4.3.1. Field Monitoring Methods

In the following, field monitoring methods [48, 49, 70], which are commonly applied for monitoring PV operations, are described.

- Visual Inspection/Assessment

  Visual inspection is a very popular, easy, and simple way to detect defects in a PV module, as it allows data collection and visual observations in a wide range. Although its detectability imposes restrictions due to the fact that several complications occurring in a material go unnoticed by the naked eye, this technique is effective, rapid, and does not require specialized equipment. It can be carried out by naked-eye examination or by the use of magnifying glasses. This inspection method aims at the recognition of obvious degradation signs [48], such as corrosion, discoloration, delamination, hot spot formation, glass cracks, cell cracks, junction box failures, bubbles (provided that they have sufficient dimensions), or module frame damages. Köntges et al. [80], in their work for enhanced comparability, summarized the defects that can be identified during visual inspection. Following the PV module manufacturing process, visual assessment is compulsory [120] and should be carried out on field conditions as well.

- Current-Voltage curve (I-V Characterization)

  Another valuable test tool for ensuring the proper operation of PV modules is the I-V curve. This method is applied to monitor and evaluate the electrical output of the module under different operating circumstances, such as levels of irradiance and variations in temperature. The procedure for engraving the curve requires a natural or artificial illumination of the module, a DC power supply, and an I-V curve tracer. The analysis and study of the curve can reveal useful information, as crucial performance parameters of the module can be assessed. These parameters include maximum power values, fill factor, and both open and short circuit voltage.

  Within a laboratory, sun simulators are of primary importance for testing PV modules under controlled standard test conditions [120] (STC - AM1.5 G spectrum, 1000 W/m^2 radiation power at 25 °C module temperature). Before modules are set for deployment, they undergo measurement and evaluation tests of their electrical behavior inside a laboratory. These reference values are then compared to those obtained in a subsequent stage, where the aged module is tested outside of the field. The obtained I-V profile is then normalized to the STC profile by measuring the real incident irradiance and the actual ambient temperature. By this comparison, the effect of the field exposure and aging of the PV module is underlined, as one can observe deviations between the reference and the measured values. I-V curves also provide the opportunity to identify degradation signs, such as a reduction in current, voltage, or power of the module. The parameters of the I-V curves are directly connected to the electrical profile of the module. Discoloration, delamination, and glass corrosion can cause a drop in short-circuit current, while losses in open circuit voltage are often the result of PID, temperature-induced degradation (TID), LID, or a breakage in the cell interconnections. The slopes in each case denote an increase in shunt and series resistance, respectively. The I-V curves can be used to evaluate both the annual rate and the percentage of the degradation of the PV module.

- Ultraviolet Fluorescence (UVF)

  UVF technique is widely used to measure degradation in c-Si-based solar cells. The phenomenon of the absorption of electromagnetic radiation and the following emission at a different wavelength is called fluorescence. The module absorbs UV radiation (high energy and lower wavelength) and then emits the light, with lower energy and higher wavelength, in the visible region of the electromagnetic spectrum. When excited by UV light, a microscopic compound called fluorophore can re-emit light at higher wavelengths (visible light). This re-emission is related to degradation marks on the PV module. The

application of the technique requires a spectrometer and a UV irradiation source, which can be used to detect cell cracks, hot spots, and EVA degradation.

The method is mainly used for an in-depth examination of the encapsulation material of a PV module [118]. The encapsulation material is typically EVA, along with various additives, such as oxidation stabilizers and UV absorbers, and acts as an accumulation region for fluorophores. The fluorescent response of the encapsulants depends on their composition and content in additives, but the most common case is the following: The exposure to UV light creates fluorophores as degradation products, which achieve a sufficient fluorescence signal after around 1.5 years of operation in outdoor conditions in regions with middle latitudes. Oxygen induces photobleaching, an effect counteracting fluorophores, and delves into the EVA through the backsheet. The entry of oxygen in the front EVA is possible only through cell cracks or gaps. Months after the appearance of cell cracks, the fluorescence signal captured at the front of the module exhibits signal-free elongated lines above the cracks.

- X-ray Scanning

  This method, with the advantage of not destroying or degrading to any extent the modules, is applied in order to detect delamination and incoherence among the elements of a PV module. The application of the X-ray scanning method produces two-dimensional (2-D) images, the analysis of which can indicate possible copper etching backsheet lamination, and misalignment of the components in the backsheet system [121] of the module, electrically conductive adhesive, backsheet foil and back contact cells.

- Ultrasonic Inspection

  Similar to the X-ray scanning method, ultrasonic inspection is also non-destructive and, therefore, beneficial for testing the reliability and operation efficiency of a PV module. This method is the ultimate combination of transmission and echo pulse methods (2-D scanning methods) [122], and it is based on scanning the PV module with the assistance of a moving ultrasonic transducer with an integrated X-Y indicator. Being a hybrid method with enhanced potentials, ultrasonic inspection can, on the one hand, identify the ultrasonic pulses reflecting back after scattering at the defects (echo pulse method) and, on the other hand, map the diversion in the path of ultrasonic beams due to the interaction with the defects (transmission method, ultrasonic energy scan). This can define the dimensions and location of the defects.

- Infrared Thermography (IR-T)

  Thermal or infrared imaging is one of the most well-known testing techniques for the detection of potential thermal abnormalities and electrical failures in a PV module. The method is non-destructive, contactless, and yields fast results, while it only requires a DC power supply and an IR camera with a spectral range between 8-14 μm. Compared to other techniques with the same purpose, IR-T stands out due to the possibility of its application in large-scale photovoltaic arrays. The method is based on collecting temperature data and recording the spatial distribution of the temperature of the PV module during operation. With the assistance of the thermal camera, the IR radiations emitted from objects with different temperatures can be distinguished. Then, on the display of the device, one can visualize the profile of the temperature distribution of an object versus the levels of IR emission. For the data illustration, a red-to-blue color scale corresponding in high to low temperatures, is selected. Solar cells or modules that exhibit temperature anomalies need further investigation. During PV operation, a localized heating increase is mainly caused by current runaway and broken or loosened contacts. Bright spots on the screen of the thermal camera, which correspond to high-temperature regions, indicate precisely the locations in which a growth of heating is taking place. According to [123], the performance of the IR-T can be conducted in two ways; a thorough inspection and a simplified inspection. The first one refers to a detailed quantitative examination of the module by measuring its absolute temperature. The second one describes a qualitative assessment of the module, detecting disturbed heat patterns that

indicate underlying defects. Nowadays, the defect detection investigation of PV modules is conducted via the integration of thermographic image sensors over drones in terms of deep learning convolutional networks [124].

- Luminescence techniques

The term "luminescence radiation" has been introduced to describe light emitted by radiative recombination of charge carriers in semiconducting materials. It can be initiated externally and gathered in order to depict the conductive characteristics of the solar cells. The emission of Si takes place at 1140 nm, which corresponds to the short-wave infrared region of the electromagnetic spectrum. Fast imaging requires short time frames of exposure and is based on a camera with a sensor made of Indium–Gallium–Arsenide. The combination of these materials demonstrates enhanced quantum efficiency in the aforementioned spectrum. Due to the increased luminescence intensity with the cell voltage, construction industries focus their interest on larger cell voltages, e.g., Si-based heterojunction PV modules. The techniques used to trigger luminescence radiation can be divided into two categories: electroluminescence (EL) and photoluminescence (PL).

-Electroluminescence (EL). In this method, the luminescence signal is stimulated externally by a DC power source. The induced current activates increased recombination, and, therefore, photons with the band gap energy are emitted. The technique can be applied in both laboratory conditions and in a dark outdoor environment on single modules [125]. Using a high-resolution camera, a precise and thorough scan of the solar cells can be conducted. The capture of an EL image provides information and a quantitative explanation of several cell properties, including shunt and series resistance, diffusion length, and minority carrier lifespan. Besides this, a qualitative examination of an EL image intends to detect easily recognizable signs of possible degradation processes and aging effects in PV modules, which could, in the immediate future, question the durability and reliability of the module [126]. For example, the observed dark lines in an EL image correspond to crystallographic defects in multi-crystalline solar cells. Furthermore, EL imaging can accurately identify cracked cells, hot spots, and shunts in c-Si cells, and corrosion and delamination signatures in thin-film solar cells. Given that the appearance of PID in a PV module is connected to reduced performance and power losses, EL imaging is widely applied to evaluate the severity of PID as a degradation mechanism. The potential difference between the electrodes of the front and the back sides of the PV module can induce a flowing electrical current. This current, in turn, modifies the light emission pattern that characterizes the module. The detailed analysis of EL images taken from the PV module can reveal the existence of PID at an early stage. Last but not least, EL imaging outperforms IR imaging in the sector of unraveling the differences between the increased Rs and the reduced Rsh. The utilization of EL imaging is growing at a rapid pace as solar energy attracts more and more interest.

-Daylight photoluminescence (dPL). The main difference between EL and PL is the method of activation of the luminescence signal. During the manufacturing process of solar cells, typical PL procedures include external illumination of the cells by man-made, homogeneous light sources. Nowadays, daylight has prevailed as the stimulation source for the PL technique [127]. In order to isolate the luminescence signal, which is weak compared to the intense sunlight, images from two separate operation points of the PV module need to be acquired. The first image is captured at open circuit voltage and gathers the luminescence signal. The second image is recorded at a high current state, for instance, at maximum power and does not carry a luminescence signal, as the carriers recombine or create the current. By direct comparison of the two images, sun radiation is excluded, and the luminescence signal is highlighted [128]. Due to the faint final signal, the signal-to-noise ratio grows by averaging over multiple PL pictures. The alternate between the working points can take place in various ways. Koester et al. [129], in their recent work, used existing field electrical devices for unhampered switches between the operating points. Despite being in a primary stage of development, EL exhibits a series of

advantages; it can utilize PL during the day without interrupting the electrical circuit and does not require a power supply to power backward entire PV arrays. Daylight PL can identify cell cracks and monitor material characteristics, while it is also useful for the detection of open circuit faults in bypass diodes and the evaluation of the I-V curves of single solar cells.

- Inspection of disconnection in cell interconnection

  This method [130] is widely used as a means of evaluating the condition and effectiveness of the interconnection between PV modules and/or solar cells. Its application requires an interconnect breakage tester, which can detect possible breakages in the interconnection system. This device can identify interconnection damages and faults, which can cause efficiency problems in the PV modules.

- Insulation Testing

  Insulation testing [130] is a technique used to examine the condition of insulation materials, which are integrated with the electrical components of a PV module. The method requires an insulation resistance tester, which evaluates the effectiveness of the insulation. This device can detect potential insulation faults and defects in connections and wiring, which can induce safety issues and electrical faults.