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Dynamic Reconfiguration Systems for PV Plant: Technical and Economic Analysis

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Abstract: Solar plants suffer of partial shading and mismatch problems. Without considering the generation of hot spots and following security issues, a monitor system for the health of a PV plant should be useful to drive a dynamic reconfiguration system (DRS) to solve bottlenecks due different panels shading. In the years, different DRS architectures have been proposed, but no suggestion about costs and benefits have been provided. Starting from technical subjects such as differences of the topologies driving the hardware complexity and number of components, this paper identifies the cost of DRS and its lifetime, and basing on these issue it faces an economic analysis for a 6 kWp PV plant in different countries of United Europe, in which dissimilar incentives policies have been considered.

Keywords: energy policies related to PV power plant; economic analyses; monitoring and case studies

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1. Introduction

The trend of the last decade to reduce greenhouse gas emission and the decarbonisation of the energy sources, it is mainly due to the increase of the temperature of the planet, allowed the development and improve the technologies for renewable energy sources. As well known, solar energy is the most available renewable energy source in the world with respect to the other sources and an interesting topic of research is the evaluation of the economic convenience. For this reason, in much study reported in literature, the economic convenience of grid connected PV systems has been evaluated with respect to the other technologies. The traditional approach is based on the use of the "levelized cost" method that represents the per unit value of total costs (i.e., capital, operation and maintenance, fuel) over the economic life of the power plant [1][2]. The economic convenience of PV plants emerged from these studies.

In European Union (EU), the number of the PV plants is significantly increasing thanks to the policies of the different countries that have led to economic benefits through incentives systems for the private citizens and in particular for small size PV plants called "residential plant" (from 1 kWp to 10 kWp). The international policies to encourage the installation of the PV plants consist in an incentive on the total "green energy" produced and in an incentive for the energy injected to the grid only for the grid-connected plants.

As well known, a typical issue of PV plants is the power loss due to the differences of irradiation (partial shaded or wrong design) among the cells of the same module or among different modules of an array. This phenomenon, known as mismatch, can generate a considerable power loss of the total system with a consequent economic loss. In [3] an interesting estimation of PV mismatch losses caused by moving clouds is reported. Moreover, this phenomenon can be caused from a fixed obstacle that can have appeared after years of the installation of the PV plant. The presence of a fixed obstacle after the installation is a frequent case in residential PV plants.

In order to limit the mismatch phenomenon, monitoring systems are extensively used in renewable energy applications to track the performances of the generation plant. A monitoring system for PV arrays is usually needed to collect power production and performance data as well as weather conditions information and relate them [4]-[6]. These systems allow detecting a fault condition but they are not effective about the power reduction of a PV plant.

The issue of the different irradiation levels among the cells of a module has been studied in [7], where an investigation on partially shaded modules with different connections of PV cells has been reported. The authors compare five different connection configurations in order to find the best solution to increase the maximum power production and the fill factor of a module. The same problem has been studied in [8] and [9].

The different irradiance causes also problem on the Maximum Power Point Tracking algorithm (MPPT) because the P-V curves of the PV module exhibit multiple maximum power points due to the bypass diodes, which are used to exclude the module of an array. In [10], the authors classified MPPT techniques for different PV array configuration. Obviously, each method presents advantages and drawbacks. Again, an interesting MPPT strategy for PV arrays under uniform and non-uniform irradiance condition is described in [11].

A recent solution proposed in literature to reduce the power losses is the Dynamic Reconfiguration System (DRS). The DRS allows to change the configuration of the PV plant in order to increase the power production. Different solutions have been recently proposed in literature to optimize the power output adopting dynamic reconfiguration systems for PV modules interconnection [12]-[19].

An interesting topic about the DRS is about the economic benefits introduced by the use of these systems. In [20] a technical-economical evaluation on the use of a DRS in some EU countries for PV plants is reported. In particular, by considering the incentives policies and others technical aspects about a 3 kW PV plant the NPV have been evaluated for each country taken into account. Nevertheless, in this study the technical aspects and different configurations about the DRS is not considered. For this reason, it is necessary to extend the economic analysis by introducing the real technical considerations of the DRS for different configurations reported in literature.

The aim of this paper is to evaluate the economic benefits introduced by using a DRS in a residential PV plant. At first, an economic analysis on different DRSs due to the costs of the components and to the adopted topological schemes, is carried out: in the authors' knowledge, this issue has never been faced in the technical literature. Architectures involve switching matrix, sensing network and driving circuit, the choice of switches affects the electro-technical and, electrical endurance. As will be shown in the following sections, the choice of a more flexible DRS comprises higher initial cost due to the number of switches required by the adopted architecture, but at the same time a less exploitation and therefore a longer useful life.

In particular, the study takes into account different technical and economic aspects about a PV plant in order to present a complete economic analysis. In other words, the study is focused on the use of different configuration of DRS, reported in literature, in some countries of EU in order to evaluate the performances of the investment. The economic tools are the Net Present Value (NPV) and Payback time.

This paper is organized as follows: Section 2 provides a brief description of the DRS topology taken into account in this work and technical considerations to estimate the costs and lifetime of DRS. Section 3 describes the experimental set-up to perform the evaluation of performance of DRSs. In section 4 the economic data are reported and in Section 5 the economic results are presented. Finally, Section 6 concludes the paper.

2. Dynamic Reconfiguration Systems

A DRS allows changing the connection among the PV modules in order to increase the total power production from a PV plant in wrong conditions of irradiance or other situation, that determinate the degradation of the performance. In this way, the hardware complexity of the DRS depends on the possible connections among the modules. Generally, in a reconfiguration algorithm each panel is a node of the dynamic array; the number of the nodes is identified as m while n switches perform the dynamic connection among the panels. A plant with high number of panels requires a DRS with high number of switches in order to connect all the nodes. Thus, a topology with more switches guaranties a high number of possible configurations for connection of the panels.

In this section, a brief state of art of the Dynamic Reconfiguration Systems (DRS) and a technical-economic analysis, of the four-case studied, are reported.

A. Case Studies

In order to carried out a complete technical-economic analysis, four cases of DRS have been investigated. The same cases have been studied in [21] but without considering the implications in terms of cost and lifetime of the DRS.

The first case under test has been presented in [22]. The authors propose an optimised Switch Set (SWS) topology for reconfiguration of PV panels based on Particle Swarm Optimization (PSO) algorithm. Figure 1 shows the optimised topology structure suggested by the authors, in which there are four lines and ten switches.

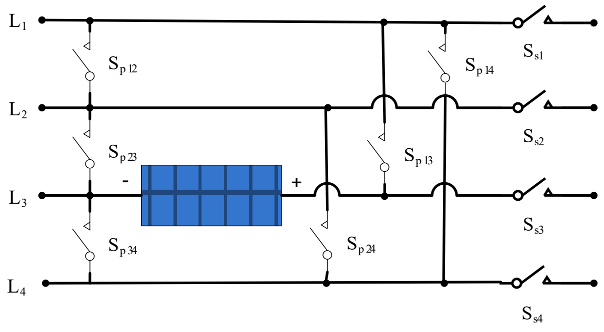

Figure 1. Optimised topology structure proposed in [22].

From Figure 1, it can be possible to observe that the number of switches *n* for each node *m*, is equal to:

$$n_{case1} = m \cdot 10 \tag{1}$$

An interesting low-cost method has been presented in [23]. This method does not require any additional MPPT controllers or sensors and it is based on the use of Fuzzy Logic (FL). The FL is used to identify the shaded, dirty or faulty panel, to estimate the percentage of shading or dust and to evaluate the minimum and maximum voltage values at which PV panels should be connected/disconnected. The validity of this system has been demonstrated through experimental tests. Figure 2 shows the connection of the system with four panel obtained in case 2.

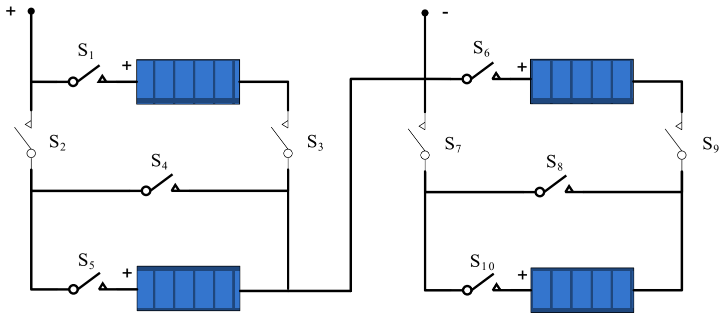

Figure 2. Topology structures obtained with the method proposed in [23].

The number of switches required for the case 2 can be evaluated as:

$$n_{case2} = m + 6 \tag{2}$$

In [24] a Photovoltaic Array Switching algorithm is presented. This algorithm, in order to find the best configuration of a PV array, is based on the use of only two parameters: the array load voltage and the PV module's temperature. The study has been focused on the evaluation of the performance of four PV modules, as shown in Figure 3.

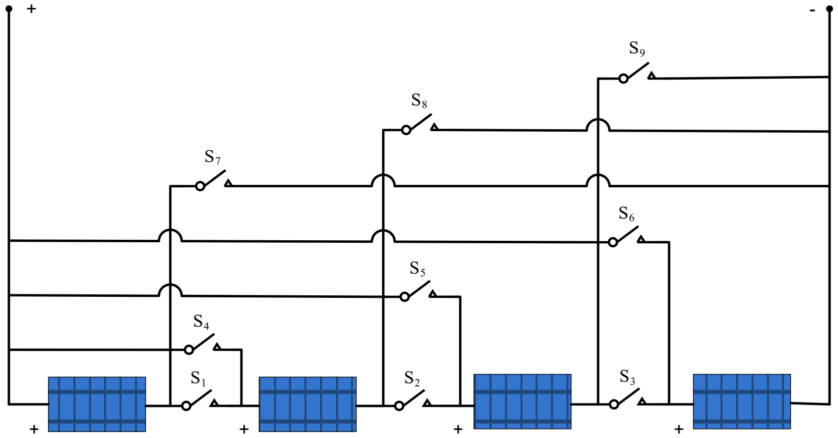

Figure 3. Topology structures obtained with the algorithm proposed in [24].

The number of switches necessary in case 3 is equal to:

$$n_{case3} = 3 \cdot (m - 1) \tag{3}$$

The last case taken into account in this work is presented in [25]. The case 4 is a system configuration approach using adaptive architecture based on a switching matrix. The adaptive strategy is based on the fact that the switching matrix allows to rearrange the active PV modules in series into multiple strings to meet the required voltage level. Figure 4 shows the proposed switching matrix of the case 4.

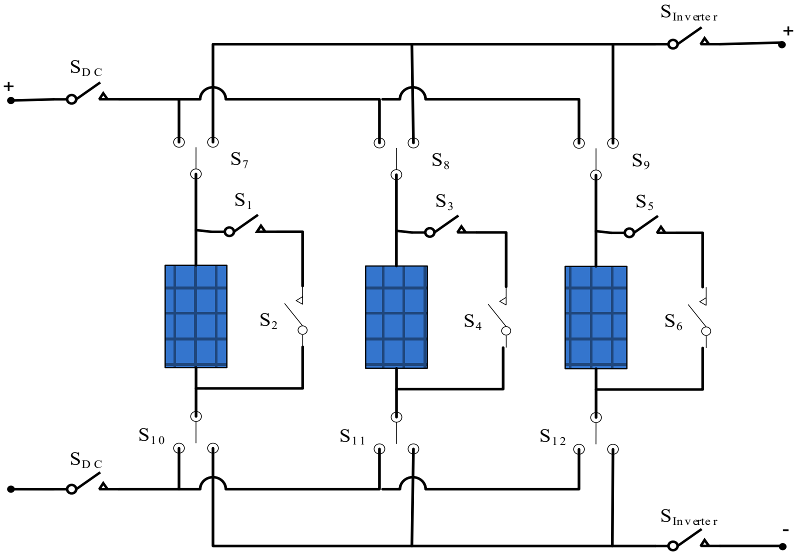

Figure 4. Switching matrix proposed in [25].

Also, in this case, the number of switches of the matrix depends by the number of modules in the PV array. The number of switches can be expressed as:

$$n_{case4} = 4 \cdot (m) + 2 \cdot (dc) + 2 \cdot (inv) \tag{4}$$

where the terms 2dc and 2inv represent the switches to connect the PV array with the inverter and the dc converter.

In the next section, the cost estimation analysis is reported.

B. Costs Estimation of DRS

The cost of each reconfigurator system has been evaluated on the basis of the direct proportionality between the number of switches composing the system and the cost of the technology needed to produce it.

For each of the four considered reconfiguration cases, a cost estimation of the reconfiguration system has been carried out according to the following procedure: for each case, the required amount of components has been evaluated; after that, for each type of electrical component, a specific item which is available on the market has been chosen, compliant with the technical requirements of the system; finally, for each of the selected components, a price is given, as provided by a major distributor of electronics [26]

Generally, the hardware of a dynamic reconfigurator basically consists of three different parts: the switching matrix, the sensing network and the driving circuit.

The switching matrix includes all the switches that are used in the reconfiguration system. Taking into account the solutions available in the market, each switch is generally assembled through two parallel-connected devices: an electromechanical relay and a semiconductor device, e.g. a MOSFET [27][28].

A state-solid relay is a valid alternative as well, but it turns out to be more expensive. Whenever the switch has to be put in the off state, the semiconductor switch is closed as first, so that the electromechanical switch can be switched off at a low voltage. When the switch is on, the electromechanical relay guarantees the conduction losses minimization. In this way, the current breaking capability of the electromechanical switch is fully employed, since it is better to be opened at a quite low voltage. The number of parallel-connected MOSFETs arises from the type of electromechanical switches: one MOS has to be connected to one SPST (Single Pole Single Throw), whereas two MOSFETs have to be connected to one SPDT (Single Pole Double Throw). In Table 1 the chosen electromechanical relays are reported along with their respective prices[26][29][30].

TABLE 1. Electromechanical relays types.

Component	**Switch**	
Type	SPDT	SPST
Brand	Finder	Hongfa Europe GMBH
Price (€)	5.22	2.6

In Table 2 the selected MOSFETs and drivers and respective prices are reported as well [26] [31][32].

TABLE 2. Mosfet and driver taken into account.

Component	**MOSFET**	**Driver**
Type	n - ch.	Isolated
Brand	IPB08CN10N	MAX845
Price (€)	1.273	3.2

As far as the sensing network, three types of measurements are generally needed: voltage, current and temperature. In all the four cases provided in this paper no irradiance sensor is required. The electronics involved in the voltage sensing circuit is normally very cheap, therefore voltage sensors are not considered in the hardware balance for the sake of simplicity. The selected sensors of temperature and current and their price are reported in Table 3. Note that for the current measurement, the selected sensors are compliant with a 6A rated current [33][34][26].

TABLE 3. Selected sensors for current and temperature.

Component	**Sensors**	
Type	Temperature	Current
Brand	LM35	LEM
Price (€)	1.393	12.11

Table 4 provides the details concerning the number of the different components which should be used in the four considered reconfiguration cases: PV modules (Np), SPST and SPDT switches (N_{SPST} and N_{SPDT}), MOSFETs, drivers and sensors. The total price has been calculated according to the cost tables previously reported.

TABLE 4. Components considered cases.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Np	20	20	20	20
NSPST	200	26	57	44
NSPDT	0	0	0	40
MOSFET	200	26	57	124
Drivers	200	26	57	124
Current sensors	20	0	0	20
Temperature sensors	0	0	20	20
Total price (€)	**1 657**	**184**	**431**	**1 148**

Note that each driver is supposed to drive one MOSFET.

C. Lifetime Estimation of DRS

A significant contribution to the overall economical impact of each reconfiguration solution is represented by its lifetime, even though in scientific literature this aspect is generally neglected [35] Regarding this, the most important issue to be addressed is the lifetime of the relays, due to their mechanical characteristics. Both the electrical and the mechanical endurance are reported in the technical datasheets. Indeed, both the electrical and the mechanical behaviour of the relay are affected by the switching operations. More in detail, the electrical endurance, given by the maximum number of cycles recommended not to affect the electrical behaviour of the relay, is usually much shorter than the maximum number of cycles recommended not to affect the mechanical behavior Therefore, being first in the course of time, only the electrical endurance has been considered in the overall lifetime estimation.

As reported in the technical datasheets, the maximum number of cycles for the selected SPST switches is 10^5, whereas for the selected SPDT switches this value is $60x10^3$ [29][30].

In order to evaluate the actual number of switching operations for each case of reconfiguration, the specific algorithm as well as the irradiance conditions should be exactly known. Nevertheless, being these data due to the designer in the first case and unpredictable in the second, a simple approach has been here adopted. Considering NSPST and NSPDT the number of SPST and of SPDT respectively, the probability of a switching operation for each of them has been considered to be 1/NSPST and 1/NSPDT. These are meant to be the probability values whenever the algorithm and the irradiance condition lead to a reconfiguration operation. As far as the hours of sunlight and the frequency of reconfiguration are concerned, two "worst case" values have been considered: 16 hours of sunlight and 1 reconfiguration every minute. Even though these values are generally peak values across the whole day, these are meant to be the average values, so that a "worst case" situation is taken into account.

In Table 5, the number of considered sunlight hours, the number of considered reconfiguration operations per minute and the electrical endurance of SPST and SPDT are given, referenced as ESPST and ESPDT respectively.

Table 5. Main characteristics of the proposed study case of reconfiguration.

Sunlight hours	**16**
Reconfigurations per minute	1
ESPST	10^5
ESPDT	$60x10^3$

According to the 16 light hours and to one reconfiguration per minute, 350 400 operations are calculated per year, so that the corresponding number of reconfiguration per switch is calculated, according to (5):

$$\begin{aligned} R_{yrsw,SPST} &= R_{yr} \cdot \left(1/N_{SPST}\right) \\ R_{yrsw,SPDT} &= R_{yr} \cdot \left(1/N_{SPDT}\right) \\ N_{yr,SPST} &= E_{SPST} / R_{yrsw,SPST} \end{aligned} \tag{5}$$

$$N_{yr,SPDT} = E_{SPDT} / R_{yrsw,SPDT}$$

where: R_{yr} is the number of reconfigurations per year; $R_{yrsw,SPST}$ and $R_{yrsw,SPDT}$ are the number of reconfigurations per year per switch for SPST and SPDT respectively; $N_{yr,SPST}$ and $N_{yr,SPDT}$ express, in terms of number of years, the endurance of SPTS and SPDT switches respectively.

Table 6 reports the data referring to both types of switches and to the four considered cases of reconfiguration, obtained from (5). Note that the number of total reconfigurations R_{yr} has been considered the same for all the cases.

Table 6. Estimated number of reconfigurations per year and endurability of the switches in the four cases, for the "worst case" condition.

	Case 1	Case 2	Case 3	Case 4
$1/N_{SPST}$	0.005	0.038	0.018	0.023
$1/N_{SPDT}$				0.025
R_{yr}	350 400	350 400	350 400	350 400
$R_{yrsw,SPST}$	1 752	13 477	6 147	7 964
$R_{yrsw,SPDT}$				8 760
$N_{yr,SPST}$	57	7	16	13
$N_{yr,SPDT}$				7

According to that, the total cost evaluation, including the overall system, is considered and reported in Table 7 for different cases of years to come before the switches are changed.

Table 7. Cost evaluation according to the estimated endurability, as reported in Table 6 in the four cases, for the "worst case" condition.

after n years	**Switches cost evaluation**			
	Case 1	**Case 2**	**Case 3**	**Case 4**
n=10	0	67.6	0	208.8
n=20	0	135.2	148.2	532
n=30	0	270.4	148.2	1064
after n years	**Total cost evaluation**			
	Case 1	**Case 2**	**Case 3**	**Case 4**
n=10	1 657 €	251 €	431 €	1 357 €
n=20	1 657 €	319 €	579 €	1 680 €
n=30	1 657 €	454 €	579 €	2 212 €

The economical contributions concerning the switches and the overall system, as reported in Table 7, arise from the data reported in Table 1 and Table 2 respectively.

Note that the configurations with the lowest number of switches are less convenient if the only price of the switches is considered, supposed that in the same number of years they require to be changed a higher number of times. On the contrary, if the total cost of the reconfigurator is considered, the cases with the lowest number of switches are the most convenient. Indeed, the initial price in terms of sensors, drivers and MOSFETs is generally higher if the number of mechanical switches is higher, due to the higher hardware complexity.

Note as well as that if a low number of switches is associated to a more complex algorithm, so that the reconfiguration frequency is higher, the frequency of maintenance increases. As example, Table 8 refers to 2 reconfigurations per minute in the case 2, whereas the number of reconfigurations per minute in the other cases is kept at 1.

Table 8. Cost evaluation if in the case 2 (case of minimum number of switches) the number of reconfigurations per minute is 2 instead of 1.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Reconfigurations per minute	1	2	1	1
after n years	**Total cost evaluation**			
n=10	1 657 €	319 €	431 €	1 357 €
n=20	1 657 €	522 €	579 €	1 680 €
n=30	1 657 €	725 €	579 €	2 212 €

Note that in this case the most convenient solution, after 30 years, is the one corresponding to the case 3.

Although the obtained economical results of this comparison among different reconfiguration cases shall not be critically considered, what is significant in this paragraph is the proposed approach for an economical estimation of the system lifetime.

3. Experimental set-up

Figure 5 sketches a realistic situation in which, during the day, a shadow overlays different panels. As a consequence, the shadowed panels disturb those connected in parallel: a decrease in voltage of shadowed panel involves a decrease of not shadowed ones and a rise of current for the power balance. This rise of current is not constantly probable: if the not shadowed panels are in the area of maximum power point, any decrease of voltage decreases the power.

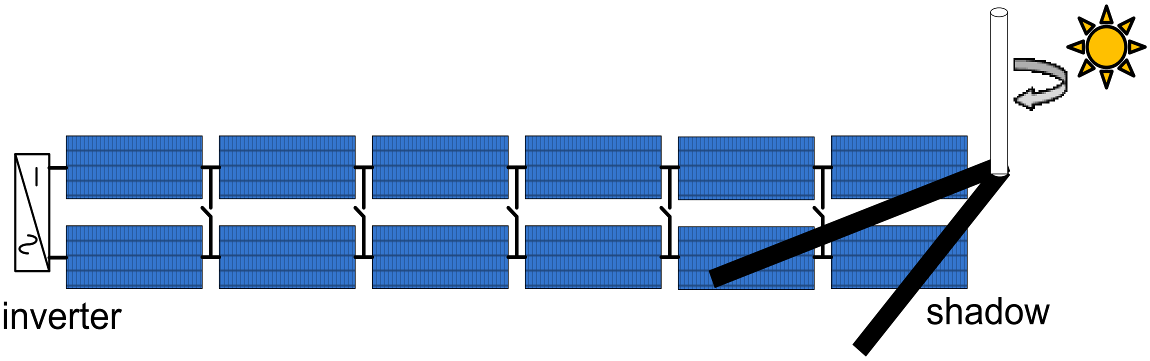

Figure 5. Probable shadow projections in the studied situation.

Figure 6 shows the effect of a shadow due to the presence of a pole by considering a PV DRS scheme. The hypothesis is that each panel has three lines of cells and is connected to the DRS. DSR is connected to a two channels inverter.

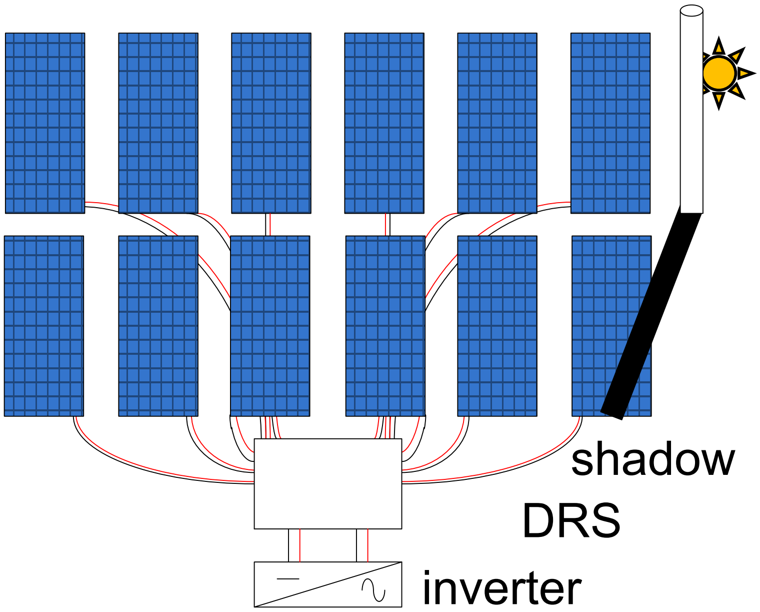

Figure 6. DSR in a PV plant.

Reconfiguration performances were tested with a prototype DSR developed at the University of Palermo and laboring on a twelve panels system. DSR acquires the state of every panel with a sensing system (voltage, current and temperature).

Figure 7 shows the experimental system of DRS. Twelve panels (Conergy, PMMP 215 W, VMPP 28.27 V, IMPP 7.59 A, Voc 36.37, Isc 8.21 A) have been connected individually to the DSR.

Figure 7. Experimental system with panels individually connected to DRS.

Without shadows, each panel works in the same point: the DRS generates basic topology, in this case, two parallel identical strings of six modules in series. To perform the behavior of the DRS, different resistive loads have been considered and **Errore. L'origine riferimento non è stata trovata.**Table 9 collects the different working conditions.

Table 9. Electrical characteristics in different load conditions evaluated by reconfigurator for each panel.

	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

In order to test the DRS, an artificial shadow has been created. Figure 8 displays three shadow cases for a panel connected in series with five others. The artificial shadow cuts one, two or three lines of modules, dropping the performance of the panel and of the string. Each stoppage of line requires the action of the bypass diode, and a successive voltage decrease of the panel. The shadowed panel has labelled with the number 6, so V1-V5 are the voltages of normally irradiated panels and V6 is the shadowed one; DRS evaluates the power of each panel and connects the panels into the string.

Figure 8. Shaded panel case 1, 2 and 3. In case 1 shadow can vary from 225 to 450 cm^2; which corresponds to one interruption of a line of cells; in case 2 shadow varies from 450 to 900 cm^2, which corresponds to two interruption of lines; case 3 corresponds to the interruption of the panel.

Table 10 recapitulates the behavior of the DRS with shading and without; P1-P5 are the powers of the not shadowed panels, P6 is the power of the shadowed one in three cases, I is the current of the system in the different cases taken into account.

Table 10. Electrical Characteristics of the string in different shadow conditions

		$V_{1\text{-}5}$ [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
loa	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

Figures 9 and 10 show respectively the voltage-current and voltage-power profiles of the panel with three working lines of cells, two working lines of cells and only one working line.

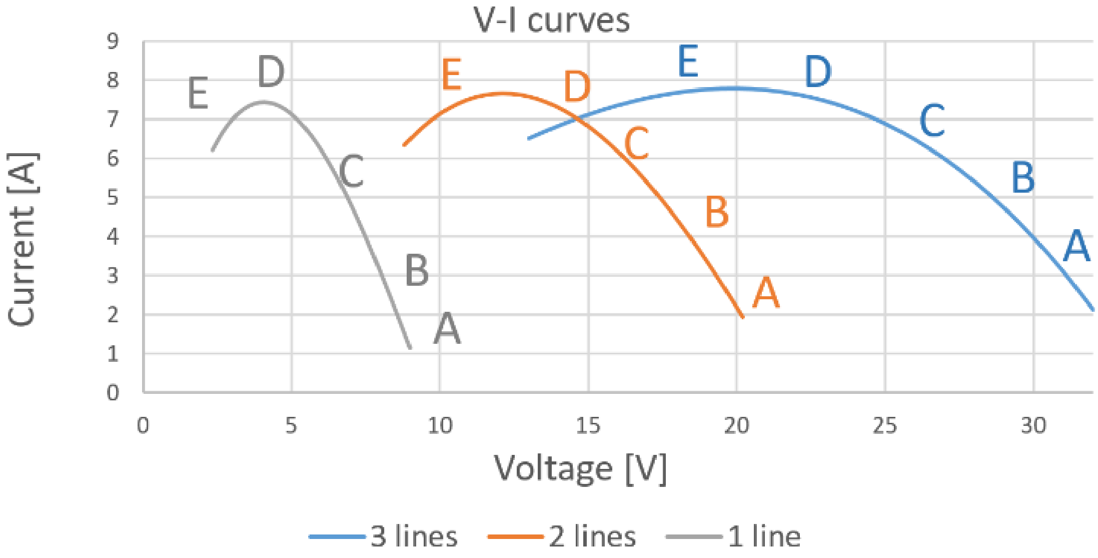

Figure 9. Interpolated V-I curves of the panel with different shadows. Working lines have been described.

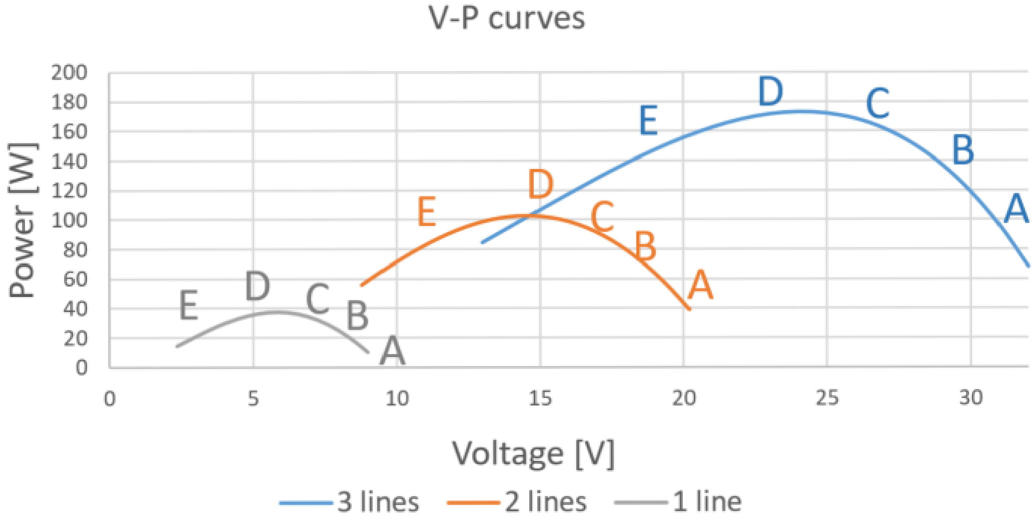

Figure 10. Interpolated V-P curves of the panel with different shadows. Working lines have been described.

Blue curve describes the working point without any shading, if a line of cells is shaded orange curve has to be considered, maintaining a similar current and with a new voltage. When a shadow covers two lines of cells from blue curve the gray curve has to be considered, maintaining a similar current and with a new voltage.

New voltages indicate the new power conditions. The DRS is able to regroup similar irradiated panels and/or exclude the densely shaded panels. The different operation is due to the DRS architecture and the algorithm implemented. A not smart DRS can only exclude shaded panels, a high performance DRS relocates them on suitable dynamic arrays.

3.1 Evaluation of Power Losses for a single shaded panel

In the following part three cases are evaluated: case 1, only a line has been interrupted; case 2, two lines were interrupted; case 3, the whole panel is shadowed.

By excluding the shaded panels there will be 16.7% of losses. DRS can enable the power increases shown in Table 11.

Table 11. 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

Data presented in Table 11 can be plotted in Figure 10: in case 1 and for the lower currents (load A, B and C) there is an increase of power, for higher currents (loads D and E) there is a decrease; in case 2, for lower currents (loads A, B, C and D) there is an increase, for the higher current (load E) there is a decrease.

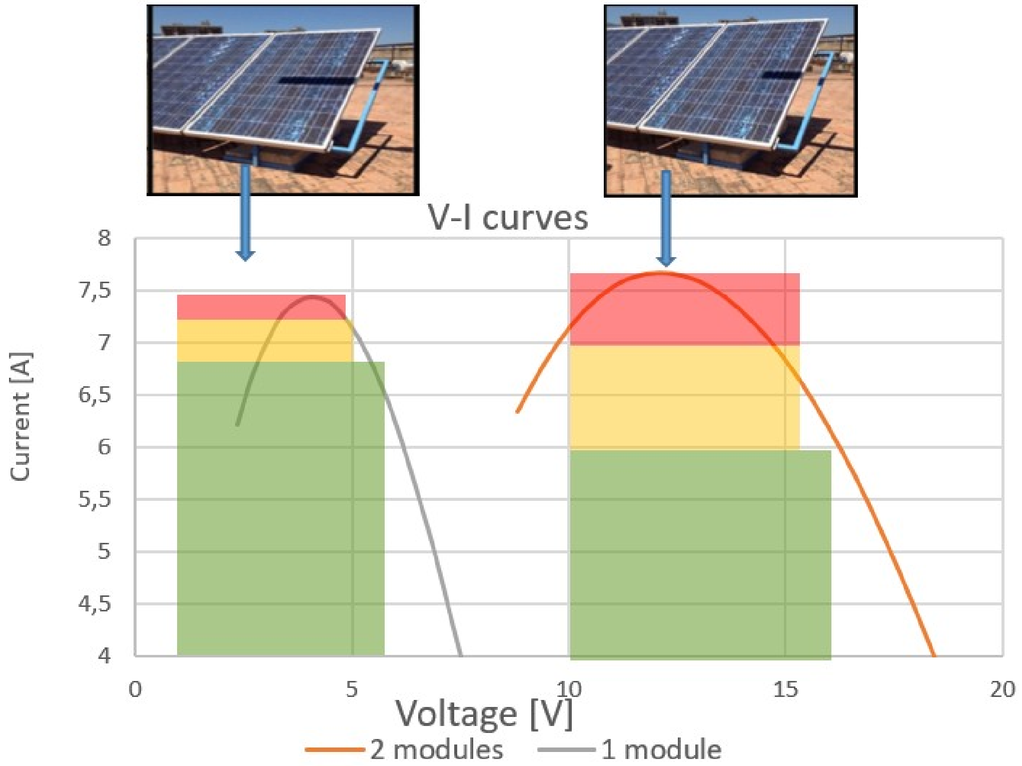

Figure 11. Zones of convenience of the disconnection of shaded module

Case 3 is now considered: the shadow cuts entirely the panel, as shown in Figure 8. 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, to compensate the voltage drop on the shaded panel and to try to maintain a high current. Table 12 shows the increase of power when a panel is totally shaded. The study of case 3 shows that when the shadows cuts in two parts the panel 6 and it becomes a load, reconfiguration reduces always the loss of power.

Table 12. Characteristics in different load conditions evaluated by reconfigurator for each panel.

		V_{1-5} [V]	V_6 [V]	I [A]	P_{1-55} [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

Case 3 shows the real performance of the DRS. Between loads C and D the maximum power point is performed. By considering the overall behavior of two shaded strings used simultaneously, a possible performance increase between 12 and 25% can be stated.

3.2 Evaluation of Power Losses for two shaded panels

The previously obtained performances, consider only a shaded panel, and the logic is to maintain it (partially shaded) or exclude it (totally obscured). Now if two panels are shaded there is the possibility of placing in parallel. Panels named 6 and 7, can be re-configured to ensure the maximum current of the arrays. This feature requires a more evolved DRS, which can put in parallel panels belonging to different arrays, the sum of which currents is equal to the current of not obscured panels.

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Table 13. Electrical characteristic of the string in different shadow conditions.

	load C			**load D**		
	Not shaded	**Case 1**	**Case 2**	**Not shaded**	**Case 1**	**Case 2**
V_{1-5} [V]	26.1	27.7	29.1	23.1	25.9	27.7
V_{6-7} [V]	26.1	17.1	7.4	23.1	15.6	6.8
I [A]	6.0	5.0	4.2	7.0	6.4	5.2
P_{1-5} [W]	156.6	138.5	122.2	161.7	165.7	144.0
P_{6-7} [W]	156.6	85.5	31.1	161.7	99.8	35.4
P_{string} [W]	1096	863.5	673.3	1132	1028	755.6
Loss%	-	-21.2	-38.5	-	-9.2	-33.2
V_{6-7} [V]	-	19.3	6.2	-	15.0	5.0
I_{6-7} [A]	-	6.0	6.0	-	7.0	7.0
P_{6-7} [W]	156.6	60	36.1	161.7	101.0	36.3
P_{string}[W]	1096	903.3	909.2	970.2	1010	881.1

ΔP%	-	+4.2	+21.4	-	-1.5	+11.1

This feature is useful only when it considers the case 2 as shown in Table 13.

The performances of different DRS are a mixture of the ones presented in Tables 12 and 13.

For the economic analysis the increased power given by the reconfigurator is taken as an increase of the energy produced during the day.

4. Economic Data

In order to carry out a complete study, the economic analysis presented in this paper take into account different aspects about a PV plant, such as: PV technology, location of installation, government incentives, lifetime components, aging and periodic maintenance costs.

This study is based on the use of economic a tool called Net Present Value (NPV), in order to evaluate the benefits of an economic investment in PV field with innovative devices such as a DRS. The NPV allows to evaluate the economic convenience of an investment for a specific period from a sum of cash flows actualized at time zero. In (6) the mathematic expression to evaluate the NPV is reported.

$$NPV = -C_0 + \sum_{y=1}^{n} \frac{C_y}{(1+i)^y} \qquad (6)$$

With reference to expression (6), C_0 is the cash flow at time zero, C_y is the cash flow at the year y, i is the interest rate and y is the year of investment. Thus, the sign of the NPV, positive or negative, indicates the infeasibility of the investment and therefore the economic convenience. The interest rate i% considered in this work is equal to 5%. In this study, the technical-economic analysis has been carried out by considering an investment time equal to 20 years.

In the following, detailed description of different aspects taken into account for the economic analysis and economic data are reported.

A. PV Plant

Since the first PV plants commercially available on the market the cost of PV components, installation and maintenance has notably changed. In particular, in the last years there has been a constant decrease of the costs in the world market.

In this study, only residential PV systems have been taken into account with 6 kWp of power. This choice is motivated by the fact that the use of DRS is very interesting in residential PV plants, where the probability of installation of a fixed obstacle is high in respect to other type of plants. Indeed, 4 years after the installation, a fixed obstacle reducing by 35% the total power is assumed to appear. This value of reduction has been demonstrated in study [20]. Moreover, in order to carry out a complete analysis among different locations of installation taken into account, an installation of the PV plant between 2013 and 2014 was assumed, considering that in those years there were incentives in all the countries.

Regarding the cost of the PV plant, the average estimated price for this type of plant is about 2500 €/kWp (included installation).

In Table 14 the economic data about the PV plant under test are summarized.

Table 14. PV plant data.

PV plant type	Residential grid connected
Power	6 kWp
Number of modules	20
PV plant Cost (installation included)	15000€
Power reduction	35%
Year of installation	2013/2014

B. Location of Installation and Economic Aspects

The locations of installation represent an interesting point of analysis in terms of production capability, government incentives and prizes paid to private citizens for the production of the energy. Moreover, also the lifestyle of the people plays an important role and therefore the average consumption per capita of the electric energy. In order to extend the economic analysis Italy, Germany, France, Spain, Bulgaria, Romania, Greece and Croatia have been considered as reference countries. As well known, these countries allow different performances of the PV plants, different policies to improve the use of electricity generated from renewable sources and different lifestyle of the people. In detail, the common strategy is based on a Feed-In Tariff (FIT) system with different values and time of the incentives.

The economic data for each country (average consumption per capita, production facility, energy cost and incentives) have been referred of a PV plant installed in the capital of each countries. Moreover, has been considered a family composed by four people that lives in the capital of each countries. In Table 15 the considered economic data are reported.

TABLE 15. Economic data of the reference countries [20].

	Average consumption per capita [kWh/year]	Production facility [kWh/year]	Energy cost [€/kWh]	Incentives per years [€/kWh]	Incentive duration [years]
Italy	3200	9900	0.200	0.208	20
Germany	3512	6240	0.330	0.130	20
France	6343	7020	0.180	0.280	20
Spain	4131	9960	0.280	0.340	20
Bulgaria	4640	9000	0.090	0.240	20
Romania	2495	8400	0.125	0.160	15
Greece	5029	11100	0.180	0.140	20
Croatia	3754	9600	0.132	0.150	14

These data are refereed as follow:

- a family composed of four members and living in each capital of the considered countries;
- the electrical energy produced per year by a 6 kWp PV plant has been taken into account.
- the installation of the plant has been assumed between the year 2013 and 2014.

It should be noted that France has the highest value of average consumption per capita. This data is very high with respect to the production facility of the PV plant, so the analysis is particularly difficult for the use of DRS. The higher value of the energy production is in Greece. Whereas, Romania and Croatia take incentive only for 15 and 12 years. It should be noted that these considerations have influenced the economic results.

C. Inverter

The inverter represents the heart of the production from the solar energy. In particular, as well known, this system allows the electric energy conversion from DC to AC in order to inject the surplus of power into the grid. Therefore, in the case of inverter fault it is not possible to use the energy with a consequence economic loss. From different studies, it is known that the inverter is the component more sensitive to failure. In [2], the authors considered an inverter life equal to 10 years. Nevertheless, it is not possible to estimate with accuracy the lifetime of an electronic component. For this reason, by considering a possible worst case, in this study it was assumed that the average lifetime of the inverter is equal to 7 years. As far as the cost is concerned, according to [36] for a residential PV plant with 6 kWp of power the average cost is equal to 1000€.

D. Increase of Production by DRS

The purpose of a DRS system is to increase the power of a PV plant in the case of a reduction of the total power production. The increment of the power production is a parameter that depends on the DRS topology and therefore hard to estimate. Indeed, the increment of power depends on the type of DRS and therefore of the number of possible available configuration. Thus, the number of possible reconfiguration available play an important role. By considering that a DRS with high number of switches allows many reconfigurations with respect to a DRS with a low number of switches, it is supposed to provide a higher increment of power. Nevertheless, this consideration is not enough to estimate the increment of power provided by a DRS with a defined number of switches, because it is possible that a DRS with high number of switches has redundant configurations.

For this reason, in this work the same value of power increment has been considered for each DRS and fixed equal to 10% for the sake of simplicity. This obviously represents an unfavourable condition for DRS with high number of switches and higher costs. Nevertheless, this choice allows to emphasize the effect on the economic analysis of the costs and lifetime for each DRS.

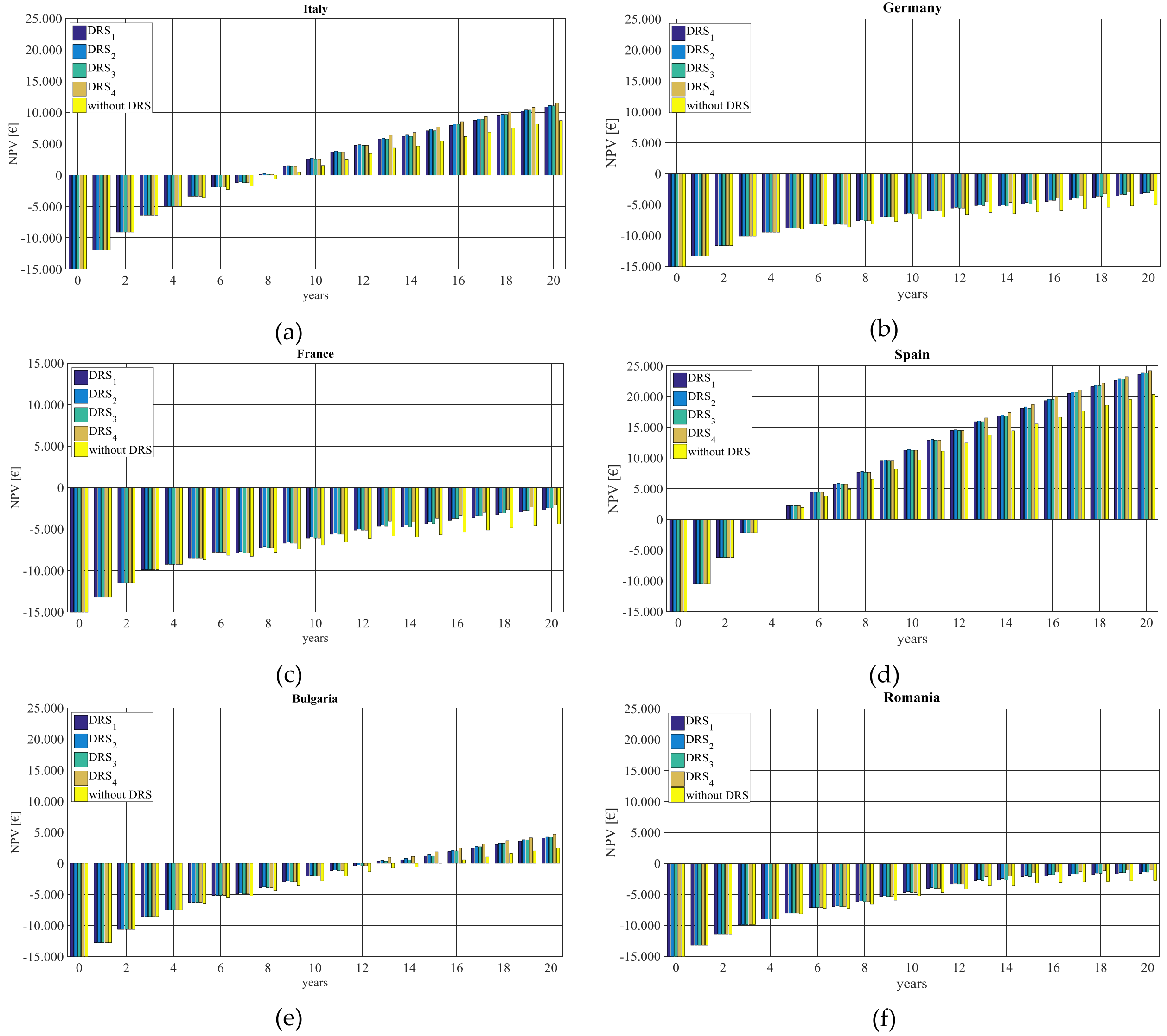
E. Aging and Maintenance of PV Plant

After the installation, a natural phenomenon is the aging of the PV components. This phenomenon causes a reduction of the power and it increases over the time. Thus, in the economic analysis has been considered a reduction of power after the first year of the installation equal to 3% and a reduction for each year equal to 0.5%. Moreover, also a periodic maintenance has been considered with a cost equal to 100 €/year.

5. Economic Results and Discussion

As above described, the economic analysis of this study is focused on the evaluation of the economic benefits by using a DRS system after 4 years of the installation of the PV plant with a power reduction equal to 35%. In particular, four cases of DRS have been analysed in different countries of EU in order to extend the economic results.

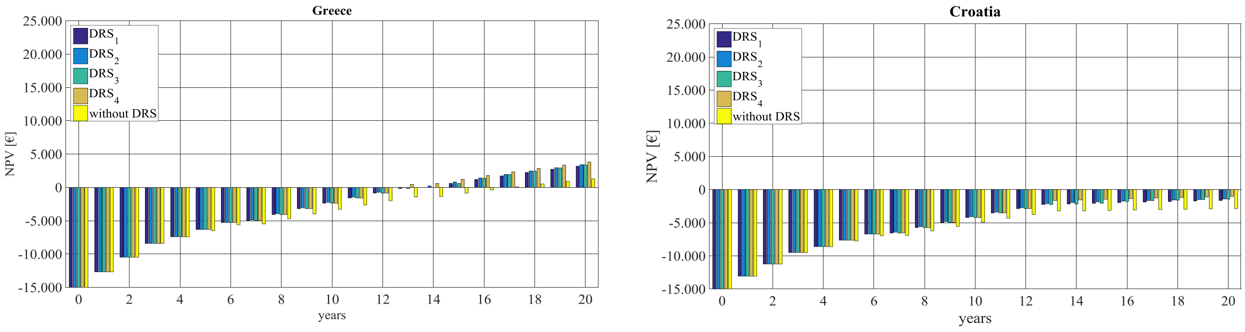
Figure 12 shows the NPV trend over the time of four cases of DRS1-4 and without DRS for each country.



(a) (b)

(c) (d)

(e) (f)



(g) (h)

Figure 12. NPV trend over the time of four cases of DRS$_{1\text{-}4}$ and without DRS, in (a) Italy, (b) Germany, (c) France, (d) Spain, (e) Bulgaria, (f) Romania, (g) Greece and (h) Croatia.

The best result has been obtained in Spain with the highest value of the NPV after 20 years due to the incentives per years. The positive NPV values have been obtained in Italy, Bulgaria and Greece thanks to the high values of the production facility. Romania and Croatia have been penalized by lower duration of the incentives. Whereas, France and Germany have been penalized by the lower values of the production facility. In Table 16 are summarized the values of the NPV for each country and for each DRS.

TABLE 16. NPV values after 20 years (increment power 10%).

Countries	**NPV after 20 years [€]**				
	DRS$_1$	***DRS$_2$***	***DRS$_3$***	***DRS$_4$***	***without***
Italy	10871	11095	11068	11480	8723
Germany	-3298	-3075	-3101	-2689	-4991
France	-2663	-2439	-2466	-2054	-4380
Spain	23633	23856	23830	24241	20349
Bulgaria	4076	4300	4274	4685	2497
Romania	-1601	-1377	-1403	-992	-2713
Greece	3186	3410	3384	3795	1297
Croatia	-1646	-1423	-1449	-1038	-2873

By analysing the NPV values of Table 16, it is interesting to note that DRS$_4$ allows to obtain the best results also in the cases in which there the negative values of NPV. Moreover, this result is interesting because the DRS$_4$ present the second highest cost equal to 1148€ also by considering the worst case for the DRS with higher costs. Other interesting consideration can be done by changing the increment power. By considering an increment of the power equal to 20%, the NPV values obtained are reported in Table 17.

TABLE 17. NPV values after 20 years (increment power 20%).

Countries	**NPV after 20 years [€]**				
	DRS$_1$	***DRS$_2$***	***DRS$_3$***	***DRS$_4$***	***without***
Italy	13019	13243	13217	13628	8723
Germany	-1606	-1382	-1408	-997	-4991
France	-946	-722	-748	-337	-4380
Spain	26917	27140	27114	27526	20349
Bulgaria	5656	5879	5853	6265	2497
Romania	-489	-265	-291	120	-2713
Greece	5075	5299	5273	5684	1297
Croatia	-420	-196	-222	189	-2873

In respect to the previous case, the DRS4 with an increment of power equal to 20% allows to obtain positive values of the NPV also for the Romania and Croatia. This result is realistic because the DRS$_4$, thanks to the high number of switches and thus the high number of the possible configurations, may generate an increment of power equal to 20%.

Another interesting point of analysis is the payback time. In Table 18, the payback times for each country and for each DRS in two cases of power increment are reported.

Table 18. Payback time for increment of power equal to 10% and 20%.

Countries	**Payback time [years]**							
	DRS_1		DRS_2		DRS_3		DRS_4	
	10%	**20%**	**10%**	**20%**	**10%**	**20%**	**10%**	**20%**
Italy	8	8	8	8	8	8	8	8
Germany	-	28	-	27	-	27	-	25
France	-	25	-	24	-	24	-	23
Spain	5	5	5	5	5	5	5	5
Bulgaria	13	12	13	12	13	12	13	12
Romania	-	-	-	27	-	-	-	20
Greece	15	12	14	12	15	12	13	12
Croatia	-	-	-	-	-	-	-	19

Spain and Italy present the best results and it is interesting to note that the same values in the two cases of the increment of power have been obtained. In other countries (Germany, France and Romania), it was necessary to extend the duration of the investment in order to find the payback time but in all cases the best results have been obtained with DRS_4 and an increment of power equal to 20%. Only in Bulgaria and Greece a reduction of the payback time has been obtained, an increment power equal to 20%, 13 years to 12 years and from 15 years to 12 years, respectively.

6. Conclusion

This paper presents a complete analysis on the real benefits introduced by a DRS system in a PV plant after a considerable power reduction. In particular, in order to evaluate the overall economic impact on the costs of a PV plant the technical and economic aspects about the DRS have been considered.

In the first part of the paper an economic analysis on different DRSs due to the costs of the components and to the adopted topological schemes, is carried out. Switching matrix, sensing network and driving circuit constitute the architecture of DRS, the choice of switches and their number affects the electrical endurance. A more flexible DRS involves higher initial cost due to the number of switches required by the adopted architecture, but at the same time a less exploitation and therefore a longer useful life.

From the economic point of view, the analysis has been extended to different countries of EU in order to considerate incentives policies, location of installation and life style of the people. While, from a technical study, that taken into account the hardware complexity in terms of the components required and others technical aspects, the costs and lifetime of four DRS have been estimated. The economic tool used in this analysis is the NPV and the payback time.

Firstly, in all scenarios the analysis has demonstrated the positive economic impact on the use of a DRS in a PV plant with respect to the cases without DRS. The best results have been obtained in Spain thanks to the higher value of the incentives per years in terms of the NPV and payback time. Whereas, good results have been obtained for Italy, Bulgaria and Greece. The worst results have been obtained for France and Germany due to the lower values of the production facility. Among the DRS considered in the economic analysis, the DRS4 allows to obtain the best results in all cases. The best performance of the DRS4 is attributable on the high number of switches that allow to increase the life time of the system.

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