degradation coefficient, which indicates the annual percentage decrease compared to the nominal rated power, during the module operating cycle. It cannot be properly considered a technical parameter, but gives an indication on product reliability.

These parameters are provided through the technical specifications of the manufacturer of the modules or can be experimentally verified by performing on-field analysis in outdoor and heat stress conditions. In the present work, analyzing the technical characteristics of several PV modules available on the market and considering the results of some experimental tests [8], it was decided appropriate to identify three main product categories that have been considered representative of the present market, defined as follows:

- type A: photovoltaic modules with high power density, which are characterized by performance and costs higher than the market average;
- type B: photovoltaic modules with average power density, with performance and costs corresponding to the market average;
- type C: photovoltaic modules with average power density, good performance and lower cost than the market average.

3.1.2. Inverter.

The technical features of static-converters are associated to several parameters, but main characteristics can be summarized by:

- MPPT voltage range on DC side and capability to manage independently the various strings of modules;
- Euro-efficiency, which represents a weighted average of DC/AC conversion efficiency at different load input levels.

Analyzing the main products on the market it was found that they are characterized, on average, by good performance levels. However, in the presence of high peak power PV systems, it is possible to select two different conversion configurations, distributed or centralized, respectively achievable through small size inverter or a few units with high power. Because each of them is characterized by different performance levels, in this analysis two main categories of inverters were identified:

- type 1: single-phase inverter with small size, suitable to work autonomously or as a part of distributed conversion configurations;
- type 2: three-phase inverter for large size, suitable for centralized-conversion configurations.

In the first case, usually, inverters can be placed nearby the plant, without constructing a specific technical space, that is however necessary in the second case. In general, the first configuration is typically more expensive than the second one.

3.1.3. Other BOS components.

The other components of the BOS of a PV plant consist primarily of electrical wirings, DC and AC boards, monitoring instrumentation and BT/MT transformers, if present. For the purposes of this work, it was assumed that the choice of these components does not significantly affect the final performance of a system. Even if, generally, mounting structures are included among BOS components, in the present work they will be analyzed separately.

3.2. Climatic context

The main characteristics of the climatic conditions that could significantly influence the energy production of a photovoltaic system are the following:

- the total solar radiation level and the distribution percentage of beam and diffuse components;
- the air temperature.

In the present work, therefore, three different Italian locations were identified, considered representative of different climatic conditions that characterize the Country, but that can also be used as a reference to Central and South European contexts.

Irradiation and air temperature data were obtained from the database contained in the Meteonorm software [9]. In Table I, the average values of irradiation and air temperature are shown for the selected sites.

3.3. Ground-placing layouts and strategies

Photovoltaic modules can be placed on the ground by different types of mounting structures, with fixed or mobile planes. The last ones are available in different configurations, with different technical and structural solutions, capable to collect different levels of solar energy. So, also with regard to ground-placing layouts and tracking strategies, it is possible to define the following categories, according to most popular ground-mounting solutions on the market [10]:

1. structures with fixed inclination and orientation;
2. one-axis tracking structures, provided with horizontal axis parallel to the East–West direction;
3. one-axis tracking structures, provided with horizontal axis parallel to the North–South direction;
4. one-axis tracking structures with optimum tilted axis, toward North–South direction;
5. two-axis tracking structures.

In Figure 3 are shown the above described categories:

Table I. Weather data for reference sites

Irradiance level	Reference site	Irradiation on horizontal plane [kWh/m^2]	Average year temperature [°C]
Medium-low	Milano	1255	11.85
Medium	Roma	1549	15.79
Medium-high	Palermo	1690	18.01

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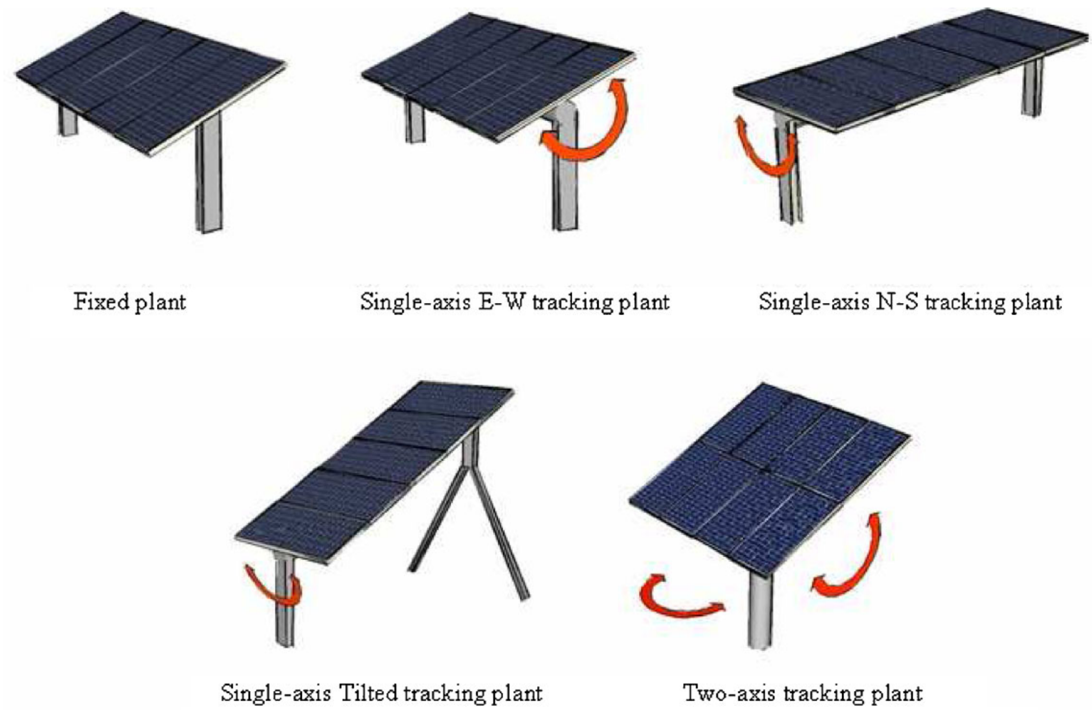

Figure 3. Different configurations of ground-mounted PV plant.

In order to define the possible layouts for each analyzed configuration, the following reference angles were chosen:

- γ angle, is the angle among the horizontal projection of the normal to the surface and the South semiaxis; it indicates the orientation of the surface compared to the geographic South. It is 0° when the surface is oriented to the South, it is positive for rotations to the East and negative toward the West.
- ψ angle, indicates the tilt of the surface compared to the horizontal plane. It is 0° when the surface is horizontal, is positive for anticlockwise rotation and negative for clockwise ones.

For one-axis structures it was always considered a variable ψ tilt angle, among $+80°/-80°$, while for the biaxial structures the following limits have been set: $\gamma = +90°/-90°$ e $\psi = 0°/+80°$. These values derive by analyzing the operational constraints, imposed on average by the most popular manufacturers on the market.

4. PV PLANTS ENERGY SIMULATION

The energy performance estimation of a photovoltaic system can be carried out by different methods of calculation or simulation procedures. In particular, in order to carry out the preliminary analysis, the PV electricity production can be evaluated using the following expression:

$$E_{PV} = PR \times P_{PV} \times \frac{H}{I_{STC}}$$

where E_{PV}, expressed in kWh, is the amount of electricity produced during the analyzed period; P_{PV} is the rated PV nominal power;

H is the solar irradiation on the unit-surface under consideration, during the analyzed period [kWh/m^2]; I_{STC} is the solar irradiance at Standard Test Conditions (STC), equal to 1 kW/m^2. PR represents the PV plant performance ratio. This coefficient, whose average value is around 75–85%, summarizes the overall effect of all elements influencing the final productivity of a photovoltaic system connected to the grid and can be defined according to the following factors:

$$PR = k_O \times k_{BI} \times k_T \times k_W \times k_M \times \eta_{INV}$$

where k_O indicates the influence of optical and spectral losses, k_{BI} indicates the influence of the low-irradiance losses, k_T indicates the temperature losses, k_W indicates the DC and AC wiring losses, k_M indicates the influence of the mismatching losses, η_{INV} is the DC/AC conversion efficiency.

However, to carry out detailed annual productivity analysis of a PV plant by this method could be laborious or inaccurate. In fact, to precisely determine PR values with short time steps requires long analytical examination and, in reverse, to adopt average PR values cause imprecise results.

In the literature, there are quick and user-friendly estimation tools, such as the PV Potential Estimation Utility developed by the Joint Research Center of the European Commission [6]. They allow to determine the average solar radiation available in various European locations and consequently the photovoltaic installations productivity. However, the final accuracy is not typically high.

In order to obtain more detailed analysis, on the market are available some simulation software, that can perform energy calculations using the hourly climatic data. To do so, it is possible to use methods based on the reconstruction of a Typical Meteorological Year (TMY), using statistical series of data acquired during several years. Therefore, this procedure allows to evaluate accurately the parameters previously mentioned.

In the present study, it was so decided to use PVSyst software [11] tool, that allows to make evaluation with an high level of accuracy, following the previously described criteria. Then, by defining climatic context and the PV plants parameters, it was possible to simulate the performance behavior of different configurations.

This software is used to predict in detail the performance of a specific photovoltaic system, using the hourly meteorological data for the analyzed location as a reference. In particular, starting from the horizontal plane irradiation, the software is able to simulate the incident radiation on fixed or tracking surfaces. Subsequently, by defining the technical characteristics of the selected components, such as inverters and modules, it was possible to simulate the PV plant's behavior, depending on the operating conditions of the selected site and the assumed configuration.

5. PERFORMANCE ANALYSIS OF DIFFERENT PLANT CONFIGURATIONS

In this part of the analysis, on the basis of the previously made considerations about the plant's components, the climatic context, the ground-placing layouts and the simulation tools, detailed energy assessments have been carried out, as described in the following paragraphs. Step 1 has been carried out on a small size plant, characterized by optimal technological components and without considering neither self-shadowing effects between plant's elements nor ground costs, in order to establish best achievable performance in all analyzed conditions. By further examinations made in Step 2, a large size PV central has been analyzed, considering all energy and economic performance influence-factors, but also evaluating different types of technological components between those available on the market.

5.1. Performance analysis — Step 1

In the first phase of the analysis, energy performance achieved in the different climatic conditions were estimated, by analyzing a PV plant reference section. Subsequently, the increased performance associated to different spatial variations and tracking logics were evaluated.

5.1.1. Reference case.

The reference case is characterized by a 6.3 kW_p section, with fixed ground-mounting structure, characterized by optimal inclination and orientation angles (respectively, $\gamma=0°$ and $\psi=30°$). The chosen peak power is the result of three strings of ten 210 W_p modules each and represents roughly the maximum peak power connectable to a single-phase inverter.

The technological components used in this section have been selected among those with higher efficiency, compared to the common available alternatives on the market. In particular, regarding the PV modules, the choice fell on type A, with a peak power of 210 W_p. With regard to the DC/AC converter, a type 1 inverter has been selected, according to main categories described in Section 3.1. To be able to consider detailed reference parameters, two different specific products (a PV module and an inverter) have been selected. The reference case is thus realized by

- 30 SANYO HIP-210 NHE5 modules;
- a POWER-ONE OUT PVI-6000 inverter;
- cables and connectors on DC side.

In order to estimate the maximum achievable performance in the assumed climatic conditions, the effects of mutual (because of the presence of different modules rows) or reported shading were considered null in this part of the analysis.

The obtained results are summarized in Figure 4.

As can be observed, productivity in Milano is about 1120 kWh/kW_p, in Rome the value is close to 1400 kWh/kW_p and in Palermo, characterized by highest productivity, specific energy production rise 1500 kWh/kW_p. Obtained data are in agreement with literature and existing plants productivity values [12,13].

5.1.2. Ground-placing variations.

As previously mentioned, open-field-installed photovoltaic modules can also be anchored to moveable mounting structures, which can be characterized by different techniques and tracking systems. In this phase, the analysis has been carried out for the performance achieved by the

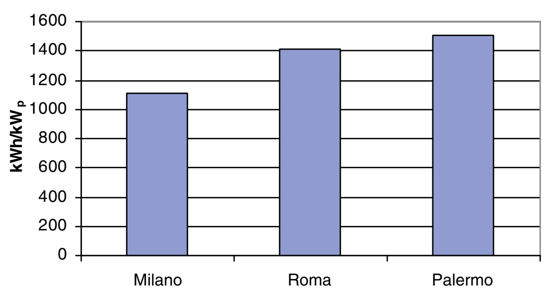

Figure 4. Specific energy production in the selected sites.

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Table II. PR, specific energy production and productivity increase compared to reference case

Site	Plant type	ψ	γ	Irradiation on modules surface kWh/m^2	PR %	Specific energy production kWh/kW$_p$	Productivity increase on reference case
Milano	Fixed	30	0	1333	80.9	1114	Reference Case
	1 axis E-W	variable	0	1396	81.3	1170	5%
	1 axis N-S	0	variable	1556	82.2	1311	18%
	1 axis N-S tilted	30	variable	1661	82.6	1407	26%
	2 axis	variable	variable	1703	82.8	1445	30%
Roma	Fixed	30	0	1693	81	1414	Reference Case
	1 axis E-W	variable	0	1807	81.5	1514	7%
	1 axis N-S	0	variable	2035	82.3	1712	21%
	1 axis N-S tilted	30	variable	2190	82.6	1850	31%
	2 axis	variable	variable	2249	82.8	1920	36%
Palermo	Fixed	30	0	1813	80.7	1509	Reference Case
	1 axis E-W	variable	0	1936	81.1	1614	7%
	1 axis N-S	0	variable	2228	82.1	1867	24%
	1 axis N-S tilted	30	variable	2370	82.3	1989	32%
	2 axis	variable	variable	2427	82.4	2062	37%

same technological configuration used for the PV plant reference section, in presence of various ground-placing layouts and tracking strategies. The obtained results are summarized in Table II. Figure 5 represents the energy production's trends for the specific sites and configurations analyzed.

5.1.3. Preliminary observations.

Analyzing the obtained results, following observations can be made:

- PR increases for tracking configurations compared to fixed ones, independently from the plant location;
- for tracking configurations, irradiation on the modules surface and hence the productivity, increase more in southern locations, if compared with the reference case. In facts, by moving toward South, the ratio of beam and total available radiation is higher than in the North. In detail, in Milan the average annual beam radiation is approximately 59% of the total, while in Palermo this ratio is approximately 70% [14];
- the difference in productivity among various specific configurations increases while decreasing site latitude, in a proportional way to global irradiation level;
- the maximum achievable enhancement with tracking systems, compared to fixed ones, is observed in Palermo,

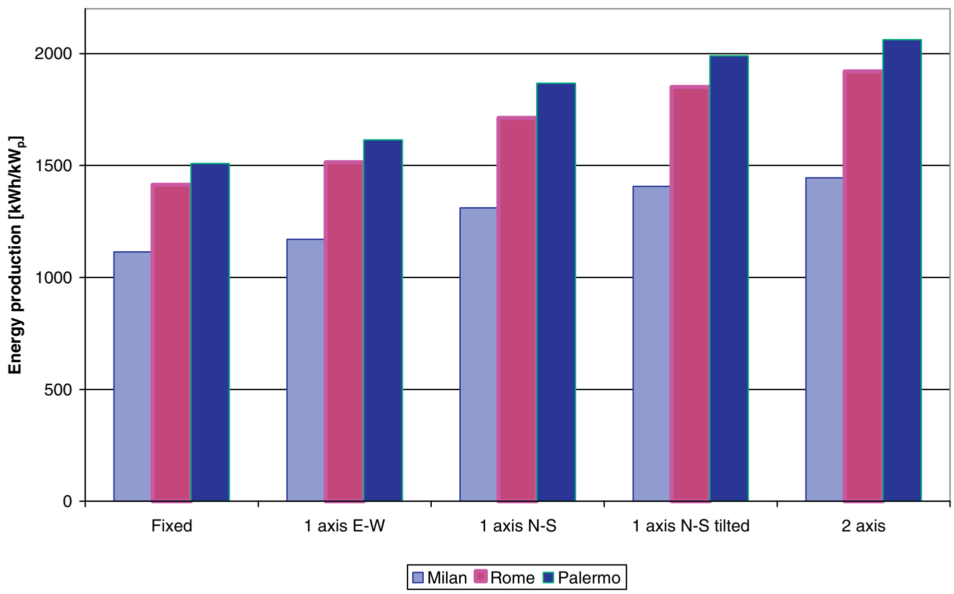

Figure 5. Specific energy production's trend.

with values ranging between 7% for tracking systems with one-axis parallel to east–west direction, and 37% for two-axis systems.;
- biaxial configurations are always characterized by highest energy production;
- the productivity of a biaxial configuration located in Milan is higher than that of a fixed one placed in Rome, and almost similar to the one generated by fixed configuration placed in Palermo. As a consequence, tracking systems could make more productive a plant located in a place characterized by low solar irradiation in comparison to a fixed plant located in a higher solar irradiation climatic zone.

It would be very interesting to validate the above results with the actual monitoring data, however, due to recent mass-scale diffusion of high-performance solar tracking systems in the market, it is very difficult to get a complete set of experimental productivity data on actual systems. Anyway, at present the available literature data [15,16] substantially agree with obtained results, which confirm a maximum achievable performance enhancement due to solar biaxial trackers placed in south Europe ranging from 25 to 45%.

5.2. Performance analysis – Step 2

In consideration of the emerged results in the preliminary analysis, in this part of the work more detailed energy assessments have been carried out, for a large PV plant (the power is a multiple of the one selected for the reference case and equal to 957.6 kW_p) having a configuration characterized by specific spatial layout and selected technology components.

In addition to the energy performance assessments, a profitability analysis has conducted, with the aim to identify not only the most energy-intensive configurations, but also those with higher profitability. This parameter, in fact, in case of PV field, depends on several factors, including:

- type and characteristics of the chosen technologies;
- layout and spatial influence resulting from the different constitutive elements of the plant;
- specific components and configurations costs;
- operation and maintenance costs.

In this phase of the work, the layout design and the subsequent energy assessments were made only for Palermo location, because, as previously shown, the site was found able to ensure best performance among those tested.

5.2.1. Technological components.

At this stage of the analysis, the technological components were selected from those that have been considered more representative of the different categories identified in Chapter 3. To limit the cases of analysis, the choice was made on glass-Tedlar laminated with aluminum frame and consisting of mono or polycrystalline silicon cells, with a peak power equal to 210 W_p.

With regard to the PV modules, the selection have been made on following products:

- type A: SANYO HIP-210 NHE5 (Heterojunction with Intrinsic Thin layer), characterized by higher efficiency compared to alternatives available in the market;
- type B: SOLARWORLD SW-210 Poly, polycrystalline silicon, can be regarded as representative of a medium price and performance level range;
- type C: TRINA TSM 210, polycrystalline silicon, it was considered a product with a medium performance rating and a low price range.

Relating to DC/AC converters, two types of inverter have been chosen, single and three phase, respectively, by which it was possible to obtain distributed or concentrated conversion layouts. Also in this case, according to the above mentioned categories, two specific models of inverter have been identified, by which it was possible to define the layout of the power conversion:

- 1 category: N° 152 POWER-ONE PVI-6000 OUT inverter;
- 2 category: N°2 Elettronica Santerno SUNWAYS TG 610 800 V inverter.

The analyzed PV sample central is thus composed of:

- 4560 210 W_p PV modules;
- 152 single-phase or 2 three-phase inverter;
- wiring, connectors and DC boards.

Consequently, combining the different modules and inverters categories, it is possible to obtain several configurations, as shown in Table III.

5.2.2. Layout and spatial influences.

In presence of specific plant spatial layout, the placement of ground-mounting elements influences the incident radiation through mutual shading and, consequently, the plant productivity. Therefore, it is essential to determine the optimal distance between rows of modules or between solar tracking units. This calculation is necessary in order to optimize the relationship between reported shadows and the ground surface occupied by the generator. In particular, the influence of shading can be determined by quantifying

Table III. Configuration list

Plant configuration	Modules	Inverter
A 1	Sanyo	Power One
A 2	Sanyo	Santerno
B 1	Solarworld	Power One
B 2	Solarworld	Santerno
C 1	Trina	Power One
C 2	Trina	Santerno

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the SF factor (Shading Factor) which is the percentage of solar radiation intercepted by the surface of the modules, compared to the total available irradiation. For example, a shading factor equal to 0.95 means that, on average, 5% of incident solar radiation will be lost due to the shading on the PV active surface during the analyzed period. The ground occupation can be evaluated through the GCR (Ground Cover Ratio) parameter [17], which indicates the ratio between the active PV area and the total ground surface occupied by the installation.

The spatial layout of a large PV plant should be defined optimizing the values of SF and GCR as a function of the location and land specific costs. However, in this work, the optimal tilted and oriented fixed structure was used as a baseline solution, setting the distance between different rows of modules in order to minimize self-shading effects. Through computer simulations the value of SF for that configuration was then estimated, considering the result as optimal reference value.

For solar-tracking installations, however, in order to reduce the ground occupation within realistic values typically used for large PV plants, information provided by some system integrators, operating in the Italian market, were considered as a reference [18].

So, in order to define the optimal distance between the various rows, it is appropriate to evaluate the minimum solar height reached by the sun at 12.00 on winter solstice, calculated using empirical methods. In Palermo, considering a latitude equal to 38°N, the minimum solar height is 28.5°, minimizing the self-shading phenomenon between rows, a 15° shading angle was adopted, as shown in Figure 6.

Assuming, therefore, a regular geometric shape with rectangular base, the layout of the fixed photovoltaic field has been defined, consisting in 10 rows with 456 modules each, as shown in Figure 7.

SF factor for the defined configuration was thus calculated, and an annual value equal to 0.98 is obtained. Subsequently, some layouts were developed for the other analyzed configurations (tracking structures) with the aim to determine the different SF values on the basis of assumed GCR.

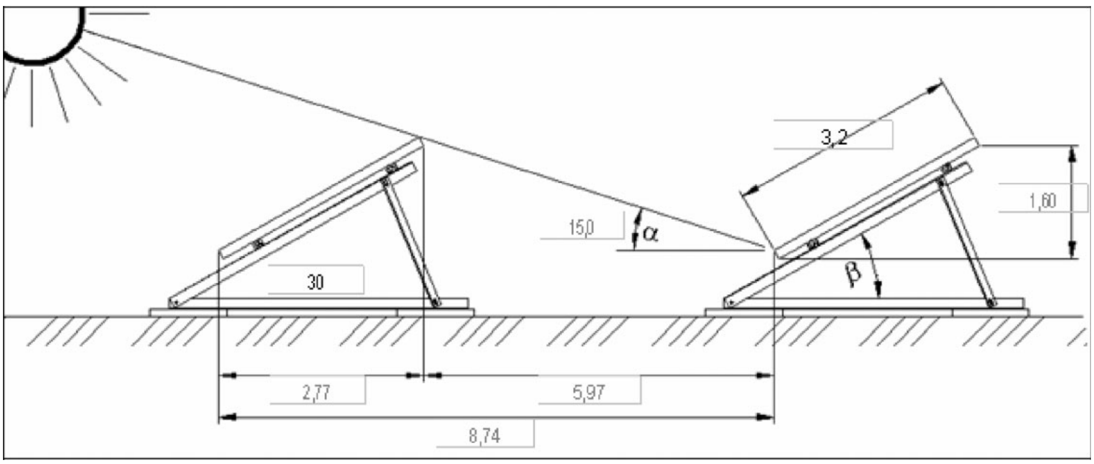

Figure 6. Shading angle for fixed ground mounting structures.

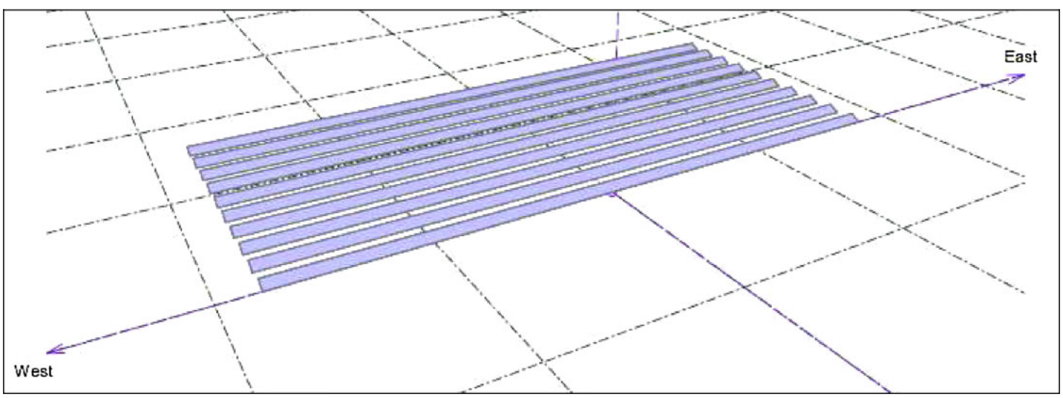

Figure 7. Fixed plant layout.

Table IV. Covered surface, GCR, and SF values

Plant type	Rows/columns distance	Covered surface	GCR	SF
	m	m^2	—	—
Fixed	8.75	15 000	0.39	0.98
1 axis E-W	12	20 000	0.29	0.97
1 axis N-S	17	28 000	0.21	0.965
1 axis N-S tilted	10 × 15	38 000	0.15	0.95
2 axis	19 × 19	48 000	0.12	0.94

The general layout of the plant, with respect to one-horizontal-axis tracking systems was kept constant to the one described above for the fixed configuration, using 10 rows of 456 modules each and changing just the distance between rows. For tilted one-axis and biaxial configuration, however, the plant has been divided into elements composed of 30 modules each. This choice agrees to the usual dimensional size of the supporting structures available on the market.The results of optimization process are shown in Table IV.

5.2.3. Capital cost.

In order to provide a complete evaluation about the profitability of the described hypotheses, a market survey was performed through some national System Integrators [19] involved in medium and large size photovoltaic systems implementation.

This survey was useful to evaluate cost ranges for each main category identified on the basis of market prices of the various components. Obtained data are listed in Table V.

Besides, regarding the mounting structures, Table VI summarizes the costs for square meter, to facilitate evaluations made on different module surfaces.

In addition, the different average cost impact was detected, in relation to installation design and accessories for each type of plant. The total plant cost of each case, in fact, is determined by both the variability of the market costs of component and labors, but also by the different weight of each item on the total cost. For example, in configurations with tracking system, the installation cost, expressed in €/kW_p, is on average higher than that of fixed installations.

Moreover, it is essential to add to the total components' cost identified for each plant's type, average prices that have to be paid to purchase land required for installation, expressed in €/m^2. This cost, related to southern Italy agricultural zones, was assumed on average between 2 and 3 €/m^2, according to actual market costs.

So, on the basis of the above specified average ground cover areas and on costs per square meter detected for southern Italy, it was possible to determine the range of average costs for different plant's types, as summarized in Figure 8.

In relation to the different assumptions made for the analyzed plant, it was possible to obtain the final "turnkey" cost, depending on the different plant configurations (mounting system typology: fixed/one-axis/two-axis, technological components type: A/B/C modules, 1/2 inverters). Obtained results, expressed in €/kW_p, are summarized in Table VII.

5.2.4. Annual costs.

Once determined the initial investment costs, it was also necessary to quantify the weight of annual management, maintenance, and insurance, for which the following market average costs have been recorded:

- O & M: 1.8% of the total plant's cost;

Table V. Market cost survey

		Min	Max	Average
Modules	€/kW_p	2900	3500	3200
Inverter	€/kW_p	180	280	230
Fixed mounting structures	€/kW_p	180	260	220
One-horizontal-axis mounting structures	€/kW_p	400	600	500
One-tilted-axis mounting structures	€/kW_p	600	900	750
Two-axis mounting structures	€/kW_p	900	1200	1050
Installation	€/kW_p	250	350	300
Design and accessories	€/kW_p	600	1000	800

Table VI. Mounting structures costs for square meter

		Min	Max	Average
Fixed mounting structures	€/m^2	25	35	30
One-horizontal-axis mounting structures	€/m^2	55	75	65
One-tilted-axis mounting structures	€/m^2	75	115	95
Two-axis mounting structures	€/m^2	110	150	130

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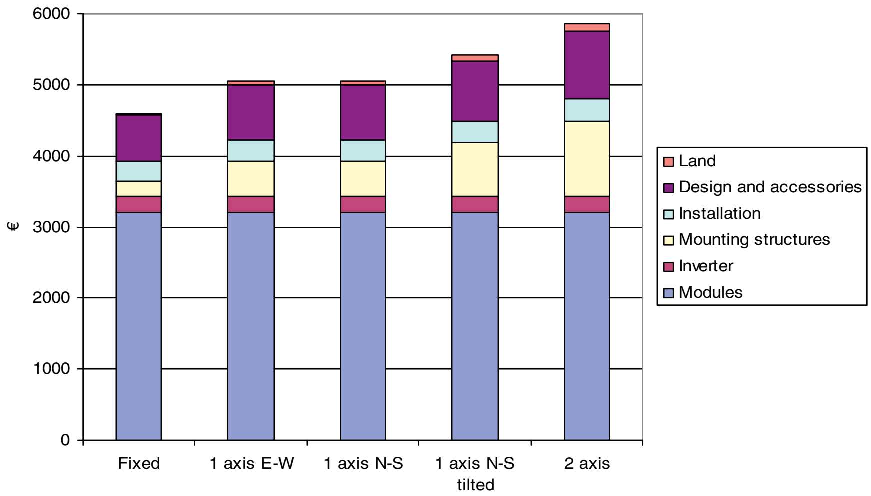

Figure 8. Average costs for different plant types.

Table VII. Total capital costs

Plant type		A 1	A 2	B 1	B 2	C 1	C 2
Fixed	€/kW$_p$	4.931	4.841	4.531	4.441	4.331	4.241
1 axis E-W	€/kW$_p$	5.372	5.282	4.972	4.882	4.772	4.682
1 axis N-S	€/kW$_p$	5.388	5.298	4.988	4.898	4.788	4.698
1 axis N-S tilted	€/kW$_p$	5.749	5.659	5.349	5.259	5.149	5.059
2 axis	€/kW$_p$	6.190	6.100	5.790	5.700	5.590	5.500

- ''All Risk'' insurance (it includes theft insurance and damages for natural or others accidental events): 0.3% of the total plant's cost.

These effects, related to the total costs described above, have provided the results summarized in Table VIII.

5.2.5. Performance analysis.

On the basis of the previously made considerations, computer simulations were performed to estimate energy production for each case, obtaining the results shown in Tables IX and X.

As can be seen from data shown in the tables, the configuration characterized by the best productivity is the one equipped with modules that belong to category A, distributed inverters and biaxial mounting-structure. In contrast, the less productive configuration among those taken into account is characterized by fixed support structures, modules belonging to category C and centralized inverter.

5.2.6. Profitability analysis.

In order to exactly determine the suitability of the different analyzed hypotheses, taking into consideration the impact of all involved costs (components, land, operation and maintenance, insurance) compared with generated incomes, an economic assessment has been therefore carried out by determining the IRR (Internal Rate of Return).

The IRR is a capital budgeting metric also called discounted cash flow rate of return (DCFROR) or rate of return (ROR). It is an indicator of the efficiency or quality of an investment, as opposed to net present value (NPV),

Table VIII. Annual management, maintenance and insurance costs

Plant type		A 1	A 2	B 1	B 2	C 1	C 2
Fixed	€/year	99.167	97.357	91.123	89.313	87.101	85.291
1 axis E-W	€/year	108.024	106.214	99.980	98.170	95.958	94.149
1 axis N-S	€/year	108.360	106.550	100.316	98.506	96.294	94.485
1 axis N-S tilted	€/year	115.617	113.808	107.574	105.764	103.552	101.742
2 axis	€/year	124.483	122.674	116.440	114.630	112.418	110.608

Table IX. Specific energy production and PR for distributed inverters

Modules			A 1		B 1		C 1	
plant type	Peak power	Irradiation on modules surface	PR	Specific energy production	PR	Specific energy production	PR	Specific energy production
	kW_p	kWh/m^2	%	kWh/kW_p	%	kWh/kW_p	%	kWh/kW_p
Fixed	957	1769	78.6	1479	76.4	1428	75.7	1414
1 axis E-W	957	1890	79.0	1572	76.4	1520	75.7	1507
1 axis N-S	957	2158	79.7	1803	77.1	1744	76.5	1731
1 axis N-S tilted	957	2237	78.2	1876	75.5	1821	75.2	1810
2 axis	957	2280	78.3	1900	75.8	1836	75.3	1827

Table X. Specific energy production and PR for centralized inverters

Modules			A 2		B 2		C 2	
plant type	Peak power	Irradiation on modules surface	PR	Specific energy production	PR	Specific energy production	PR	Specific energy production
	kW_p	kWh/m^2	%	kWh/kW_p	%	kWh/kW_p	%	kWh/kW_p
Fixed	957	1769	78.5	1469	76.0	1421	75.3	1407
1 axis E-W	957	1890	78.7	1566	76.2	1517	75.4	1502
1 axis N-S	957	2158	79.6	1799	77.0	1741	76.4	1728
1 axis N-S tilted	957	2237	78.0	1872	75.4	1816	74.9	1806
2 axis	957	2280	78.2	1895	75.7	1835	75.2	1824

which indicates value or magnitude. The IRR is the annualized effective compounded return rate which can be earned on the invested capital. Put another way, the IRR for an investment is the discount rate that makes the NPV of the investment's income stream total to zero. Given a collection of pairs (time, cash flow) involved in a project, the IRR follows from the NPV as a function of the ROR. An ROR for which this function is zero is an IRR.

So, once defined the NPV value according to the following formula:

$$\mathrm{NPV} = -\mathrm{TC} + \sum_{t=1}^{25} \frac{F_j}{(1+r)^t}$$

where TC is the total capital cost of the analyzed PV plant. F is the annual cash flow, including incomes generated both by the feed-in tariff and the energy trading with the national electric grid. t represents the analyzed year; it can varies from 1 (that is the first working year of the plant) and 25 (corresponding to the end of the PV modules' warranty period, provided by the manufacturer).

IRR is the r value by which $\mathrm{NPV} = 0$.

The reference conditions adopted in the analysis are listed below:

- plant size: 957.6 kW_p;
- feed-in tariff [20]: 0.353 €/kWh (valid if the plant starts working before 12/31/2009);
- mean yearly performance degradation coefficient: −0.5%;
- tariff for the electricity sold to the grid : 0.098 €/kWh;
- yearly electricity cost average increase: 3%;
- plant working life: 25 years.

The mean yearly performance degradation coefficient is assumed equal to −0.5%, according to experimental data [21,22] and the maximum degradation guaranteed by manufacturers for C-Si modules, typically −20% in 25 years operating-life.

It was thus possible to calculate the IRR values for all configurations, obtaining the results summarized in Table XI.

Observing obtained data, it emerges that C2 configurations is the most profitable, with an IRR ranging from

Table XI. IRR values for analyses configurations

	A 1 (%)	A 2 (%)	B 1 (%)	B 2 (%)	C 1 (%)	C 2 (%)
Fixed	10.0	10.2	10.8	11.1	11.4	11.7
1 axis E-W	9.6	9.8	10.3	10.6	10.9	11.1
1 axis N-S	11.9	12.1	12.7	13.0	13.3	13.6
1 axis N-S tilted	11.4	11.7	12.2	12.4	12.8	13.1
2 axis	10.4	10.6	10.9	11.2	11.5	11.8

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11.1% (1 axis E-W) to 13.7% (1 axis N-S). In contrast, A1 configurations result characterized by lowest profitability, with internal rates of returns from 9.6% (1 axis E-W) to 10.9% (1 axis N-S).

6. FINAL CONCLUSIONS

According to obtained estimations, it is possible to conclude that, thanks to irradiation levels and economic incentives, all analyzed configurations are able to assure good economic returns.

However, it appears that specific energy production is not the main influence factor on plants profitability. For example, biaxial configurations, that in Step 1 resulted characterized by highest energy productions, are not the most economically profitable. N-S one-axis tracking systems, despite lower specific energy production for each kW_p than biaxial ones, resulted the best choice among all analyzed configurations because of reasonably low capital and O&M costs.

Moreover, it can be assumed that tracking strategies are not always the best choice under economic points of view. For example, a fixed plant guarantees better profitability than a E-W plant with equal technological configuration.

Regarding to PV modules, type C products, characterized by lesser energy performances, resulted the most profitable, thanks to low market cost. It means that, concerning large-size ground mounted PV plants, applying high power-density modules could not be the best choice under an economic point of view, because they are usually characterized by higher costs than the market average.

Anyway, it is essential to remember that all products utilized in the present work are characterized by good/optimal quality levels. So, modules with prices and quality standards excessively low can cause a reverse effect on long-term plant profitability.

Concerning to inverter configuration, from obtained data is reasonable to assume that a centralized-conversion layout is cheaper enough, in comparison to a distributed one, to assure slightly higher IRR values. Also in this case some clarification have to be made; for example, in case of DC/AC converters malfunctioning or faults, energy production losses are lower with distributed inverters than with centralized ones, because the plant fraction that could be involved in the failure is significantly smaller and technical assistance can be made also off-site. So, in both cases, considering small differences among IRR values, products reliability and O&M strategies/timings could have significant influence on final economic performance.

Moreover, analyzing specific case-studies, it is possible to conclude that the choice of technological components can make significant changes on general considerations made on ground mounting structures. For example, the C2 fixed configurations achieves an IRR value similar to the one reached by C1 biaxial plant and higher to A1/A2, B1/B2 biaxial ones.

It means that specific energy and profitability analysis are always inescapable, because the several influence parameters involved in the plant's operating-life energy production can considerably change technical and economic preliminary evaluations.

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