Caruso M. [1]**,**
Di Noia L. P. [2]**,**
Romano P. [1]**,**
Schettino G. [1]**,**
Spataro C.[1]
Viola F. [1*]**,**

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Regular paper

PV Reconfiguration Systems: a Technical and Economic Study

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Dynamical electrical array reconfiguration strategies for grid-connected PV systems have been proposed as solution to improve energy production due to the mismatch effect of PV plants during partial shading conditions. Strategies are based on the use of dynamic connections between PV panels given by the employment of switches that allow for each panel the series, parallel or exclusion connections, physically changing the electrical connections between the related PV modules, consequentially modifying the layout of the plant. Usually the cost of the dynamic matrix is not taken into account. This novel work evaluates the economic advantages obtained by the use of reconfiguration strategies in PV systems, by taking into consideration the price of energy due to incentives in different European and non-European countries and correlates it with the employment of two types of reconfigurators, with different internal structures. For each of the incentives proposed by the different Countries, the main strength and weakness points of the possible investment are highlighted and critically analyzed. From this analysis, it can be stated that the adoption of reconfiguration systems, in certain cases, can be a very convenient solution.

Keywords: Photovoltaic; renewable energy sources.

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Nomenclature

DES	Dynamic Electrical Scheme
I-V	Current-Voltage
MPP	Maximum Power Point
PS	Partial Shading
PV	Photovoltaic

1. Introduction

One of the main goals of the international community is the reduction of the greenhouse gas emissions, replacing the traditional fossil fuels energy generation sources with renewable energy sources in the frame of a distributed generation. Such perspective is made possible by the use of power converters even more flexible and efficient in the management of the power flow in grids that are becoming *smart-grids*, including electric vehicles and co-generation systems. With this aim, the European Union issued the Directive 2009/28/EC, also known as 20-20-20 Directive, which promotes, starting from the situation of the year 1990, three targets to obtain by the year 2020: a 20% reduction of greenhouse gas emissions, a 20% increase of energy produced from renewable sources and a 20% of energy saving [1]. Obviously, an efficiency improvement of the technologies applied to renewable energy sources can help to obtain the three objectives.

In this framework, the photovoltaic (PV) power generation plays an important and strategic role [2,3]. In fact, it is possible to state that: PV generation does not produce gas emissions,

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[*] Corresponding author: Fabio.viola@unipa.it

[1] Department of Energy, Information engeneering and Mathematical models DEIM, viale delle Scienze, parco d'Orleans, University of Palermo, Palermo, Italy

[2], Department of Electrical Engineering and Information Technology, University of Naples Federico II, Via Claudio 21, 8012 Naples, Italy,

except the ones due to their manufacturing; during their lifetime, PV panels generates much more energy than that required for their manufacturing; often PV plants can be installed in locations not usable for other applications, such as roofs; PV generation is one of the most economical approach to deliver energy in remote areas. However, there is a flip side, since, due to the equipment required, the PV power generation is more expensive than other sources. In order to minimising this problem, various countries are promoting the PV plant installations with subsidies or incentive tariffs, which could become competitive in the near future [4-11], increasing the efficiency of the PV plants and, consequently, reducing the cost of the generated power thanks to technical and technological improvements in the whole generation system [12-17]. The promotion of PV generation is also carried out because also the other renewable energy sources are affected by some technical problems [18-19] and this requires the introduction of novel control techniques [20-27] for the correct management of the distributed energy sources.

The paper proposes an approach aimed to enhance the productivity of the photovoltaic (PV) arrays, in particular reducing the power losses due to electrical mismatch effect, by using a device called *PV array reconfigurator*.

Dynamical electrical array reconfigurator have been proposed as solution to recover energy production due to the mismatch effect of PV plants during partial shading (PS) conditions. Strategies use dynamic connections between PV panels, given by the employment of switches physically changing the electrical connections between the related PV modules, consequentially modifying the layout of the plant. In figure 1, a switch set allows for each panel the series, parallel or exclusion connections.

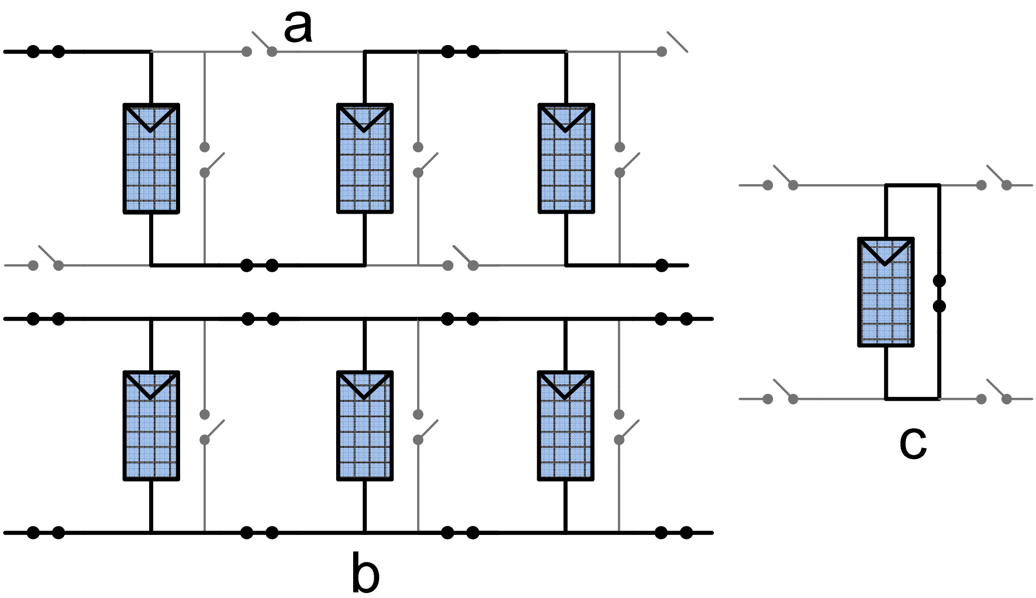

Fig. 1. Use of switches for the reconfiguration of panels. In (a) the series configuration is realized, whereas in (b) the parallel connection and in (c) a possible exclusion are provided.

The paper is divided in different paragraphs: session 2 is dedicated to the discussion of the mismatch problem; section 3 is devoted to performance of the PV system with shading; section 4 introduces the incentive policies in different Countries; section 5 evaluates the economic convenience of the employment of a reconfigurator; section 6 discusses on the different cost of reconfigurators; finally section 7 introduces the conclusions.

2. The mismatch problem

Since each characteristic of a PV module differs from its rated value and varies within its tolerance limits, when various cells are connected in series and/or in parallel, their working point moves. As a consequence of this mismatch, the total power generated by a PV array is significantly less than the sum of the power outputs of the individual modules that work independently. Moreover, even if the modules had the same values of their characteristics, the mismatch effect would arise simply because of the partial or total shading of a single cell of the module, due to clouds, bird's droppings, dirt falling, trees, neighbor's houses, or the shadow of one solar array on the other. Moreover, this circumstance leads to nonlinearities in characteristics of the PV modules [28].

In many new applications, such as solar power plants, Building-Integrated Photovoltaic (BIPV), it is quite important to optimize the performances of the arrays under non-homogeneous shading conditions. Because of the electrical characteristics of solar cells, the power losses are not proportional to the shadow, but they increase nonlinearly.

In order to face these problems, in literature, various approaches to optimize the power output under non-optimal irradiance conditions have been recently proposed, adopting dynamic reconfiguration systems for PV modules interconnection [29-40]. To implement these optimization approaches, monitoring systems are needed in renewable energy applications to track the performances of the generation plant, collecting power production and performance data as well as weather conditions information [41-44]. However, to control efficiently the PV system, there is the need to measure accurately the characteristic of each module. In this way, it would be possible to track the working conditions of each module, recognizing faulty units [45-47] and preventing mismatch and partial shading conditions through suitable control actions [48-49].

References [50-51] deal with the power losses due to partial shading (PS). Fig.2 shows the power losses caused by PS. A light shadow reduces the power of the array from 1000 W to 800W; if a panel is heavily shadowed, a bypass diode excludes the shaded panel and the voltage moves from 80 V to 50 V with another reduction of output power. Finally, if two bypass diodes are activated, voltage moves to 25 V and the array greatly reduces the generated power.

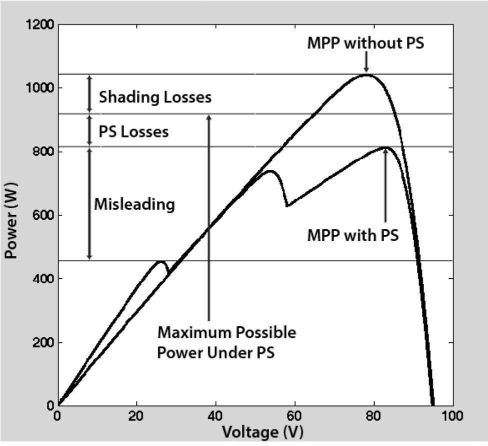

Fig. 2. Shading, partial shading, and misleading losses for a photovoltaic array. Three levels of losses are present, depending on the lines of cells of the panel: when only one is shaded the voltage is higher, while for two or three, voltage is considerably reduced.

The maximum available power does not equal the array maximum power without partial shading. The difference is the shading losses, which cannot be avoided. Moreover, such phenomenon can mislead MPPT algorithms.

The techniques for reducing partial shading losses could be grouped into the following categories [52]:
- Distributed Maximum Power Point Tracker (DMPPT);
- Multilevel inverters;
- Photovoltaic array reconfiguration.

Focusing on the last group, the existing state-of-the-art strategies for PV array reconfiguration utilizing the "irradiance equalization" principle are extensively reviewed in [52-53].
The reconfiguration strategy can be applied to two different typical situations. The first one is when fixed objects (i.e., chimneys) project their shadow onto a part of the plant. This is common for PV plants placed on the roof or integrated in a building (Fig.3), even if, installers usually avoid placing PV modules in these locations.

Fig. 3. Partially shaded roof of a building. Different panels are shaded, global production is greatly reduced and investiment plan varies.

Another situation of unpredictable shading derives from passing clouds. In this case, there is a distributed drop of irradiance above all the PV plant. Depending on the speed of the passing clouds, the irradiance conditions can change suddenly, causing a large reduction of the PV plant efficiency. Moreover, it is necessary to consider that, in case of failure of one or more modules, these can be automatically disconnected by the reconfigurable array.
The shaded solar cells may work on the negative voltage region, becoming a resistive load and dissipating energy. Bypass diodes are sometimes parallel connected to the solar cells in order to protect them from damage. However, in most cases, just one diode is parallel-connected to a group of solar cells [53] and this hides the potential output power of the array. While they are active, diodes can reach very high temperatures.

3. PV system and Reconfigurator

During the design phase, it is essential to predict the best exposure to solar radiation for PV modules. A wrong choice can seriously affect the energy output of the PV plant. The PV modules are more efficient when the incident solar radiation is perpendicular to their surface, the best roof orientation is usually southward. Moreover, the total absence of any sort of fixed obstacles, closely around the PV plant, should be satisfied. This happens because in a fixed PV plant, the shadows of such obstacles over one or more modules, could cause undesirable and persistent module PV power output reductions that undoubtedly would affect the performances of the whole string which the disadvantaged module belongs to. Unfortunately, in practical applications, the southward installation is not always practicable and even when it is possible, there can be many factors that can disturb the performances of the PV plant such as the presence of dormers, chimneys, satellite dishes, trees and so on. Fig.4 shows a possible scenario, in which a shadow overlaps different panels. The effect on a shadowed panel affects also the panels connected in parallel, since a reduction of a shadowed panel voltage entails a reduction of not shadowed ones and an increase of current in order to balance power. This increase of current is not always possible, if the not shadowed panel works around its MPP, i.e. at 80 V in Fig.1, therfore any reduction of voltage reduces significantly the power.

Another issue, which negatively jeopardize the plant production, is the damage of one or more modules. In all these adverse cases, a monitoring system, which is not limited to the measure of the decrease of produced energy, but also indicates the causes, could be useful. In these cases, a system that can remove the deteriorated module is desirable. The deployment of a modules reconfiguration technique can represent a smart solution for the maximization of a PV plant output power, since a reconfigurator can also provide the function to exclude the damaged modules.

Fig.5 shows a PV plant on which a shadow, due to a pole, is projected. Each panel has three lines of cells and is connected to the reconfigurator, which, in turn, is connected to two channels inverter. The reconfigurator is set with two outputs.

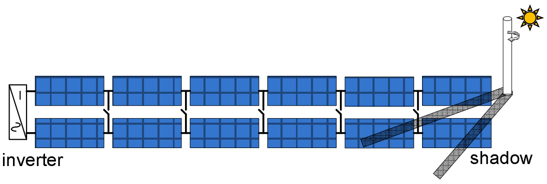

Fig. 4. Possible shadow projections in the analysed scenario. The moving shadow cuts different modules.

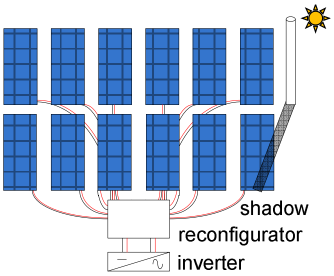

Fig.5. PV reconfigurator scheme. Each panel is connected to the reconfigurator and a dynamic plant configuration can be achieved.

Reconfiguration performances were tested with a prototype reconfigurator developed in the University of Palermo and employed on a twelve panels installation. The system acquires the state of every panel. In particular, voltage, current and temperature are collected by the twelve inputs. Fig. 6 shows the experimental setup for which the algorithm was tested. Twelve eight years old panels (Conergy, P_{MMP} 215 W, V_{MPP} 28.27 V, I_{MPP} 7.59 A, V_{oc} 36.37, I_{sc} 8.21 A) were connected independently to the reconfigurator.

When no shadow engages the plant, each panel shows the same behavior, and the reconfigurator creates its standard topology, that consist of two parallel identical strings of six modules in series. In order to test the system performance, various resistive loads were considered. Table 1 reports the electrical characteristics of these working conditions.

Fig. 6 Experimental setup with 12 panels individually connected to the reconfigurator.

Table 1: Electrical characteristics in different load conditions evaluated by reconfigurator

	load A	load B	load C	load D	load E
Voltage [V]	31.3	28.9	26.1	23.1	16.8
Current [A]	1.9	4.0	6.0	7.0	7.4
Power [W]	54.5	115.6	156.6	161.7	124.3
String [W]	356.2	693.7	939.2	970.2	745.5

With the aim to test the reconfiguration algorithm, an artificial shadow was generated. Fig.7 shows three shadow conditions onto one of the panels of a parallel string. Panel is made by 6 orizonthal x 9 vertical cells; a single line is made by a series of 18 cells (2 x 9). If only one cell is shaded, all the line of 18 cells does not produce. The artificial shadow cuts one, two or three lines of cells, reducing the module and string performance. Each line interruption causes the operation of the bypass diode and the consequent voltage reduction of the panel. Let us indicate with V_1-V_5 the voltages of the five non-shadowed panel and with V_6 the voltage of the shadowed one. The reconfigurator evaluates the power of each panel and reconfigures the panel connections into the string.

Fig. 7 Shaded panel. Case 1: the minimum shadow can vary from 225 to 450 cm^2, (one or two cells covered); case 2: shadow varies from 450 to 900 cm^2; case 3 corresponds to the interruption of the panel.

Table 2 summarizes the behavior of the system with and without shading. P_1-P_5 are the output powers of the panels that are not shadowed, while P_6 is the power of the shadowed panel in all three cases and I is the current of the system in the cases taken into account.

Table 2: Electrical characteristics of the string in different shadow conditions

	Shadow condition	V_{1-5} [V]	V_6 [V]	I [A]	P_1-P_5 [W]	P_6 [W]	P_{string} [W]
load A	Not shaded	31.3	31.3	1.9	54.5	54.5	356.2
	Case 1	31.6	20.2	1.6	50.5	32.3	285.1
	Case 2	31.8	9.0	1.2	38.1	10.8	201.6
load B	Not shaded	28.8	28.8	4.0	115.2	115.2	691.2
	Case 1	29.2	18.7	3.3	96.6	61.7	543.5
	Case 2	30.1	8.2	2.6	78.3	21.3	412.6
load C	Not shaded	26.1	26.1	6.0	156.6	156.6	939.6
	Case 1	27.7	17.1	5.0	138.5	85.5	778.0
	Case 2	29.1	7.4	4.2	122.2	31.1	642.2
load D	Not shaded	23.1	23.1	7.0	161.7	161.7	970.2
	Case 1	25.9	15.6	6.4	165.7	99.8	928.6
	Case 2	27.7	6.8	5.2	144.0	35.4	755.6
load E	Not shaded	16.8	16.8	7.4	124.3	124.3	745.9
	Case 1	16.8	11.0	7.4	124.3	81.4	703.0
	Case 2	16.8	4.2	7.4	124.3	31.1	652.6

Fig. 8 shows the voltage-current and voltage-power profiles of the panel with three working lines of cells (blue curve), two working lines of cells (orange curve) and only one working line (grey curve).

Without any shading, the working point is on the blue curve. If a line of cells is shaded, the working point moves from the blue to the orange curve, maintaining a similar current, but changing in terms of voltage. Furthermore, if the shadow covers two lines of cells, the working point moves from the blue curve to the grey curve, maintaining a similar current and, once again, changing its voltage. From Fig. 8 it can be also noticed that a voltage variation entails new power conditions.

The reconfigurator is able to regroup similar irradiated panels and/or exclude the highly shaded panels. In dependence of both the technology and the algorithm implemented into the reconfigurator, different working operations can occur: a simple and traditional reconfigurator can only exclude shaded panels, while a high-performance reconfigurator can relocate them on suitable dynamic arrays.

Under reconfigured configuration, the increases of the obtained power are shown in Table 3. From these data it can be stated that the reconfiguration system through the monitoring facility can also show the improvement due to the disconnection of shaded panels.

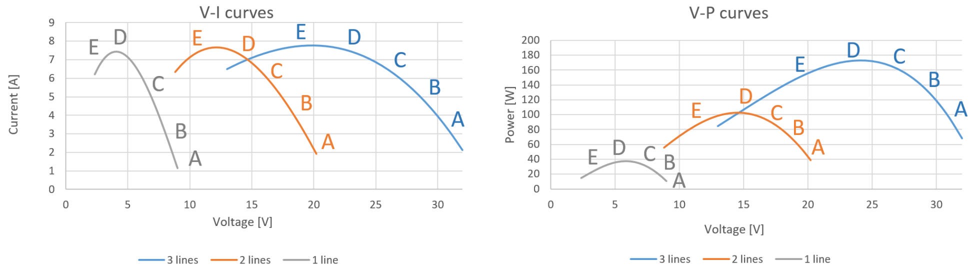

Fig. 8 Interpolated V-I and P-V curves of the panel with different shadows. Blue: without shadow, Orange: with a shaded line, Gray: with two shaded lines. Points A, B, C, D, E are due to different loads.

Table 3: Electrical characteristics in different loading conditions evaluated by reconfigurator for each panel

	$loss_{case1}\%$	$loss_{case2}\%$	Reco [W]	Loss rec%	ΔP1%	ΔP2%
load A	20.0	43.4	297.3	16.7	+3.5	+26.9
load B	21.4	40.3	576.0	16.7	+4.8	+23.7
load C	17.2	31.6	783.0	16.7	+0.6	+15
load D	4.3	22.2	808.5	16.7	-12.3	+5.6
load E	5.7	12.5	621.6	16.7	-10.9	-4.1

Fig. 9 shows the benefits of the employment of the reconfiguration technique: in case 1 and for the lower currents (load A-B-C) an increase of power is verified, while for higher currents (loads D-E) a decrease can be detected, as well as for case 2 (lower currents, loads A-B-C-D and higher current, load E).

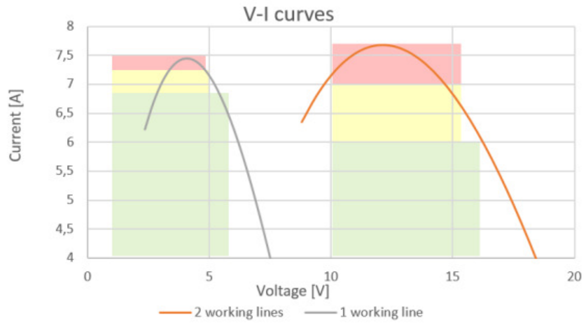

Fig. 9. Zones of convenience of the disconnection of partially shaded module. Green zone: exclusion of panel is convenient; Yellow zone: exclusion of panel can decrease the produced energy; Red zone: energy lost from the esclusion of panel is higher then the one recovered by the other panels.

Fig. 7 show a further case, consisting in an entirely shadowed panel. In such case, a negative voltage of the shadowed panel affects the performance of the string. Each not shaded panel varies its operating condition assuming a voltage slightly higher than the non-perturbed condition.

Table 4 shows the increase of power when a panel is totally shaded. The study of case 3 shows that when the shadows cut in two parts the panel 6 (becoming a load), reconfiguration reduces always the loss of power.

Case 3 shows the real performance of the reconfigurator. The MMP working points are all taken between loads C and D. By considering the overall behaviour of two shaded strings used simultaneously, a possible performance increase between 12% and 25% can be stated.

It is now considered the possibility of placing in parallel connection partially obscured panels in order to ensure the maximum current of arrays. Thus, this feature requires a more evolved reconfigurator, whose current sum is equal to the current of the non-shadowed panels.

Table 4. Electrical characteristics in different load conditions evaluated by reconfigurator for each panel

	Shadow condition	V_{1-5} [V]	V_6 [V]	I [A]	P_1-P_5 [W]	P_6 [W]	P_{String} [W]	Loss%	ΔP3%
load C	Not shadow	26.1	26.1	6.0	156.6	156.6	939.6		
	Case 3	26.7	-2.9	5.1	136.1	-14.8	665.7	-29.1	
	reconfigurated	26.1	open	6.0	156.6		783.0	-16.7	+12.4
load D	Not shadow	23.1	23.1	7.0	161.1	161.1	970.2		
	Case 3	23.7	-3.0	6.5	154.0	-19.5	750.7	-22.7	
	reconfigurated	23.1	open	7.0	161.1		808.5	-16.7	+6.0
load E	Not shadow	16.8	16.8	7.4	124.3	124.3	745.9		
	Case 3	17.4	-3.1	7.4	128.7	-21.5	620.8	-16.7	
	reconfigurated	16.8	open	7.4	156.6		621.5	-16.7	0

Table 5. Electrical characteristics of the string in different shadow conditions

	Shadow condition	V_{1-5} [V]	V_{6-7} [V]	I [A]	P_1-P_5 [W]	P_{6-7} [W]	P_{string} [W]	Loss %	$V_{6//7}$ [V]	$I_{6//7}$ [A]	P_{6-7} [W]	P_{string} [W]	ΔP %
load C	Not shaded	26.1	26.1	6.0	156.6	156.6	1096.0				156.6	1096.0	
	Case 1	27.7	17.1	5.0	138.5	85.5	863.5	-21.2	19.3	6.0	60.0	903.3	+4.2
	Case 2	29.1	7.4	4.2	122.2	31.1	673.3	-38.5	6.2	6.0	36.1	909.2	+21.4
load D	Not shaded	23.1	23.1	7.0	161.7	161.7	1132.0				161.7	970.2	
	Case 1	25.9	15.6	6.4	165.7	99.8	1028.0	-9.2	15.0	7.0	101.0	1010.0	-1.5
	Case 2	27.7	6.8	5.2	144.0	35.4	755.6	-33.2	5.0	7.0	36.3	881.1	+11.1

As shown by Table 5, this feature is beneficial only when case 2 is considered. For a two arrays PV system, a possible increase of performance is about 20%.

In order to perform an economic analysis, two reconfigurators will be taken into account: Type 1, which consists of a simple “exclude or not” feature with a cost of 500 € and Type 2,which consists of the advanced feature of parallel scheme. For the economic analysis the increased power given by the reconfigurators will be taken as an increase of energy produced during the day.

4. Policies of Incentives

Italy

The so called "Conto Energia" (C.E., [4-6]) has opened the opportunities of investment on PV systems along the Italian country. This policy, which has been introduced in 2005 and subsequently integrated in 2006, has changed significantly the way to encourage the owner of a PV plant, providing opportunities and incentives for both the new installation and the energy production from photovoltaics. With respect to the dimensions of the PV plants, the incentives bought by the C.E. can vary in a significant way. However, the favorable climate of this Country and the long-term duration of the incentives (20 years) allows the owner of the PV system to have returned the related investment costs within a period of about ten years. As a matter of fact, for the first C.E. (2005), in just nine days the planned financed amount was already reached and the Italian Minister was forced to increase the incentive capacity from 100 MWp to 500 MWp. Then, several others C.E.s have been proposed, but the tariffs were considerably and progressively reduced.

In order to better assess the economic capability of the investment, it is useful to recall the specific characteristics of the most recent C.E. and the current incentive system, which are described in the next paragraphs.

Conto Energia V

In 2012, July 5th, the Ministerial Decree defined the incentive program Conto Energia V [4], which has been legally introduced on August 27th of the same year, covering an indicative annual financial incentive of 6.7 billion of euros. As for the previous programs, the Conto Energia V classifies PV systems into three main categories (subsequently divided into other two subcategories in dependence of their installation site):

- Simple PV systems
- Concentrated PV systems, where the sunlight is concentrated by means of optical systems on photovoltaic cells
- Innovative or integrated PV systems, which use particular technologies to improve the production, such as movable panels

In addition, C.E. V introduces two rates:

- The all-inclusive tariff, consisting of an incentive for the amount of produced energy and then sold to the grid
- The self-consumption tariff, which corresponds to an incentive for the amount of produced energy and then locally consumed.

Moreover, as for the previous C.E.s, the incentive rates are still during for twenty years and vary in dependence on the type of system and the type of installation.

Simple PV systems and plants integrated with innovative features, may give rise to particular incentive bonuses: by employing components made in the EU or in the EEA (European Economic Area), the bonus is equal to:

- 20 € / MWh if the PV is activated no later than December 31st, 2013;
- 10 € / MWh if the PV is activated no later than December 31st, 2014;
- 5 € / MWh if the PV is activated after December 31st, 2014.

Table 6 summarizes the feed-in-tariffs for a simple PV system installed on building, whose maximum power is less than 3 kW. It can be noticed that, in dependence on the activation of the system, the incentives significantly vary.

Table 6. Incentive to production of a simple plant for C.E. V in different periods

Semester	I Sept. 2012 Feb. 2012	II Mar. 2013 Aug. 2013	III Sept. 2013 Feb. 2014	IV Mar. 2014 Aug. 2014	V Sept. 2014 Feb. 2015
All-inclusive	208	182	157	144	133
Self- consumption	126	100	75	62	51

Tax deduction for photovoltaic systems

The policy of encouragement towards renewable energies in Italy has effectively ended together with the conclusion of C.E. V, on July 6th, 2013. On the other hand, the Italian

Revenue Agency, in its resolution 22/E of 02.04.2013, has officially confirmed the applicability of the tax deduction provided for building renovations, regarding the costs of purchase and installation of PVs on residential buildings.

In order to benefit from the aforementioned tax deduction, the installation of the plant must be done primarily to meet the energy needs of the building. For a maximum amount of € 48,000, the deductible expenditure is equal to 36%.

In addition, two different services can be chosen by the owner of the PV plant:

1. The "on-site exchange", which compares the commercial value of the electricity furnished into the grid and the energy withdrawn. In addition, a reimbursement of expenses (incurred by the user to pick up electricity from the grid for the balance between fed and drawn energy) is provided.
2. The "dedicated withdrawal", which consists in the sale of electricity produced and fed into the grid, remunerated at a minimum guaranteed price, with a subsequent verification at the end of the year to determine adequate refinements (if the revenue from a zone time price exceeds the revenues from the guaranteed minimum price).

Germany

During the last years the German government has adopted the strategy for the nuclear exit and, at the same time, it has improved the German Renewable Energies Act (Erneuerbare-Energien-Gesetz or EEG) by modifying some aspects of the Fixed feed-in Tariff (FiT) system, even if its basic structure has remained unchanged [7]. Under the terms of the EU Renewable Energy Directive (Directive 2009/28/EC), the 18% of the German gross final energy consumption must be provided by renewable energy source. In this country, despite its geographical location, the PV plants have a good income. Due to the high consumption, the investment in PVs is already cheap enough. The values of average consumption per capita, energy cost, incentives and production facility can be summarized as follows:

- Average consumption per capita: 3,512 kWh/year;
- Energy cost: € 0.33 /kWh;
- Incentives: € 0.13 /kWh;
- Production facility: 3120 kWh/year.

France

The consumption per capita in France is very high if compared with other countries (doubled in comparison with Germany), as well as the incentives [8]. However, but the energy price is relatively low (almost halved with respect to Germany) because of the high number of nuclear power plants spread along the Country. The previously mentioned data are hereinafter summarized:

- Average consumption per capita: 6,343 kWh/year;
- Energy cost: € 0.18 /kWh;
- Incentives: € 0.28 /kWh;
- Production facility: 3510 kWh/year.

Spain

Spain is one of the most affordable European Country in terms of PV investments, with incentive policies economically attractive [9].

- Average consumption per capita: 4,131 kWh/year;
- Energy cost: € 0.28 /kWh;
- Incentives: € 0.34 /kWh;
- Production facility: 4980 kWh/year.

Sweden

The Swedish country has approached the PV production only in recent years. Hydropower is the main source for the production of energy [10]. Consumptions in Sweden are high in contrast to the yield of a plant, as shown by the following data:

- Average consumption per capita: 14,177 kWh/year;

- Energy cost: € 0.10 /kWh;
- Incentives: 35% of the cost system;
- Production facility: 3090 kWh/year;

Nigeria

Nigeria is clearly the cheapest Country for investment in PV production [11]. In Nigeria, due to geographical location, a PV system produces a great amount of energy, almost 50% more of the previous evaluated production. But this is not the most important fact: the incentive is also the largest among those analysed, well above the European average. The combination of the two points makes the investment very attractive.

- Average consumption per capita: 570 kWh/year;
- Energy cost: € 0.17 /kWh;
- Incentives: 0.50 € /kWh;
- Production facility: 4810 kWh/year;

5. Evaluation of the Economical Convenience

The aim of this section is to establish the economical convenience of the reconfigurator for the PV system, by considering the year of the installation of the plant itself.

This convenience is evaluated through the Net Present Value – *NPV* [54]. This method allows to obtain the result from a sum of cash flows actualized at time zero with a rate equal to the opportunity cost of the financial capital:

$$NPV = -C_0 + \sum_{k=1}^{n} \frac{C_k}{(1+i)^k} \qquad (1)$$

where C_0 is the original investment (cost of the PV plants), C_k is the cash flow at the year k, i is the interest rate and k is the period of net cash flow. Therefore, a positive value of *NPV* indicates a convenience in terms of investment and vice versa. For its computing, the yearly data of the PV incomes and expenses, namely cash flows, are needed and their calculation is based by considering the interest rate MARR (Minimum Attractive Rate of Return). This parameter symbolizes the amount of assumed earnings for the investment. Thus, the *NPV* allows the estimation of the expected cash flow in a given period. Two investments can be, then, matched by comparing the *NPV* values obtained from them.

The payback method is a method that allows the assessment of the time interval in which there is the recovery of the costs incurred, taking into account the discounting of cash flows. This method gives information related only to the recovery time and not what can be the possible gain.

Italy

The case study consists of a PV plant installed on January 2013 with the C.E. V incentive program, with an installation cost of 7000 € and assuming the average consumption of a family composed by four elements.

Table 8 summarizes the monthly production of the PV system at 3% of efficiency reduction of the panels after the first year of operation is assumed, while for the subsequent years the power reduction due to aging is assumed equal to 0.5 % per annum. The effect of shading comes from the fourth year onwards, and it is assumed a 10% daily loss of energy, which can be compensated by reconfiguration strategies.

The amount of energy self-consumed is calculated as the minimum between the energy produced and the energy consumed, while the amount of energy injected to the network is calculated as the difference between the energy produced and energy consumed. A positive result of this difference determines the cancellation of the related bill. Table 9 summarizes the production, the consumption and the transfer of energy of the proposed system.

Table 7. Average monthly consumption for 4 members family

Two-monthly consumption							
Bimestrial	Dec-Jan	Feb-Mar	Apr-May	Jun-Jul	Aug-Sep	Oct-Nov	**Total year**
kWh	395,00	386,00	375,00	395,00	677,00	394,00	**2.622,00**
€	73,73	71,15	66,87	71,61	161,24	72,78	**517,38**

Table 8. Production on the first year, [kWh]

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
248,56	317,16	370,49	422,92	547,84	543,75	576,95	560,62	390,09	287,84	281,28	245,91	**4.793,41**

Table 9. Production, consumption and transfer of energy, [kWh]

Year	Production	Consumption	Self-consumption	**Transfer**
1	4.793,41	2.622	2.622	**2.171,41**
2	4.621,88	2.622	2.622	**1.999,88**
3	4.138,89	2.622	2.622	**1.516,89**
4	4.118,20	2.622	2.622	**1.496,20**
5	4.097,61	2.622	2.622	**1.475,61**
6	4.077,12	2.622	2.622	**1.455,12**
7	4.056,73	2.622	2.622	**1.434,73**
8	4.036,45	2.622	2.622	**1.414,45**
9	4.016,27	2.622	2.622	**1.394,27**
10	3.996,19	2.622	2.622	**1.374,19**
11	3.976,21	2.622	2.622	**1.354,21**
12	3.956,33	2.622	2.622	**1.334,33**
13	3.936,54	2.622	2.622	**1.314,54**
14	3.916,86	2.622	2.622	**1.294,86**
15	3.897,28	2.622	2.622	**1.275,28**
16	3.877,79	2.622	2.622	**1.255,79**
17	3.858,40	2.622	2.622	**1.236,40**
18	3.839,11	2.622	2.622	**1.217,11**
19	3.819,91	2.622	2.622	**1.197,91**
20	3.800,81	2.622	2.622	**1.178,81**

Afterwards, an entry-exit budget is created and shown in Table 10, by taking into account the tariffs provided by the specified period. This table summarizes, for the entry budgets, the incentive for self-consumption (A.C.), the energy fed into the grid (out) and the advantage of no bills. For the exit budgets, cost of the plant and maintenance costs are taken into account. For a plant build in the first semester of C.E. V (see table 6), FiT is 208 €/MWh, self consumption is 126 €/MWh.

In this study it is assumed that the owner of the plant, because of the reduction in production of the PV plant due to shading occurring during the fourth year, begins the adoption of the reconfigurator during the fifth year. From the fifth year, an output amount ranging from 500 € to 1000 € is considered. Two different prices are used in order to simulate different business choices and different performances of the reconfigurator.

The payback time is reached between the 7th and the 8th year for Type 1 (exclude-or-not reconfigurator, 500 € of overall cost, recover 10%) and the increase of NPV (considering the cash flow without reconfigurator) is about 443 €. For Type 2 (parallel scheme reconfigurator, cost 1000€, recover 20%) the payback is reached between the 8th and 9th year and the increase of NPV is 886 €.

By considering a plant build in the second semester of C.E. V, FiT is 182 €/MWh, the self consumption is equal to 100 €/MWh. The payback time is reached between the 9th and 10th year for Type 1, whereas the increase of NPV is about 338€. For Type 2 the increase of NPV is equal to 676€.

In the case of the tax deduction, which corresponds to the recent policy in Italy, the NPV becomes negative.

Table 10. Economic balance, [€]

	ENTRY					EXIT			
Year	A.C.	Out	No Bill	**Total**		Bill	Plant	Man	**Total**
0	0	0	0	**0**		0	7000	0	**7000**
1	330	447	517	**1294**		0	0	100	**100**
2	330	416	517	**1264**		0	0	100	**100**
3	330	315	517	**1163**		0	0	100	**100**
…	…	…	…	**…**		…	…	…	**…**
20	330	245	517	**1093**		0	0	100	**100**

Table 11. Cash flow with €500 reconfigurator

Year	Cash Flow	Discounted Cash Flow	Cumulative Cash Flow
0	-7.000	-7.000	**-7.000**
1	1.199	1.145	**-5.618**
5	1149	514	**-2398**
8	1135	782	**73**
…	…	…	**…**
20	1081	426	**6934**

Germany

The scenario is similar to previous case: a 7000 € PV system has been considered, whereas the maintenance has been set to 100 €/year, the energy reduction starts at 4th year and the reconfigurator is employed in the 5th year.

In Germany, despite the geographical location, the PV plants have good incomes. More in detail, due to the high consumption, the investment in PV systems is already cheap, even without the reconfigurator (NPV>0). However, the installation of the device is quite affordable with a substantial increase in the NPV: Type 1 has an increase of 400€, while Type 2 has an increase of 900€.

France

Even if the simulated scenario is the same of the previous cases, the choice of a 7000€ PV system is not convenient, since the production is lower than the need. However, the use of Type 1 increases the NPV of 134€, while Type 2 increases the NPV of 269€.

Spain

For the simulated scenario the application of reconfiguration techniques increases the convenience of investment in Spain: the NPV increases for both Type 1 and Type 2 of 1500€ and 2800€, respectively.

Sweden

From Table 12 it appears clear that in Sweden, the proposed investment is not convenient: the NPV is decreased of 110€ for Type 1 and 220€ for Type 2.

Nigeria

Due to its geographical location, in Nigeria the investment in PV production is very attractive: low number of consumers and the surplus energy is well paid. Therefore, the use of reconfiguration strategies extremely increases incomes. As shown in Table 12, for type 1 the NPV is increased by 1300€, while for type 2 it is increased by 2300€.

6. Results and Discussions

Reconfiguration systems are complex devices capable to perform several functions, e.g, the real-time measurement of voltage, current and temperature involved in the PV system and the optimal reconfiguration of the related modules.

A reconfigurator internally contains the following elements: microprocessor, voltmeters and switches. The quality of a reconfigurator, although it is implicitly linked to the algorithm employed in the microprocessor, from the hardware point of view is a function of the number of switches.

Fig.10 shows a very simple set of switches, panels that can be putted in series or parallel but for a selected path. Only adjacent panels can be put in parallel, as in the transition from the diagram (a) in diagram (b), in which PV1 and PV2 from the series are put in parallel. It would not be possible to put in parallel PV1 and PV3, leaving PV2 in series.

In [55] an adaptive matrix is proposed, as shown in Fig.11. A couple of switches enables the parallel (Switch parallel up and down), whereas a second couple enables the series (switch series and bypass). The used switches set are 4 x panel, but each bus requires two switches to connect the PV array with the inverter and the dc/dc converter. For a system with 16 panels the required switches are 68.

In [56] a complex mosfet switching matrix has been proposed and here reported in Fig.12.

The number of switches in the switching network is equal to:

$(m*n) + ((m*n) -1)*(2+ (m*n))/2$,

where *m* and *n* are the number of the panels in a rectangular area. For a 4 x 4 panel system, switches are 151. Obviously, by comparing the two structures, it is possible to state that a more performing system can recover a greater amount of energy, but if the number of switches is too high, the cost of reconfigurator same can not be recovered.

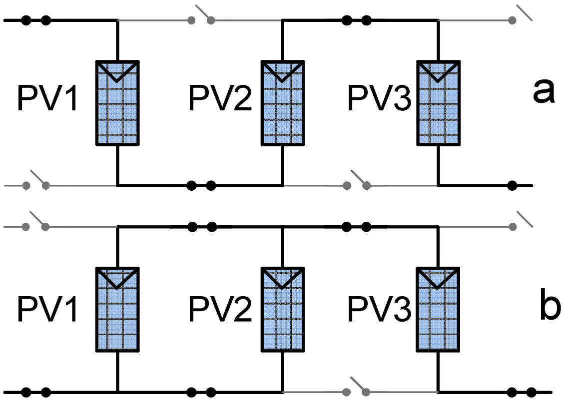

Fig. 10. Use of switches for the reconfiguration of panels. In (a) the series configuration of PV1, PV2 and PV3 is realized. In (b) the parallel connection of PV1 and PV2 is achieved.

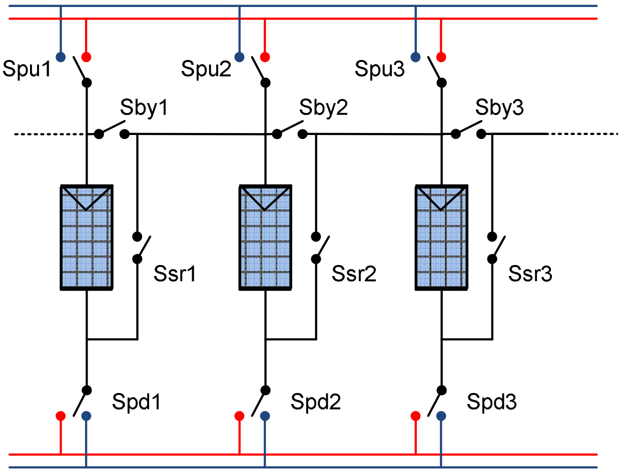

Fig. 11. Switching matrix proposed in [55].

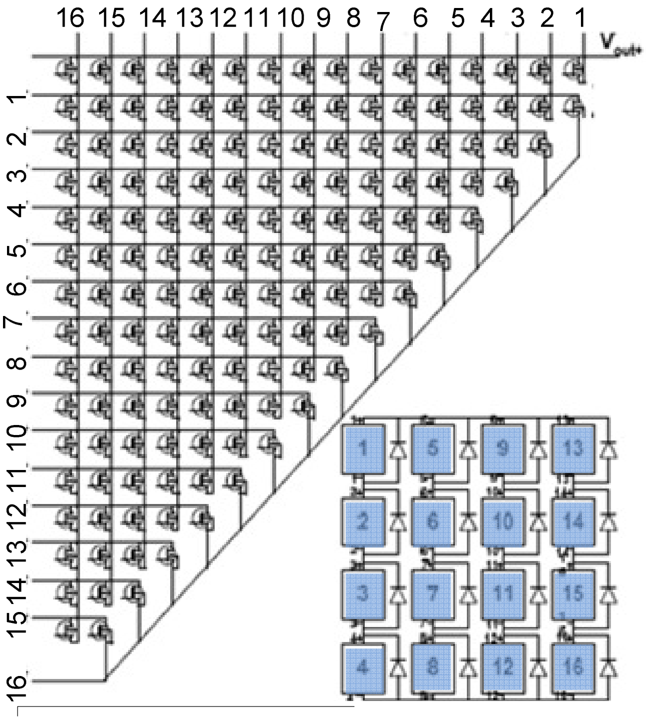

Fig. 12. Switching matrix proposed in [56].

An expensive reconfigurator (type 2) is capable to perform the previously mentioned functions in a relatively fast manner, detecting also the possible working points of the panel with accordance to its irradiation and managing the placement of each panel in a dynamic array. In addition, the tracking of the operating characteristic requires the use of robust elements. Due to these aspects, type 2 is a relatively expensive device, with inner structure closer to the one presented in [56].

On the contrary, type 1 does not possess sophisticated performances. As a matter of fact, the mode of action, only if three lines are blanked, it is the only operation that has proven to have a 100% success of increasing the power in the cases studied respect the non-intervention. The presence of a completely shaded panel is manifested by a negative reading of the voltage on the diode by-pass, due to the passage of the current of the string. The panels are inserted in series in the array, the exclusion of a panel does not require the use of a complex multiplexer, but of simple couple of switches such Spu and Spd of Fig.

11. In this way the reconfigurators can assume different prices depending on the type of elements they contain. In the following table the success of insertion in the different markets, based on the cost and type, and the possibility to replace the reconfigurator after ten years, is summarized.

Table 12. NPV in different market and at different prices

		Type 1					Type 2			
Country	cost[€]	250	500	1000	2x500		500	1000	1500	2x1000
Italy	NPV [€]	641	443	47	182		1282	886	489	364
Germany		667	468	72	219		1300	937	540	439
France		332	134	-262	-115		665	269	-128	-229
Spain		1728	1530	1134	1281		3087	2690	2294	2193
Sweden		84	-144	-510	-363		168	-228	-624	-726
Nigeria		1565	1367	971	1118		3131	2735	2338	2237

Table 12 shows the result of a use of a reconfigurator. The two type of reconfigurator are proposed, by considering the inner logic with mosfet (cheaper) or solid state relay (more expensive), prices may vary between a minimum and a maximum. It has also considered the case in which a reconfigurator can be replaced during the life of the PV system. In the absence of incentive of energy produced, as in the case of Sweden, the reconfigurator fails to repay. In the other Countries there is less advantage (France, Italy, Germany), while in Spain and Nigeria the the installation of a reconfigurator is convenient. In [57] the Bulgaria, Romania, Greece and Croatia cases can be found.

7. Conclusions

This paper has presented a discussion on the economic convenience of the application of reconfiguration systems for photovoltaic plants, considering the incentives in different countries. The goal is to understand if the object reconfigurator is able to pay for itself and also create an economic increase. The technical aspects in the increase of power due to the intervention of reconfigurator have been studied. The performance of two different reconfigurators, namely type 1 and 2, have been evaluated for different shading conditions and with different cases of study. A discussion on the strength and weakness points of two types of reconfigurators have been presented, by introducing the inner structure of reconfigurators, which is directly related to the cost of the object. The best performances of the reconfigurators have been acquired in fully shading condition: in this case, energy losses are recovered and they have been evaluated by a positive economic point of view. From the described results obtained by analysing the incentive policies of six countries, the reasonable market prices of the device have been traced, highlighting that the adoption of reconfiguration systems can be often a convenient solution. Reconfigurators are useful for Italian, German Spanish and Nigerian markets, unuseful for French and Sweden ones.

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