Statistical overview of findings by IR-inspections of PV-plants

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ABSTRACT

First statistical evaluation of IR-inspections of PV-plants reveals that 86% of the installed PV-plants show IR-abnormalities. More than 120 PV-plants with more than 160,000 PV-modules were inspected and evaluated statistically. Main IR-abnormalities or failures in modules and string installations are analyzed, respectively. The average failure rate for PV-modules is about 8% and for module strings approximately 4%. The differentiation between the installation locations reveals that small residential installation show relatively more defective modules than large field installations. – Therefore, IR-imaging is a valuable method to give fast and reliable information about the actual quality and failure rate in inspected PV-installations.

Keywords: IR-images, statistics, PV-modules, defects, failure, substrings

1 INTRODUCTION

Quality control of PV-plants is of increasing interest for service and maintenance. Failures in PV-installations may cause a safety risk as well as a severe power reduction and poor performance in the future. Therefore, many studies have been carried out about the reliability of PV-modules in the past years. Some focus more on the degradation rates of different technologies [1, 2], others on the influence of various climatic regions on the PV-installation [3, 4]. Also, there are various surveys of failure rates of PV-modules during operation [5-11].

Among the top ten module failure mechanisms are: connector failures and glass breakage as retrieved from field inspections [10]. The presented data suggest 34% of the inspected modules have some type of failure. The IEA report [5] states that the most important failures in the field are junction box failure, glass breakage, defective cell interconnect, loose frame and delamination. De Graaff's [7] survey points out that 2% of the modules do not meet the manufacturer warranty. After a certain life time the most dominant module failures are delamination, cell fracture and discolouration [11]. Most investigations focus on the impact on the actual power output. The effect on the module power output differs with the failure type.

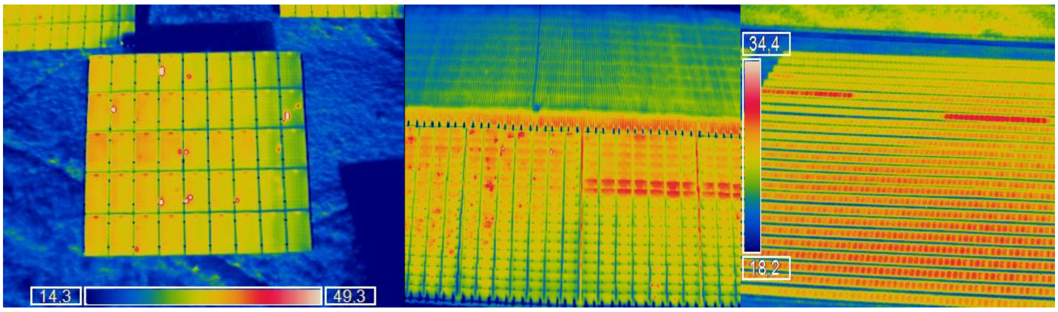

Figure 1: IR-images of different PV-plants showing certain numbers of sites with elevated temperature, left: tracked PV-table with 12 out of 45 modules showing IR-abnormalities, center: industrial roof with numerous defective modules and two suspicious module strings, right: IR-overview of a field installation with two suspicious module strings

In order to check the PV-plant quality and locate and identify potential failures IR-inspections are a valuable tool. Drone-based measurement systems enhance the fast, mobile, flexible, non-destructive inspection under real operation conditions

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without operation interruption [12-14]. Electrical malfunctioning modules show up in the IR-image because of their elevated temperature [15]. Typical IR-images of three different installations are presented in Figure 1. Here, module and string failures can be distinguished. A module failure normally shows single sites (small spots, individual cells, cell arrays typically protected by a bypass diode, so called substring) of increased temperature within the module. String failure is typically caused by a cabling problem of installed PV-modules, e. g. the connection to the inverter is interrupted. The modules within the string are at open circuit. No current flow is possible, all absorbed solar irradiance is transferred to heat. Therefore all these modules show a homogeneously higher temperature.

The scope of this paper is to give a first overview of the abnormalities in IR-inspections of PV-plants based on a statistical evaluation of the data collected in the last years. Thereby the evaluation is governed by the question “what are typical occurrences for IR-findings and how are they distributed and influenced?”.

2 EXPERIMENTAL PROCEDURE

The inspections were carried out with a measurement system consisting of a drone equipped with an IR- and VIS-camera and various sensors. The drone is an unmanned aerial vehicle (UAV). Here an octocopter is used which is equipped with a navigating system and various sensors. The IR-camera Optris PI450 has a bolometer detector with 320 x 288 pixels. The lateral resolution ranges from 3x3 pixel up to 5x5 pixel per solar cell of a standard silicon PV module. The view angle is perpendicular to the module surface in order to avoid disturbing reflections [16]. Usually the inspections were done at high solar irradiance $E > 600$ W/m², clear sky and no wind in order to obtian optimum IR-image quality.

During the last years a large number of PV-generators were investigated. They differ in cell technology (crystalline and thin film), in power output (kWp), in the number of modules, operation duration and installation location (industrial roof, residential roof, field installation, tracker) and geographic location (see Table 1). IR-inspections of approximately 120 PV-plants are evaluated statistically in this paper. Their peak power adds up to roughly 25 MWp with about 160,000 installed PV-modules. Mostly, PV-plants with crystalline silicon cell technology were analyzed.

Table 1: Overview of inspected PV-installations

Category	Variety of samples
Cell technology	crystalline Si, CIGS, CdTe
Geographic locations	Germany, southern Europe
Installation locations	Field, industrial roof, residential roof, tracker
Operation duration	0.5 to 8.5 years

The investigated plants include PV-plants of different sizes, i. e. differing nominal power output as well as differing number of modules. The percentage of house installations of up to 100 modules is appox. 45%, industrial roofs 100 to 1,000 modules cover about 36%, distinct industrial installations (carports, and others) and small field installations 1,000 to 10,000 are approx. 13%, and the extended field PV-plants with more than 10,000 modules constitute roughly6% of the inspected PV-plants. The description of the PV-installations in terms of number of modules and Plant output is given in Table 2.

Table 2: Location specification of the investigated PV installations

	Number of modules	Peak power	Number of installations investigated
Field installation	1,000 – 20,000	12 kWp -4 MWp	13
Industrial roof	80 – 4,500	21 kWp – 200 kWp	39
Residential roof	20 - 130	5 kWp – 50 kWp	58

The investigated PV-plants included half-and-half

1. Service measurements, initiated by operators assuming power reduction due to certain defective sites based on lower than expected energy yields
2. Research projects, here the PV-plants performed within the expected power output range, but were still investigated periodically.

The PV plants investigated included PV-plants with and without monitoring system. In the case of a present monitoring system the resolution, the accuracy of the measurement unit or the set-up of the module installation did usually not provide a sensitivity level sufficient for detecting the issues observed by aIR PV-check.

The IR-images were evaluated regarding their temperature distributions. At suspicious sites the absolute temperature as well as the temperature difference to adjacent cells is determined. In parallel to the IR-images, visual images are recorded. The comparison of the IR- and the VIS-images allows the recognition of artefacts, as e. g. bird droppings, which do not constitute a permanent yield risk and may thus lead to misinterpretation and were not considered in this study. Therefore, IR-features evaluated here, are indeed due to defective sites causing irregular heating in the modules and in the PV-generators.

3 RESULTS

The collected data were evaluated statistically. The appearance of different defect classes will be presented. The failure rate with respect to plant size, number of installed modules, operation period, and installation type will be discussed.

3.1 Data evaluation

The percentage p_i of aPV-plant with a specific IR-abnormality of failure type i is given by:

$$p_i = \frac{n_i}{N} \qquad (1)$$

with n_i being the number of affected PV-plants with the specific failure type and N the total number of inspected PV-plants. Calculating the failure rate of a given PV-plant the equation is given as following:

$$q_i = \frac{m_i}{M} \qquad \text{and} \qquad q_i = \frac{s_i}{S} \qquad (2)$$

with m_i the number of affected PV-modules with the specific IR-abnormality of failure type i and M the total number of PV-modules in the PV-plant, and s_i the number of modules strings with elevated temperature and S the total number of strings in the PV-plant.

The averaged values $\overline{q_i}$ are calculated on the basis of the affected PV-plants

$$\overline{q_i} = \frac{1}{n_i} \sum_{1}^{n=n_i} q_{n,i} \qquad (3)$$

Furthermore, the median is determined.

3.2 Defect classification

Based on their temperature distribution the IR results were assigned to failure modes identified by their characteristic IR-fingerprint as described in [15]. The occurrence of the specific IR-findings or failure modes in PV-plants differs strongly, see Figure 2. Only 13% of the PV-plants exhibited no IR abnormalities. Surprisingly, approximately 20% of the PV-plants show more than one complete *suspicious module string* (compare Figure 1 center and right). Possible reasons for the disconnection may be wrong installation or deterioration by animals or natural degradation. Approximately 50% of the PV-plants have *bypassed substrings*.

Further detected module failures are *defective bypass diodes*, *cell fracture*, *defective solder joints* as well as *short-circuited cells, potential induced degradation and delamination*.

Suspicious substrings and *module string*s are the features most frequently detected in the PV-plants.

Potential induced degradation (PID) has a similar IR-signature as short-circuited cells [17]. As it constitutes a fairly young failure mode [18]. Therefore, the number of inspected PV-plants is rather small. However, when PID is present often more than 35-45% of the modules are affected [8, 17].

Glass cracks in thin-film PV-plants are a common failure and are nearly detected in all inspected thin-film PV-plants [2]. No numbers representative for the occurrence of this failure type are obtained as these modules are also visible by standard visual inspections and therefore they are usually replaced frequently right upon detection.

Delamination is rarely present in this study but when it occurs, a large number of modules is affected. However, the IR-signature is not always definitely classifiable to a specific failure mode. Therefore, in a quite large rate of PV-plants IR-signatures are observed which cannot be assigned to a certain defect class doubtlessly.

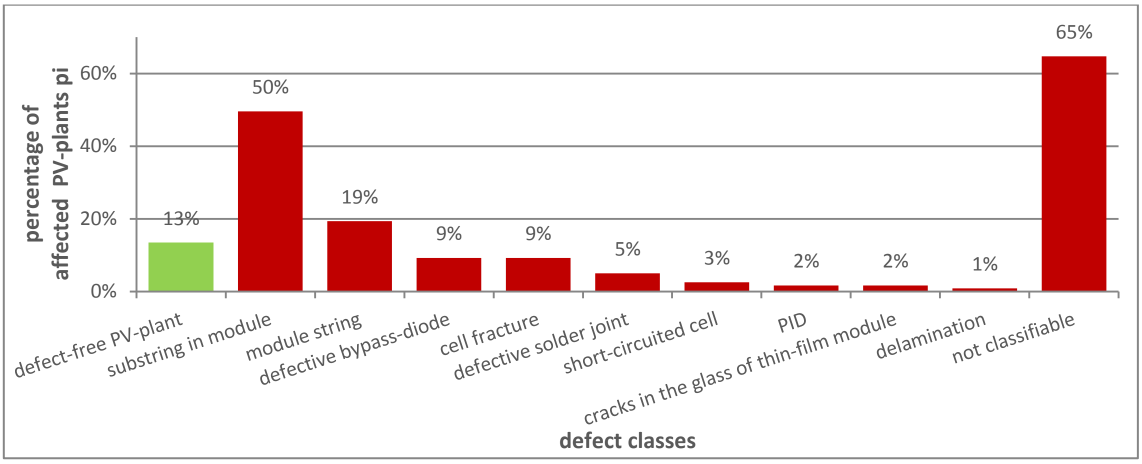

Figure 2: Distribution of the most frequent findings in IR-images

In the following it will be differentiated between module failure and installation failure, here unconnected module strings.

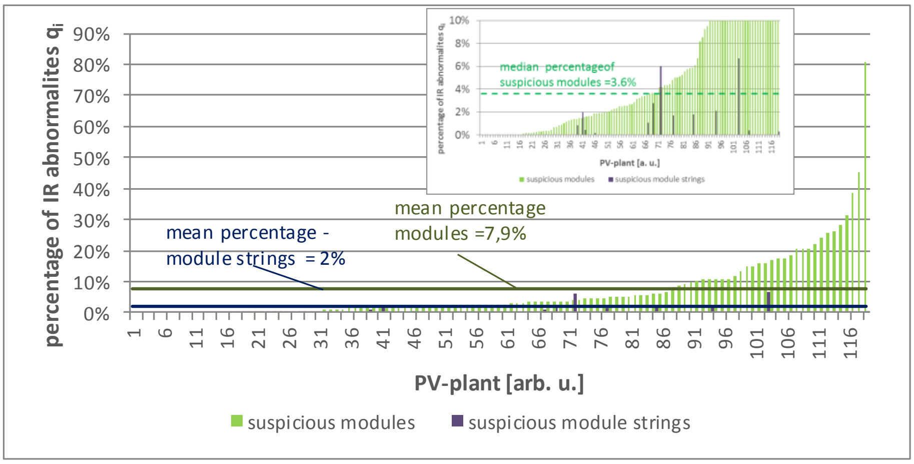

Figure 3: a) investigated PV-plants overview of inspected PV-plants sorted in ascending order of percentage of IR abnormalities. b) Zoom in into range of failure rates up to 10% abnormalities.

The calculated failure rates q_i of the inspected PV-plants are presented in Figure 3 sorted with ascending sequence of failure rate of modules (including all kinds of defects) and strings. Highest frequencies of suspicious modules were detected for PV-plants with delamination (80% of the modules are affected), or PID (35% and 40% of the modules showed the signature). In the remaining PV-plants other typical features were observed in lower numbers. Mean percentage and median percentage of failure rates are listed in Table 3 for modules and strings. Mean and median for modules differ strongly due to high failure rates in a few inspected PV-plants with PID and delamination.

Table 3: Mean and median percentage of IR-findings

	Modules	Strings
Mean percentage of IR-findings	7.90%	2.0%
Standard deviation	11.3%	2.0%
Median percentage of IR-findings	3.6%	1.7%

3.3 Operation duration

The influence of the operation duration prior to investigation on the failure rates of modules and strings as they have been detected by IR-inspection, are shown in Figure 4. Neglecting the high failure rates for PID and delamination a fairly constant percentage of suspicious modules is found. An expected increase of IR-findings for longer operating PV-plants could not be confirmed by the selected PV-plants. Since the history of the PV-plants is not entirely documented and known, possible module replacements and other repowering activities during life-cycle may falsify the statistics. The evidence for disconnected module strings is fairly high (7%) at the beginning of life-cycle and decreases with operation time.

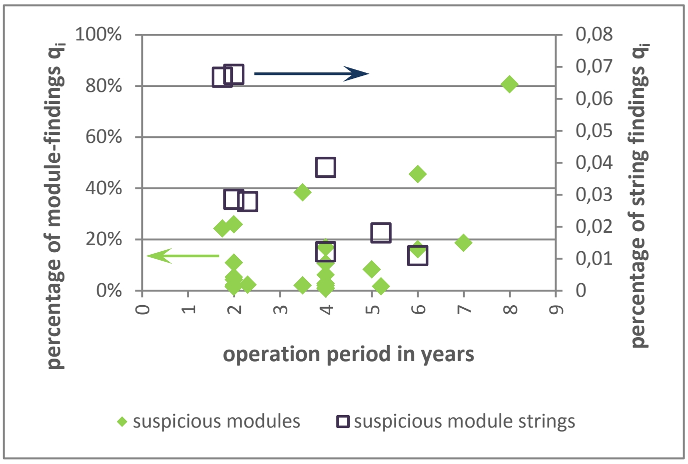

Figure 4: Percentage of thermal findings as a function of operation time

3.4 PV-plant size

The correlation between the size of the PV-plant and the failure distribution is presented in Figure 5. The statistical analysis of residential PV-plants has more a sample character whereas the evaluation of large PV-plants (>1 MWp) is more reliable.

The module failure rate increases but spreads with plant size up to 200 kWp. For large PV-plants (> 1 MWp) it is constant at a fairly low level, less than 10%.

Small and medium-sized PV-plants (with few strings due to the limited number of modules) show rarely string failures, see also 3.5, whereas it is quite often detected in MW-plants. Although the occurrence for string findings is rather high in large PV-plants, the percentage drops. Thus, a constant number of module strings at open circuit is observed.

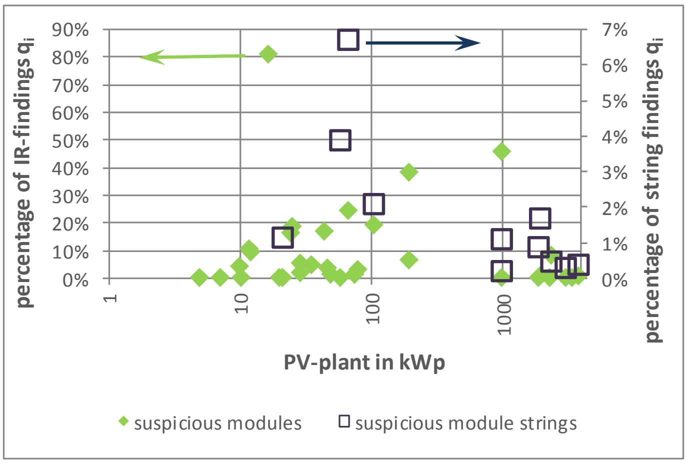

Figure 5: Percentage of IR-findings (modules and strings) as a function of PV-plant power output

3.5 Installation type

The installation locations differ between large field installations, medium and large industrial roof installations and small and medium residential roof installations. Besides the plant size the installation locations suffer from the differing complexity of the installation process and the unequal operation management and availability of reliable monitoring systems. Three IR-findings, suspicious module (except substring), suspicious substring, and suspicious module string are evaluated in detail. Module and substring abnormalities are assumed to be indicators for transport, installation and degradation problems. String findings usually indicating disconnected strings are interpreted as an indication of cabling problems due to installation or deterioration of all kinds. These string problems are often not recognized in the collected monitoring data. The reasons can be manifold: low accuracy of the collected data, complex PV-installation with sophisticated string connection of the modules, local shading, locally differing installation conditions (solar irradiance, heating, convection, shading, installation angle), module mismatch, and so on.

As figure 6 illustrates nearly all (> 80%) PV-plants of any type show IR-findings.

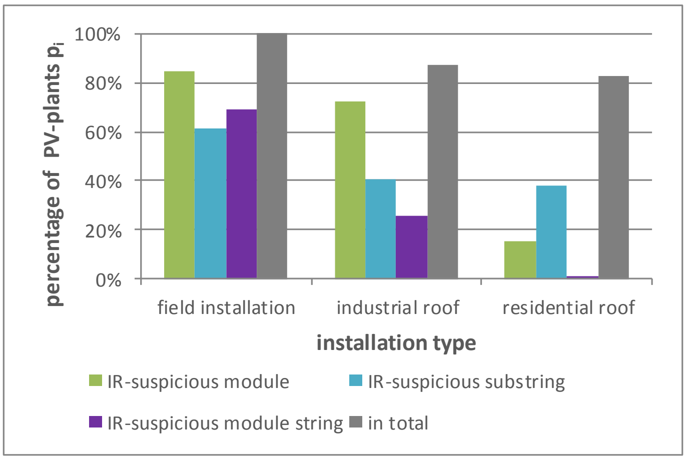

Figure 6:: Frequency of PV-plants with IR-findings differentiating between suspicious modules, substrings within modules and module strings for different installation locations

The probability to detect modules, substrings and module substrings is much higher for large field and industrial roof installations than for rather small residential roof installations. Unconnected modules strings were only counted very rarely for small installations. Adding the number of strings for all residential installations (> 230 strings) between 4 to 6 disconnected strings would be expected (and are detected) for a similar industrial roof installation. Obviously, the operators realize the unconnected string fairly early, since it has a considerable impact on the power production, if e. g. the power generation of one string out of four is missing.

Taking the average of all affected installations for all installation types 8,0% suspicious modules, 2.9% substrings and 4.2% module strings are detected. Figure 7 shows that the mean frequency for suspicious strings differs considerably for large versus small installations. Note, that only one house installation in the evaluated sampling showed one irregularly heated module string (figure 6). Typically two to four unconnected module strings are detected in large installations. The mean frequency for substring findings is significantly higher for residential installations than for large installations. Considering the detection of suspicious modules, no significant deviations between the installations were found. However, substring and module failure rates of residential installations are higher than the average values.

Large error bars of the calculated mean value indicate the diversity of the plants investigated. In order to get a better understanding of the data, the median is determined, too. The median and the mean value for suspicious substrings correspond fairly well. However, Figure 7 shows clearly that the median for the modules and the module strings are well below the mean value. Here, just a few PV-plants with quite high rates of defective modules showing up in the IR-image push the mean to high values. Such PV-plants may be affected by severe module failure mechanisms, as e. g. potential induced degradation (PID) or delamination. As PID is a fairly young module fairly not many PV-plants have been inspected to date. However, when PID and delamination are present, a very large number of modules is PID-affected and shows up in the IR-image, because of the intrinsic failure type properties.

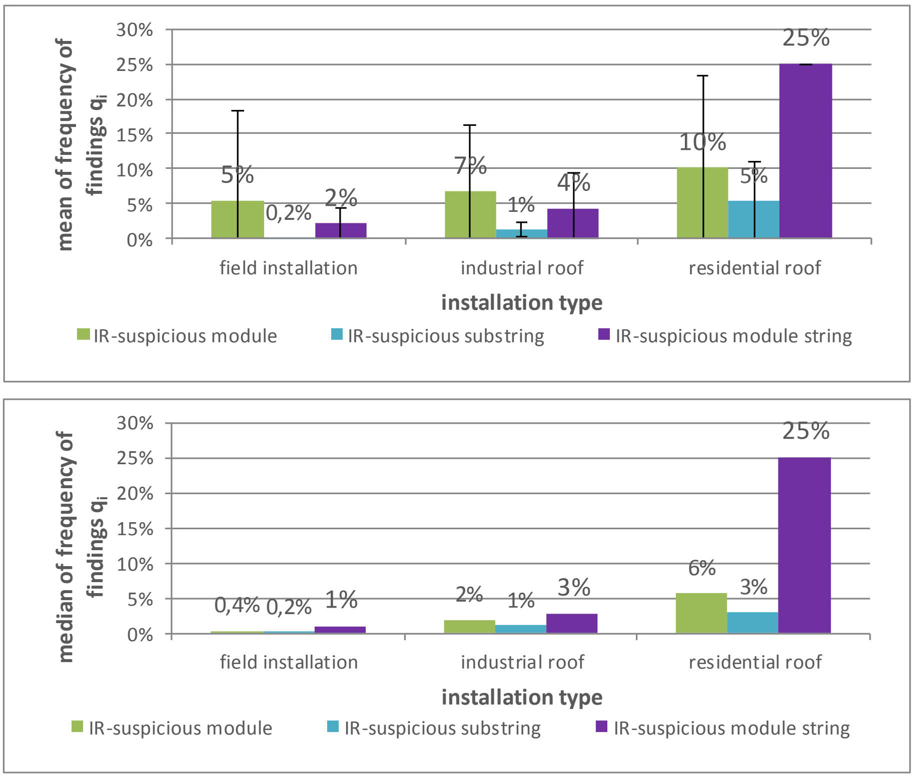

Figure 7: Frequency of IR-findings in the affected PV-plants, mean of frequency (top) and median of frequency (bottom) for different IR-findings (module, substring and module string) and three installation locations

Statistically there are more findings in house installations than in professionally operated large PV-generators. The large standard deviation corresponds to large range of data. The smaller median indicates that a few PV-plants with high failure rates are part of the investigated sample.

4 SUMMARY

The statistical evaluation of the IR-inspected PV-plants point out that only 13% of the PV-plants are without IR-findings of any kind. Various failure modes can be distinguished by their characteristic temperature distribution. The sample data reveal the mean percentage of module failure is about 8% and 2% for string failures. In large field installations string failure dominates whereas in small residential roof installations module failures, especially bypassed substrings, are detected. Future statistic work will also consider the potential impact on the power reduction in more depth.

5 ACKNOWLEDGEMENTS

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