Energy Conversion and Management 152 (2017) 1–12

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimization of photovoltaic maintenance plan by means of a FMEA approach based on real data

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A R T I C L E   I N F O

Keywords:
Renewable energy
Photovoltaic system
FMEA
Reliability centered maintenance

A B S T R A C T

There have been many scientific advances in the improvement of renewable energy systems. Recently, considerable interest has been given to their optimized management during their service life due to a large increase in the number of new renewable energy source power plants. High reliability levels are as important as high yields in order to maximize the useful green energy produced. Solar energy has been one of the most popular and exploited renewable sources in the market and therefore improvements in its efficiency and reliability have had a considerable impact. All energy systems require an increase in their conversion efficiency to reduce the consumption of primary energy. Moreover, the optimization of the performance of photovoltaic systems has increased their incidence as renewable sources in global power generation and has boosted their profitability. A failure of the components and sub-components of a working energy system cause two main issues; the first direct implication for the plant is the damage of the components and sub-components, and the second indirect implication is the consequent lack of energy production due to the plant being out of order. Furthermore, unforeseen failures of the components increase the uncontrollability of photovoltaic power systems, which worsens electric grid dispatching.

The work presented here provides, for the first time, a complete and new assessment of Reliability Centered Maintenance carried out using a failure mode and effect analysis approach to photovoltaic systems. We use a large volume of data derived from a database of real maintenance activities carried out by a multinational company. These data were interpreted by the opinions of experts with specialist experience in the installation, operation, and maintenance of photovoltaic power systems, from small to multi-megawatt size. The present work here has advantages over many previous studies since the information was derived from real experiences of photovoltaic systems which allowed for a more realistic risk analysis and, especially, this information was also used to revise the maintenance plan of photovoltaic installations and to optimize their effectiveness, concentrating on various failure modes which mostly affect production or which can be easily removed/reduced.

1. Introduction

In 2015, 50 GWs of new photovoltaic (PV) systems were installed globally and by the end of 2015, the total installed capacity was 227 GW connected to the electric grid [1]. There has been an increase in the popularity of power systems based on renewable energy sources, especially PV, due to the supporting policies [2,3] and strategies [4] and their feed-in-tariff incentives, with important implications for the investments [5], regarding wind energy [6], biomasses [7,8] solar thermoelectric [9] and, especially, solar photovoltaic [10] using various installations and technologies as integrated in greenhouses [11], large-scale ground-mounted [12], building integrated [13,14] and floating [15]. More importantly, European countries, such as Italy and Germany, now have large enough PV capacities to produce 8% and 7.1% of their annual electricity demands, respectively. PV systems provide approximately 1.3% and 3.5% of the electricity demands of the World and Europe, respectively. Furthermore, the significance of PV technology is not only reflected in the achieved goals but also in the 25% growth rate of the PV market. This has the potential to continually increase the generation of energy and requires additional working energy systems to be connected to the electric grid, including their management and maintenance.

The large size of the power capacity requires functioning plants that will begin to have an even larger impact on the global energy balance in the coming years. The long-term performance of a PV system, with an expected 20–25 years of operation, is one of the most valuable aspects

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http://dx.doi.org/10.1016/j.enconman.2017.08.090
Received 7 May 2017; Received in revised form 7 August 2017; Accepted 25 August 2017

Nomenclature

Abbreviations

PV	photovoltaic
IPP	independent power producer
LCOE	levelized cost of energy
t	time
R(t)	reliability (as a function of time)
f(t)	failure density function
h(t)	hazard rate
RCM	reliability centered maintenance
MBS	machine breakdown structure
FMEA	failure modes and effect analysis
RPN	risk priority number
D	detection
O	occurrence
S	severity
CM	corrective maintenance
CMMS	computerized maintenance management system
PID	potential induced degradation

of this sort of energy system, and since commercial contracts are based on assumptions regarding efficient life cycles, these systems are even more appealing [16]. Therefore, the reliability of PV power systems is becoming increasingly important and requires closer examination. In the present work, we will address this issue, and use the opportunity to analyze the risk of failure using the opinions of experts with experience in the maintenance of many PV systems. Furthermore, there is a need in this industry, to find a suitable balance between the savings in the construction of the PV components, such as the modules, and the creation of a reliable power system. It is becoming more apparent to the participants of the PV sector, that increasing the reliability is the most effective way to reduce the LCOE of PV technology.

The Reliability Centered Maintenance (RCM) applied here to the PV systems uses a Failure Modes and Effect Analysis (FMEA) reliability analysis approach which allows the processing of each individual analysis of a system's sub-component. This analysis identifies the various failure modes affecting each part, along with the causes and consequences, and the entire system.

Until recently, the common approach for analyzing the reliability of a PV system was to concentrate on the separate failures of single components or sub-components, with considerable attention given to the modules [17–22] and inverters [23]. However more recently, the reliability of the overall system has been considered [24]. In the previous analyses, the opinions of engineers have been sought who are experts in PV projects and theory, but are not knowledgeable in the operation of PV systems. In the present paper, we consider the opinions of technicians who are experts in the functioning of a PV system. In this study we use data from Solarig, a multinational Spanish company [25] present in 12 countries which has developed and constructed over 300 PV MW globally and with 1.3 GW under operation. The present study uses plants that are installed and under maintenance in Italy, i.e. 18 solar plants which are property of Solarig as IPP and 39 plants which are the property of the customers of Solarig. Therefore, it will be possible to discover new aspects, issues, and solutions observing these

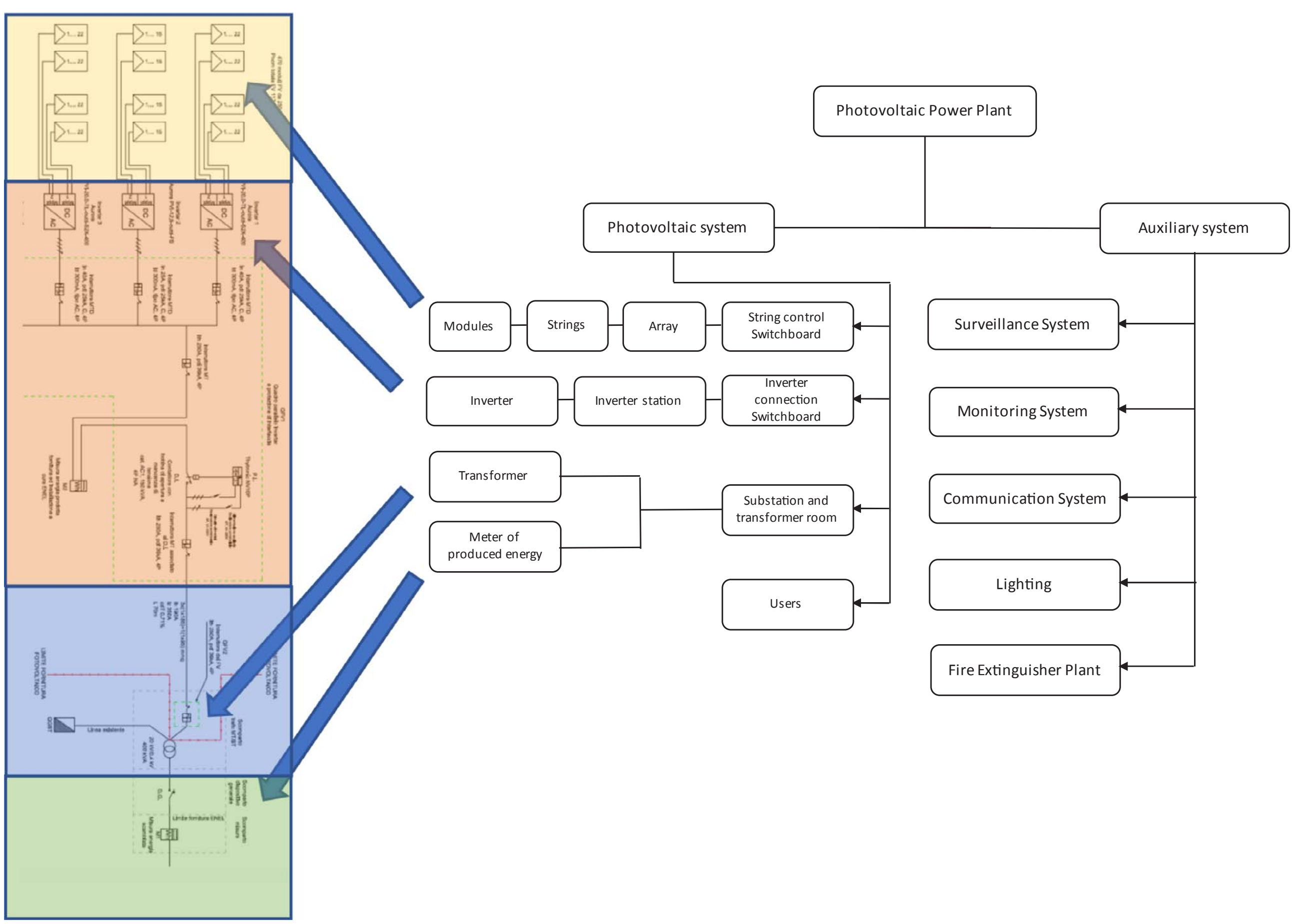

Fig. 1. PV Machine breakdown structure.

Table 1
The events occurring in the operation and maintenance company CMMS.

Component	Events occurred
Modules	Inverter block/Fault of grounding system Launch failure Overvoltage Overcurrent Short Circuits Deterioration of the properties Excessive heating Modules uprooted Partial uptake of the radiation Glass breakage Oxidation of circuits and welds of the photovoltaic cells Yellowing of Tedlar Weak sealing module connections Wrong inclination
Inverter, Inverter cabin, Switchboards to connect the inverters	Launch failure Breaking, oxidation or degradation of the elements Different absorption from normal conditions Excessive temperatures Lack of transmission Infiltrations, torques lenses, usury Degradation of plaques AC Different absorption from the nameplate data Excessive temperatures Overcurrent or Overvoltage Loss of monitoring data Damaged conditioner or extractor Connection loss
Transformer	Absorption values different from normal ones Excessive temperatures and overheating of the device Problems of connection Oxidized or degraded parts
Communication system	Failure of data processing or transmission
Monitoring system:	Loss of production data or weather parameters Wrong setting of the parameters Losses of communication Loss of monitoring
Lighting Video surveillance system	Light intermittent or cut-down Loss of monitoring Prolonged incidents when not correctly detected Power problems Fires not detected

systems using extensive knowledge from a long experience in the field.

The present article is organized as follows. In Section 2 the FMEA method and its employment is described focusing on differences respect to other methods. In Section 3 the description of the simplified model of a PV system by means of its Machine Breakdown Structure (MBS) is given, and the real failure modes obtained from the company Computerized Maintenance Management System (CMMS) database are listed. The CMMS is an organized software database aimed to support the management and maintenance activity. In Section 4, we focus on the risk evaluation and determination of the risk priority number (RPN) pertinent to each failure mode identified in Section 3 where the RPN is the parameter which quantifies the reliability of a component. In Section 5, we present the corrective actions selected in the collaboration with the maintenance men and present the results in terms of RPN reduction. In Section 6, we highlight the differences and the novelty of the present study with respect to those done previously. Section 6 also contains the conclusions.

Table 3
The occurrence ranking criteria.

Rank of occurrence	Description
1–2	Unlikely – failure rate per unit-hour in the order of E − 7
3–4	Remote probability – failure rate per unit-hour in the order of E − 6
5–6	Occasional probability – failure rate per unit-hour in the order of E − 5
7–8	Moderate probability – failure rate per unit-hour in the order of E − 4
9–10	High probability – failure rate per unit-hour in the order of E − 3 and E − 2

Table 4
The detection ranking criteria.

Rank of detection	Description
1–2	Very high probability that the problem will be detected
3–4	High probability that the problem will be detected
5–6	Moderate probability that the problem will be detected
7–8	Low probability that the problem will be detected
9–10	None or minimal probability that the problem will be detected

2. An overview of the FMEA approach and previous studies

The Electronics Industries Association (EIA) defines reliability of an item (a component, a complex system, a computer program or a human-being) as "the probability of performing its purpose adequately for the period of time under the operating and environmental conditions encountered" [26]. The reliability function can be expressed by:

$$R(t) = 1 - \int_{-\infty}^{t} f(x)dx \tag{1}$$

where f(x) is the failure density function, the derivative of the failure probability. Many probability distributions can be used to model the failure distribution for different type of components, faults and during different phases of component life cycle.

R(t) of a complex system depends on both the reliability of its components and the way components are connected within the overall system. Many different methods have been developed to assess the

Table 2
The severity ranking criteria.

Rank of severity	Description
1–2	Minor failure/degradation, hardly detected, no influence on the system performance
3–4	Failure/degradation will be detected by the plant owner/operator and/or will cause small deterioration of parts or system performance
5–6	Failure/degradation will be detected by the plant owner/operator, and will create dissatisfaction, and/or will cause deterioration of parts or system performance
7–8	Failure/degradation will be easily detected by plant owner/operator, and will create high dissatisfaction, and/or will cause extended deterioration of parts and system relevant non-functionality/loss of performance
9–10	Failure/degradation will result in a non-operation of the system or severe loss of performance

Table 5
The number and profiles of maintenance men.

Qualification	Number of members of the group	Experience
Zone manager (highly experienced electrician)	4	Very extensive profile with more than 10 years of experience on construction and maintenance of PV systems
Technician (highly experienced electrician)	9	Good profile with more than 5 and less than 10 years of experience on construction and maintenance of PV systems
Engineers (1 electrical, 1 electronic, 2 mechanical)	4	Engineer profile with more than 5 years of experience on construction and maintenance of PV systems

reliability of a complex system such Reliability Block Diagram [27,28], Faul Tree Analysis [29,30], Petri nets [31,32], Bayesan network model [28,33], Markov chain analysis and Monte Carlo simulation [34,35].

Then, the mentioned approaches aim to model the system operations to determine its reliability features. Each method has its own advantages and disadvantages which have been extensively analyzed in scientific literature e.g. [36,37].

Differently from the mentioned methods, Failure Mode And Effect Analysis (FMEA) is a bottom-up method of preventive quality assurance [38]. This method does not allow the evaluation of the reliability function of a complex system but it allows to identify and analyze all the system faults, evaluate their importance in the reliability of the system and then focus on maintenance practices and their effect on system reliability. Moreover FMEA allows to deal with uncertainty due to imprecision associated with the complexity of the systems as well as vagueness of human judgment.

FMEA uses real data coming from operation of working systems to individualize the more relevant faults of the system without theoretically modelling the cause-effects relationship of failures. The effectiveness stems from the real operation based approach: it allows to select cost-effective actions aimed to correct the maintenance plan as will be shown in the final part of this manuscript.

It is widely used to anticipate possible failures in products and processes and for correlating the failure modes of a system with their effects, and allows an assessment of their criticality. For a global complex system, the FMEA technique is used in identifying the failure modes for the components and sub-components. FMEA focuses on an individual component, so that the designers, operators, and clients can use the risk assessment of FMEA to take the precautionary steps needed to mitigate both the direct and indirect damages. This method can be used in the product development, manufacturing, quality control and maintenance stages [39].

Recent literature shows a growing interest in the application of RCM and FMEA to new fields, such as the manufacturing industries as automotive [40,41], electrical engineering industry [42], informatics [43], knitting industry [44], pharmaceutical industry [45], life care product manufacturing industry [46], petrochemical industry [47] and power distribution or generation [48,49].

Historically, FMEA was principally used in the aerospace industry, and has also been used in the automobile, semiconductor, and nuclear industries. Particular uses of FMEA suggested by Henley et al. [50] are as follows:

- the individuation of components most exposed to failure, in order to apply an appropriate succession of improvement;
- to gain a knowledge of the components in need of major quality control;
- the provision of the correct specifications from suppliers;
- to improve the procedures regarding protective equipment and the monitoring of warning systems; and
- to make provisions available to subsidize these sorts of improvements.

The criticality using FMEA is defined by the RPN which is the combination of the following ratings: severity of the effects (S), occurrence (O), and detection (D) [51]. The severity relates to the seriousness of the end effect of a component failure. The occurrence represents the frequency that a malfunctioning event is likely to occur. The detection is the likelihood of detecting a potential failure situation before it occurs. Each rating is measured on a subjectively defined scale and the assessment is based upon the three indicators with reference to this scale. The RPN is obtained by their product:

$$RPN = S\times O\times D. \tag{2}$$

The higher the RPN the more significant the criticality, and so by ranking the RPN values the riskiest components of the system can be identified. The maximum value of the three indicators S, O, and D implies large damage, a high frequency for the occurrence of failure, and considerable difficulty in identifying the root cause before a failure takes place, respectively. The value of each factor and the resulting RPN is based on the available information and supported by expert opinion and evaluation [24]. The parameter D is an interesting feature of this analysis, since only the parameters S and O are commonly used in risk matrices, but D is an important factor to consider when developing a maintenance strategy.

Within this evaluation technique, the expected subjectivity is unavoidable and perception has a relevant impact on the opinions used to analyze the risk [52]. This risk analysis is based on the opinion of experts, whose extensive experience has a relevant impact on the results and this experience comes from practical knowledge in power systems.

The FMEA method has been applied to many renewable energy systems such as wind turbines both onshore [53] and offshore [54], and geothermal [55] and ocean energies [56]. There have been also advances in single PV components [19,20,24]. Colli [24] has presented the most significant work relating to this subject, applying the first FMEA to entire PV systems and considering the analysis of more than 3500 tickets [16] which were issued in 27 months for 350 systems designed and operated by SunEdison. As mentioned in the introduction, the analysis of PV reliability, developed in previous applications of FMEA, have, mostly, concentrated their efforts on single components.

3. Breakdown Structure of PV systems and the definition of failure modes

In order to develop a FMEA analysis of a PV system it is necessary to build the PV MBS so that the system is represented by a simplified model. First, it is necessary to identify the main components of the PV system. Using the information in literature regarding core components and operation [57,58] and monitoring systems [59,60], all the necessary and auxiliary components for this kind of energy production can be represented in a MBS diagram. Since the contribution of the auxiliary parts is secondary with reference to the performance of the plant, they are generically nominated and briefly described. For all other components the breakdown is much more detailed, and the failure modes and the consequential effects for the system and adjacent equipment are listed and described for different circumstances. A diagram of the built MBS is shown in Fig. 1.

The devices that actively and primarily contribute to the PV

Table 6
The critical failure modes generated by the interviews and arranged in decreasing RPN order.

Component	Failure Mode	Cause	Effect	Current Maintenance Strategy	O	D	S	RPN
Inverter/Modules/ Electric circuit	Inverter block, leakage and earth fault	Overloads due to lack of insulation	No energy output, safety, and fire risk	Corrective	3	8	8	192
Module	Damage grounding, lightning protection, short	Storm or Lightning	Production stop	Corrective	3	7	8	168
Inverter	Inverter overheating	Possible failure of the ventilation system	Reduced energy output due to overheating and danger to insulations and parts temperature-sensitive	Cyclic preventive: Fans Replacement	3	8	7	168
Inverter Cabin	Cabin overheating and inverter stop	Conditioner or extractor malfunction with excessive temperature in the cabin	Possible interruption of energy output	Preventive: replacement fans/conditioners (under condition: alarm or manual thermometric detection)	5	5	6	150
Inverter Cabin	Danger to insulation and other components sensitive to heat	Malfunction of ventilation and air conditioning with excessive temperatures	Reduced energy output, safety, and fire risk	Preventive: replacement fans/conditioners (under condition: alarm or manual thermometric detection)	5	5	6	150
Transformer	Different performances than plate data	Excessive temperature in transformer cabin	Losses, dispersions, and possible damages to the device	Corrective	5	5	6	150
Inverter Cabin	Connectors open	Malfunctioning of electrical connection, and disconnection	Energy output partly or fully interrupted	Corrective	3	6	8	144
Inverter Cabin	Oxidized or degraded parts.	Infiltrations and/or humidity.	Problems of insulation (conditions of correct work of the inverter or what is in cab).	Corrective	5	6	4	120
Inverter Cabin	Oxidized parts or degraded	Wear cabins, locks, walls, and fixtures	Lack of Insulation	Corrective	5	6	4	120
Transformer	Detect excessive temperatures and overheating of the device	Possible failures of the ventilation system	Losses due to heat and danger for insulation and parts that are sensitive to heat	Cyclic preventive: Fans Replacement	5	4	6	120
Low Voltage section	Abnormal values of the voltage	Lost insulation or overvoltage	Losses and dispersions	Corrective	3	5	8	120
Inverter Cabin	Detecting excessive temperatures	Dirty air conditioner	Overheating and damage to the internal components of the cabin	Cyclic preventive: Cleaning	3	6	6	108
Inverter Cabin	High difference ambient temperature and thermostat	Failure cab extractor	Losses due to heat and danger for insulation and parts that are sensitive to heat	Corrective	3	6	6	108
Transformer	Breaking the transformer	Drop of oil	Loss of production	Corrective	3	6	6	108
Transformer	Different Absorption respect to plate data	Ventilation grilles closing	Suction incorrect	Cyclic preventive: cleaning with air at a pressure	5	5	4	100
Modules	Weak module connections	Clamp/Terminal damaged	Partial or intermittent production of the panel	Corrective	4	5	5	100

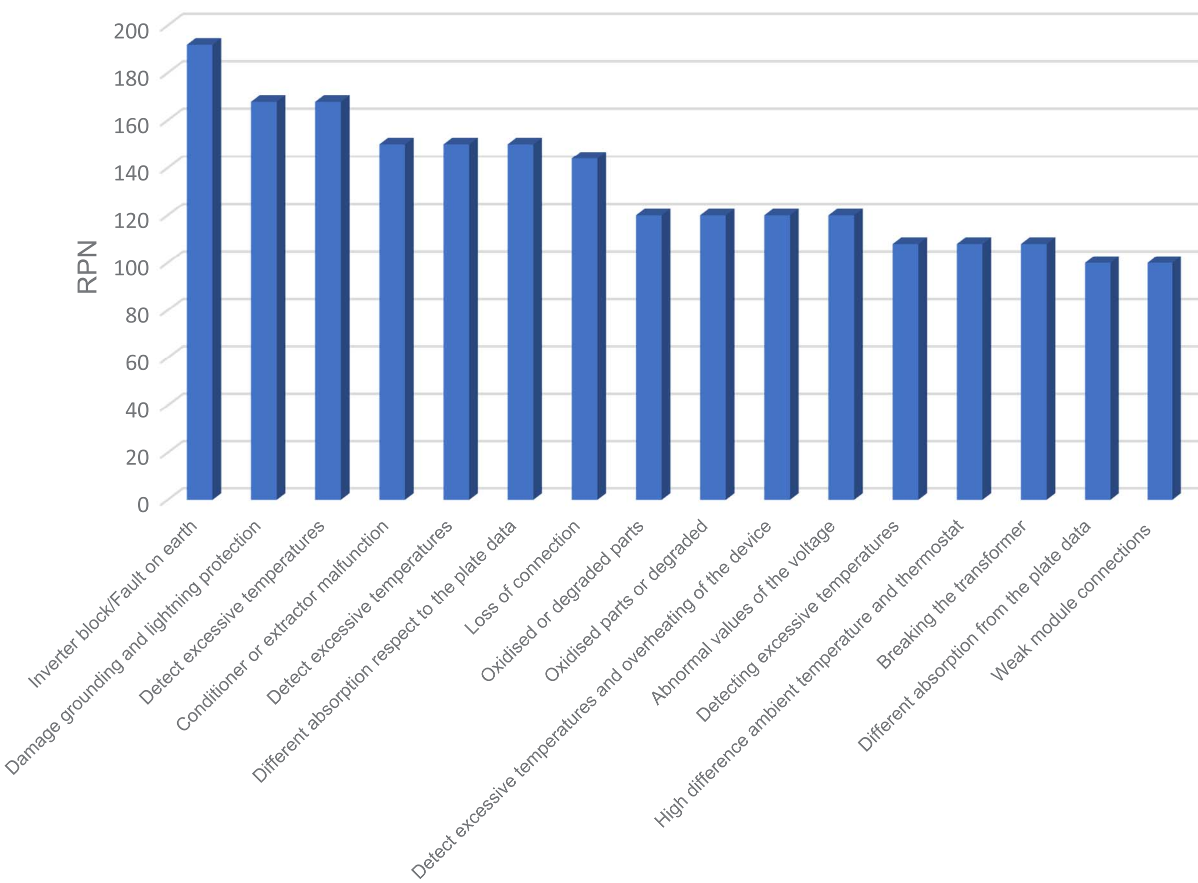

Fig. 2. Failure modes with a RPN higher than 100.

conversion of solar energy are the modules, inverters, and transformers, shown in the MBS of Fig. 1. The first modules are connected in series making a string and the more strings connected in parallel form tables. Each inverter, which converts the direct current generated from the modules in alternative current (suitable for the electric network), is connected to one table and all of them are collected in a string combiner box. The transformer is the last element involved in solar energy production, it increases the output voltage values to make them compatible with the grid. The PV components have a lifecycle and reliability that are influenced by the temperature, power losses, and ambient environments.

The low RPN of the auxiliary services, confirms their poor influence relating to this analysis; the video surveillance or monitoring systems, lighting, communication, and fire extinguishers do not directly affect the production or the safety of the personnel.

After breaking the PV systems down, CMMS is applied to the system and allows the identification of most of the failure modes occurring on the equipment of the PV plants over years of activity. It collects all the failure modes, from the accidental to the predictable ones, to those caused by natural phenomena such as storms or animals. The CMMS software contains the collected maintenance activities performed month by month and which makes the draft of the FMEA analysis easier since many failure modes and maintenance actions are standard in solar energy plants. This database will fill the gap in the PV reliability study presented in [24]. Other studies, such as that of Arabian-Hoseynabadi [53], show the relevance of the software using an integrated database.

A list of the different failure modes which occurred at each module, inverter, and transformer (the active components in the solar energy generation), as well as those in the communication, monitoring, lighting, and surveillance (auxiliary services) systems are given in Table 1.

The listed events in Table 1, were obtained from the CMMS implemented within the Maximo IBM software, and combined asset management with maintenance management. This platform allowed us to identify most of the failure modes that occurred during years of maintenance performed on the equipment of the PV plants by expert maintenance personnel.

4. Assessment of PV system failure modes

The evaluation criteria is based on a scale of 1–10, with the corresponding descriptions adapted from Towler and Sinnott [61], used by Feili et al. [55] and considering [24] and [62] are shown in Tables 2–4.

As a consequence of the scale indicators, the RPN values are ranked between 1 and 1000, with a non-linear distribution, a mean value of 166, and the criticality increases with RPN. The parameters and evaluation scales were contained in a questionnaire, corresponding to each failure for a set of items generated by CMMS.

We obtained the responses of preliminary interviews given to maintenance personnel regarding this selected set of items, using the indexes S, O and D to determine the value of RPN with a scale of the most critical events. The interview was composed of two stages; the first stage presented the cause and effect, with the corresponding maintenance action, of each failure mode; and in the second stage S, O, and D were determined for the current maintenance plan. The distinguishing features of the interviewed technicians are given in Table 5.

The CMMS generated 94 failure modes. In Table 6, 16 failure modes with a RPN higher than 100 are shown. This will be the critical failure modes.

The most remarkable failure mode generated by the whole analysis had a 192 RPN.

Between the relevant failure modes represented in Fig. 2, the most

Table 7
The comparison between the current RPN and target RPN with the proposed corrective actions (in descending order of current RPN).

Component	Failure Modes	Cause	Effects	Current maintenance strategy	O	D	S	Current RPN	New proposed maintenance strategy	O	D	S	New RPN
Inverter/Modules/ Electric circuit	Inverter block and Leakage and earth fault	Overloads due to lack of insulation	No Energy output, safety lack, fire risk	Corrective	3	8	8	192	Rate intensification of periodic multimeter test.	3	2	8	48
Module	Damage grounding and lightning protection	Storm or Lightning	Production stop	Corrective	5	5	6	168	Thermo-graphic Test	5	2	6	60
Inverter	Inverter overheating	Possible failure of ventilation system	Losses due to heat and danger for insulation and parts temperature-sensitive	Corrective	3	8	7	168	Thermo-graphic Test	3	2	7	42
Inverter Cabin	Cabin overheating and inverter stop	Conditioner or ventilation system failure	No Energy output	Preventive: replacement fans/ conditioners (under condition: alarm or manual thermometric detection)	5	5	6	150	Thermo-graphic Test	5	2	6	60
Inverter Cabin	Overheating and insulation damage	Conditioner or ventilation system failure	Reduced energy output, safety, fire risk	Preventive: replacement fans/ conditioners (under condition: alarm or manual thermometric detection)	5	5	6	150	Thermo-graphic Test	5	2	6	60
Transformer	Different performances than plate data	Excessive temperature in transformer cabin	Losses, dispersions and possible damages to the device	Corrective	5	5	6	150	Thermo-graphic Test	5	2	6	60
Inverter Cabin	Connectors open	Malfunctioning of electrical connection, disconnection	Energy output partly or fully interrupted	Corrective	3	6	8	144	Rate intensification of periodic multimeter test	3	2	8	48
Inverter Cabin	Oxidized or degraded parts	Infiltrations and/or humidity	Problems of isolation (conditions of correct work of the inverter or what is located in cab)	Corrective	5	6	4	120	Inserting UPS which does not suffer from moisture	2	6	4	48
Inverter Cabin	Oxidized or degraded components	Wear of cabins, locks, walls and fixtures	Lack of insulation	Corrective	5	6	4	120	Inserting UPS which does not suffer from moisture	2	6	4	48
Transformer	Overheating of the device	Possible failures of the ventilation system	Losses due to heat and danger for insulation, and temperature-sensitive parts	Cyclic preventive: Fans Replacement	3	5	8	120	Rate intensification of periodic multimeter test	3	2	8	48
Low Voltage section	Abnormal values of the voltage	Lost insulation or overvoltage	Losses and dispersions	Corrective	3	5	8	120	Rate intensification of periodic multimeter tes	3	2	8	48
Inverter Cabin	Detecting excessive temperatures	Dirty air conditioner	Overheating and damage to the internal components of the cabin	Cyclic preventive: Cleaning	3	6	6	108	Thermo-graphic Test	3	2	6	36
Inverter Cabin	High difference ambient temperature- thermostat	Cab extractor failure	Losses due to heat and danger for insulation and temperature-sensitive parts	Corrective	3	6	6	108	Thermo-graphic Test	3	2	6	36
Transformer	Breaking the transformer	Drop of oil	Loss of production	Corrective	3	6	6	108	Thermo-graphic Test	3	2	6	36
Transformer	Different Absorption respect to plate data	Ventilation grilles closing	Suction incorrect	Cyclic preventive: cleaning with air at a pressure	5	5	4	100	Thermo-graphic Test	5	2	4	24
Modules	Weak module connections	Clamp/Terminal damaged	Partial or intermittent production of the panel	Corrective	4	5	5	100	Test verifies PID effect.	4	2	5	40

Table 8
The comparison between the current RPN and target RPN with the proposed corrective actions for 13 non-critical (RPN(100) failure modes (in descending order of current RPN).

Component	Failure Modes	Cause	Effects	Current maintenance strategy	O	D	S	Current RPN	New proposed maintenance strategy	O	D	S	New RPN
Modules	Water or damp penetration	Watertightness degradation	Partial or intermittent production of the panel	Corrective	3	5	6	90	Test verifies PID effect	3	2	6	36
String control	Overvoltage tables	Overvoltage tables	Losses and dispersions	Corrective	4	3	7	84	Rate intensification of periodic multimeter test	4	2	7	56
Modules	Excessive heating of one or a series of cells	Wear of the materials, dispersion failure temperature, arches	Reduced or lost production, high heat	Corrective.	3	5	5	75	The drones with thermos-graphic detection	3	2	5	30
Modules	Short circuit	Misalignment between strings of PV cells	Reduced energy output	Corrective.	3	5	5	75	Diodes bypass of already included in the module; blocking diode for short circuit protection	3	5	3	45
Cables and Connections	Loss of insulation	Rodent activity	No Energy output, safety threat and dispersions	Corrective: foaming and possibly replacing damaged cables	6	6	2	72	Use of polyethylene anti-rodent cables	1	6	2	12
Inverter	Breaking, oxidation or degradation of elements	Wear and infiltrations of water moisture and dust	No energy output from array under damaged inverter	Corrective: replace component detected degraded	3	4	6	72	Insertion of electrostatic filters on ventilation system	2	4	6	48
Inverter	Different absorption respect to plate data	Deterioration of cable insulation	Current dispersions and safety threat	Corrective.	3	4	6	72	Test with multimeter to provide at least once a year	3	2	6	36
Inverter	Malfunction	Water infiltration, humidity and dust	Losses/lack of production	Corrective: replacement of worn parts	3	4	6	72	Insertion of electrostatic filter for dust	1	4	6	24
Electrical Switch-boards	Misfire switchboards	Loosening of switchboards connections	Loss of production	Cyclic preventive: Screwing terminals	3	4	5	60	Thermography	3	2	5	30
Inverter	Different absorption from the plate data	Overhang value input voltage and output	Current dispersion	Corrective	3	6	3	54	Thermography inverter, punctual heating on connector	3	4	3	36
Electrical Switch-boards	Misfire switchboards	The presence of dust and dirt	Loss of production	Cyclic preventive: Cleaning	2	4	5	40	Insertion of electrostatic filter	1	4	5	20
Paintings of subfield	Misfire frameworks of subfield	The presence of dust and dirt	Loss of production	Cyclic preventive: Cleaning	2	4	5	40	Insertion of electrostatic filter	1	4	5	20
Inverter	Mistaken starting	Obsolescence of Hardware and Software	Card or software malfunction	Preventive system updates by the supplier of the software	3	1	1	3	Purchase of tabs that can be accessed from remote directly from the supplier	1	1	1	1

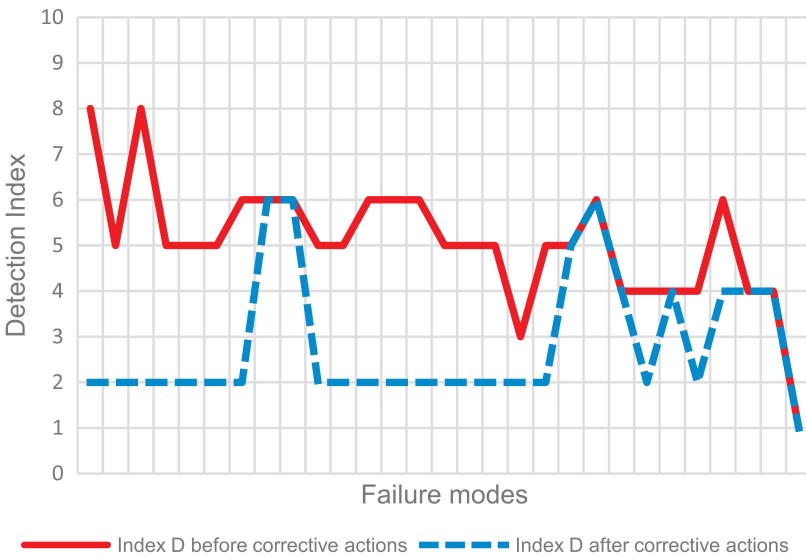

Fig. 3. The D index modification with corrective actions.

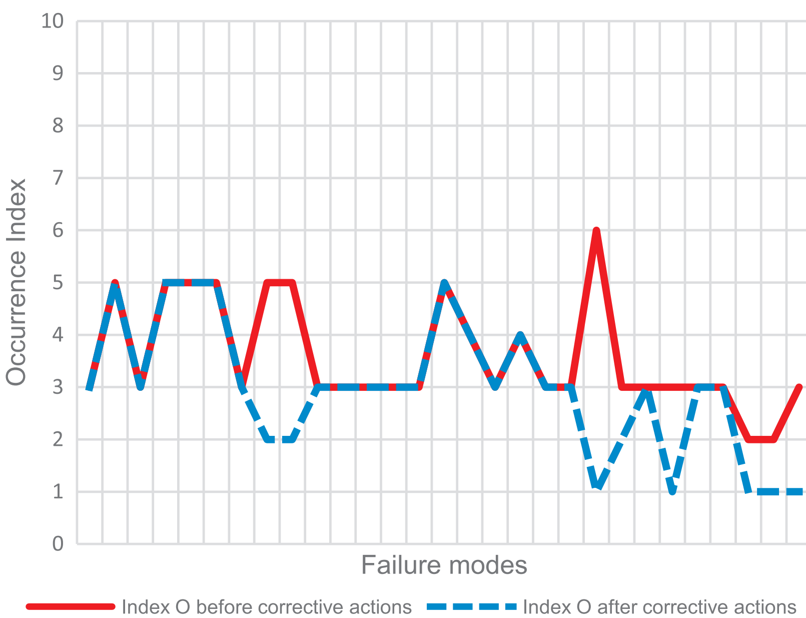

Fig. 4. The O index modification with corrective actions.

recurrent modes related to the inverters and their cabins.

5. Evaluation of criticalities and corrective actions within the maintenance plan

After the evaluation stage the maintenance plan, consisting of a set of corrective actions, was optimized using information from the technician's experience and data in the literature using plain solutions. The results of this action were 16 improved accidental critical events (the ones with RPN > 100 showed in Table 6) and 13 improved accidental events with lower RPN. Some of the failure modes are mitigated by the same action. The variation between the RPNs before and after the corrective action, included the description of the action selected to modify the maintenance plan, are shown in Tables 7 and 8 respectively for the 16 critical failure modes and the 13 non-critical ones. In the proposed 29 corrective actions, 69% reduced RPN by the reduction of the detection index and 28% by the reduction of the occurrence index. Only one case was improved by the reduction of the severity index, representing a 3%. The reduction of the occurrence using prevention measures, and the improvement of detection are the simplest ways to reduce the overall RPN. The trends of three indexes, before and after the modifications, are shown in Figs. 3–5. The relevance of the detection policy results is very high for the consulted subjects.

We describe below, some considerations regarding the most relevant groups of the failure modes:

- The highest RPN is associated with an inverter, with problems on the grounding system. The cause of this failure mode is a lack of isolation and consequent overload of the system. The proposed maintenance action is to use an overloads measurement device (a multimeter) in order to test the isolation of modules several times a year. To implement this solution, it is necessary to buy at least one device per plant and increase the recurrence of checks from one to four times per year. In this case, the RPN would pass from 192 to 48, due to the reduction in D from 8 to 2. A multimeter could be used to detect abnormal values on the low voltage line and for over voltages on the modules. Reduction of the RPN for these two failure modes balances the additional cost of this corrective action.
- Once the isolation problems are overcome there are also overheating issues. These failure modes affect inverters, inverter cabins, transformers, string controls, and modules in many different ways. The purposed corrective action is the use of a thermographic camera

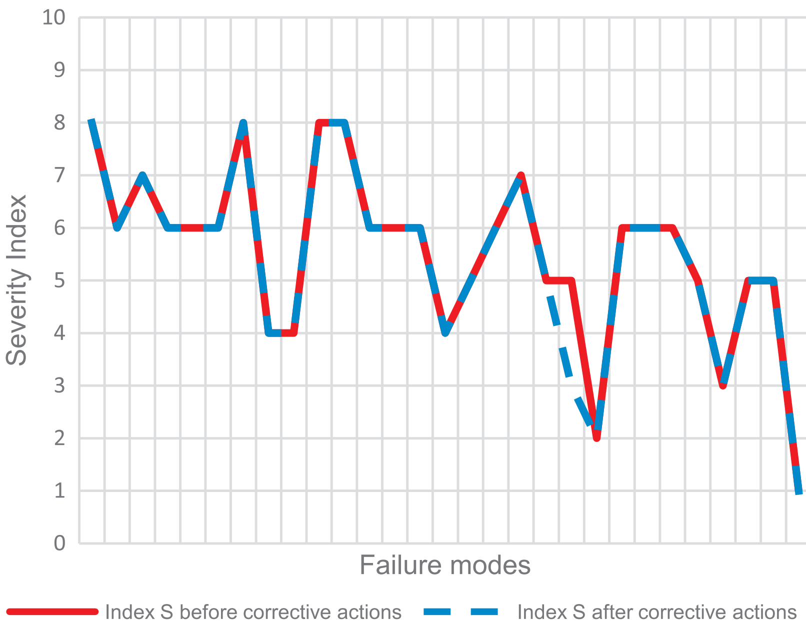

Fig. 5. The S index modification with corrective actions.

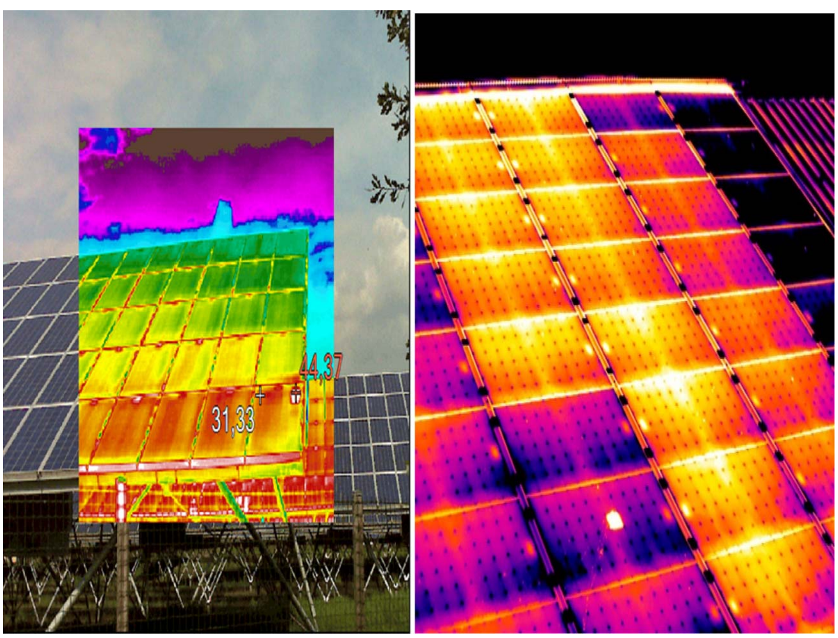

Fig. 6. The thermographic test on panels.

with new technical features that can enlarge the application field allowing an improvement in the current maintenance plans. A further evolution of this type of diagnostic, is the use of drones for thermographic survey. The associated costs related to this solution are still very high in replacing the current technology, but its popularity is leading to future reduced costs and more applications (see Fig. 6).

- Several failure modes are due to humidity and/or dust. The insertion of humidity absorbent materials such as dehydrating salt is a useful solution for humidity. The problems with dust could be rectified with electrostatic filters, however these are limited in their applications and need to be change periodically. Another solution is the use of PV components with a proper IP grade.
- For the modules, the degradation due to wear of the materials is provided as a preventive action of maintenance. The empirical RPN for this failure mode is 90, but interesting input from the interviewees was the suggestion to verify the PID effect on the modules. In fact, this effect is one of the main causes of efficiency reduction, down to 30%. Modules can have manufacturing defects due to the wrong polarization, that if not detected can seriously reduce the production. If it is detected it is possible to re-polarize the module and reduce the effect.
- A failure mode with a low occurrence but high severity, is demonstrated by the short circuit caused by the misalignment of the strings. One easy solution is to insert a diode to protect the circuit from short circuiting and the consequent overloads.

6. Conclusions

The comparison with the relevant current literature to our reliability analyses of the highlights of PV systems, emphasizes the distinct differences in the subjects interviewed. The risk analysis obtained in the previous literature, with the exception of [24], were the opinions of engineers and laboratory experts, while the present evaluation is based on the opinions of operational maintenance personnel of a company, including a database containing the details of the failures over the long-term operation. This work has been extended to include the whole PV system, without limiting the focus to issues of a single component as presented in previous studies. For example, Catelani [19], assessed single PV modules without considering the effects of their malfunctions on other components.

Typical weather conditions also effect the evaluations. Incidentally, the data in this analysis included the Italian national weather conditions. However, Colli [24], who presented the first study of the overall PV system, examined data from 600 PV SunEdison systems, situated in 4 continents where weather conditions differed from those in Italy. This factor emphasizes the subjective features of the reliability analysis approach depending not only on the subjects interviewed but also on the environmental differences. Different climate conditions effect the FMEA analysis because PV technology heavily depends on environmental factors.

A responsive updated organized plan of action is an important contribution of the present study, which adds to previous studies. New actions aimed at optimizing the current maintenance plans have been derived, with fixed features given below. In addition to a more realistic risk assessment, we have proposed a set of practical, effective, and often low-cost, corrective actions with the aim to increase the reliability of the system, obtained from maintenance personnel.

Differing to most previous studies, the FMEA approach has been applied to a PV system and corrective actions have been individualized to reduce the RPN of several characterized failure modes. The first phase allowed a novel approach of FMEA, using the practical experience of personnel working in a company in the operation and maintenance of PV systems, whose opinions and approaches are different to those of theoretical and office technicians. The lack of this kind of realistic data has limited the results presented in previous studies, and the source of information in the study increases the significance of the present assessment. The baseline of the failure modes considered here were generated using the CMMS of Solarig. Questionnaires were used to obtain the opinions of the maintenance technicians, and the failure modes were evaluated using the rating parameters O, S, and D, and the RPN was calculated. This comparison emphasized the differences in the feedback obtained by practical (maintenance personnel) and theoretical (e.g. engineers) experts, with the exception of [24], and the different issues relating to climate as mentioned by Colli [24].

Another new contribution of the present work is the derived RPN rates which, along with the associated corrective actions that have been determined to mitigate the risk, can be used in designing updated and improved maintenance programs. The new proposed plan is aimed at preventing failure using precautionary measures and, by comparing with previous maintenance plans, reduces the RPN values.

Furthermore, in many cases the maintenance plans can be made more affordable and the selected effective corrective actions are typically applicable to several failure modes. Finally, we have proposed a way to optimize the maintenance and management of PV systems, providing effective improvements in their performance, and to increase the energy productiveness of installed power stations with a small impacts on the OPEX of the PV generator and a consequent reduction of LCOE.

Acknowledgments

This work was carried out with data coming from the Italian branch of Solarig Global Services SA and thanks to the contribution of their technician. We would like to thank them all heartily.

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