Literature Study and Risk Analysis for Potential Induced Degradation

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ABSTRACT

In recent years, an increasing number of photovoltaic (PV) modules have been serially connected in PV systems, resulting in higher-voltage arrays. PV systems of 600 V had been the most common in the United States, but currently, systems operating at dc voltages of 600–2000 V are being installed. The resulting higher electrical potential relative to ground leads to a class of degradation mechanisms known as *potential induced degradation* (PID). PID has been observed to reduce a PV module's output power by 20–80%. For example, a study on a PV plant in Spain found output power reduction of 40% in series-connected PV strings. If undetected, PID can reduce the performance of PV power plants significantly and consequently lower the system's rate of return and profitability.

This report is a literature review of PID and the risks and costs associated with this failure mechanism. It gives an overview of what is currently known about PID and the consequences for a commercial PV installation. The factors causing PID, the mechanisms involved, detection of PID, and prevention are reviewed. The impact on a typical installation is considered, and an assessment of the revenue risk is included.

Keywords
Photovoltaic (PV) durability
Potential induced degradation (PID)
PV life cycle analysis
PV module degradation
PV reliability
PV system voltage

EXECUTIVE SUMMARY

This report presents a literature review on the phenomenon of potential induced degradation (PID), an issue of rising concern in the photovoltaic (PV) industry and one becoming more prominent as the industry moves toward high-voltage systems (up to 2-kW dc). PID can range from mild degradation affecting a few modules to severe PID that can significantly reduce the overall performance of the PV system. To ensure the profitability and durability of PV systems, PID must be mitigated.

The issue of stress induced by high voltage was first identified by Hoffman and Ross in 1978 as a part of tests for PV module qualification at the Jet Propulsion Laboratory [1]. More recent cases of PID include the polarization and high-voltage stress effects in solar panels that were identified by the National Renewable Energy Laboratory (NREL).The issue has not been addressed by module qualification standards such as IEC 61215 and IEC 61646, which do not test a module's durability and stability under conditions of high-voltage bias. This has resulted in significant module failure, degradation, and power loss due to PID. PID has been observed by various module manufacturers and has been observed in amorphous silicon modules at the Florida Solar Energy Center (FSEC) and in multicrystalline modules by FSEC, SOLON Corporation, and NREL [2]. To ensure system durability and performance over a module's lifetime, the causes of PID and the various mechanisms involved must be understood, and methods and stress tests to assess a module's susceptibility to PID must be designed.

The primary cause of PID in the field is high potential on a system relative to ground that results in various degradation-causing mechanisms in the PV modules. The main factors facilitating PID in modules susceptible to degradation are the environmental factors of high temperature and humidity. High relative humidity is a major contributor to PID in high-voltage systems because it induces significant leakage currents in PV panels that reduce their performance. Location and the corresponding environmental factors play an important role in determining if the system would be susceptible to PID, but PID can also be attributed to other influences at the panel and cell levels. On the panel level, the design and materials used can contribute to PID significantly. The main factors contributing to PID are the encapsulant material and the front cover—the sodium from the glass front sheet used in most commercial modules facilitates the conduction of leakage current. At the cell level, the antireflection coating (ARC) would be the main factor affecting PID because it can result in accumulation of sodium ions, which needs to be avoided.

The two main mechanisms of PID are polarization and electrochemical reactions. Most cases of PID in crystalline silicon modules have been the result of polarization. This polarization is a reversible mechanism caused by the migration and accumulation of charged ions in the encapsulant due to high leakage currents. This results in creation of shunts that reduce the system's output power. Shunting is mainly attributed to sodium ions in the glass that can migrate easily from the glass to the cell surface in the presence of moisture and a negative electric field and that are facilitated by ethylene vinyl acetate degradation. PID can also be caused by electrochemical reactions that result in the corrosion of the encapsulant or transparent conductive oxide, an irreversible process.

The literature review also presents a study on various methods and techniques being used to detect PID in the lab and field. PID effects have been replicated by many organizations—such as Fraunhofer Institute for Solar Energy Systems, Photovoltaik-Institut (PI) Berlin, NREL, and TUV Rheinland—that have developed testing procedures to determine modules' susceptibilities to PID in the field. Various round-robin tests have led to the development of the International Electrotechnical Commission's (IEC's) 62804 standard, which is still in draft stage. IEC 62804 aims to provide a standard qualification testing procedure and proposes testing conditions of 60°C temperature, 85% relative humidity, and a nameplate voltage bias for 96 hours in an environmental chamber to determine a module's susceptibility to PID. PID in modules is detected mainly by conducting electroluminescence imaging and lock-in thermography, though various other methods can be used.

One issue reviewed in this report is the effect of PID on PV systems' durability, their operations, and revenue. PID can affect a system at any point during its life cycle and can take a few months to several years to be detected. The time-scale for PID to occur is not known accurately because the effect has been observed only in the past decade, and the susceptibility to PID varies across PV systems. PID has been observed within the first two years of installation in some cases, whereas other large-scale PV systems have not been affected over their entire life. Hence, further research is required to accurately predict the period in which PID will occur in PV systems.

It has been observed that the likelihood of PID increases with system voltage. PID may not affect an entire system uniformly, and some modules might undergo severe degradation while others remain unaffected. PID can reduce a module's yield by 20–80%. In this case, the overall system performance would not be affected by a few modules with PID. However, if many modules or strings of modules experience PID, overall yield losses can range from 20% to 80%. Moreover, the inverter's losses might also increase because the PV strings' maximum voltage might fall out of the inverter's maximum voltage range. A case was reported where the electricity yield of solar panels reduced by 80% within the first two years as a result of PID. Therefore, if PID is not detected and corrected, it can impact the operations and financing of PV plants adversely.

A study by PI Berlin on a 10.7-MW plant in Spain revealed maximum power point loss of 41% on average in the strings of the system. Such high losses at the string level will reduce the overall performance of the system drastically. Lower output will consequently result in lower revenue generation and a longer payback period. This is a cause of great concern to PV plant owners and investors because an unforeseen reduction in the annual yield due to PID can drastically affect the overall profitability of the system and its return on investment. However, the actual impact of performance losses from PID on the profitability and return on investment is yet to be determined because there are insufficient reliable data quantifying the effect of PID on a system's operation and finances.

Finally, a literature review of various techniques to mitigate and prevent PID was performed. PID can be prevented at the system level by grounding the negative pole of the system.

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1 INTRODUCTION TO POTENTIAL INDUCED DEGRADATION

Potential induced degradation (PID) is a mode of degradation in solar cells occurring at high voltages, that is, a large potential of the system relative to the ground. The degree of PID is dependent on both the polarity and magnitude of the voltage. PID usually occurs under conditions of high voltage, temperature, and humidity and can reduce the performance of solar modules significantly [1].

The issue of stress induced by high voltage was first identified by Hoffman and Ross in 1978 as a part of tests for photovoltaic (PV) module qualification at the Jet Propulsion Laboratory (JPL) [2]. More recent cases of PID are SunPower's polarization effect and the high-voltage stress effect in solar panels that were identified by the National Renewable Energy Laboratory (NREL). However, the issue has not been addressed by the module qualification standards, such as International Electrotechnical Commission's (IEC's) 61215 and 61646, which do not test a module's durability and stability under conditions of high voltage bias. This has resulted in significant module failure, degradation, and power loss from PID. PID has been observed by various module manufacturers and has been observed in amorphous silicon modules at the Florida Solar Energy Center (FSEC) and in multicrystalline modules by FSEC, SOLON Corporation, and NREL [2]. In order to ensure system durability and performance over a module's lifetime, the cause for PID and the various mechanisms involved must be understood, and methods and stress tests to assess a module's susceptibility to PID must be designed.

Causes of PID

PID occurs when a large voltage bias results in a leakage current (due to ionic charges) that migrates between the cell and the other components, such as the glass, mount, or frame, resulting in reduced power output [1]. There are three main paths by which the leakage current travels from the ground to the solar cell, depending on the composition of the panels. The current can be between the module front cover, which is usually glass, and the solar cell. It can also be between the frame and the cell through the encapsulating material, which is facilitated by the presence of humidity. The third mode of leakage current would be through the back cover of the module to the cell. These have been illustrated in Figure 1-1.

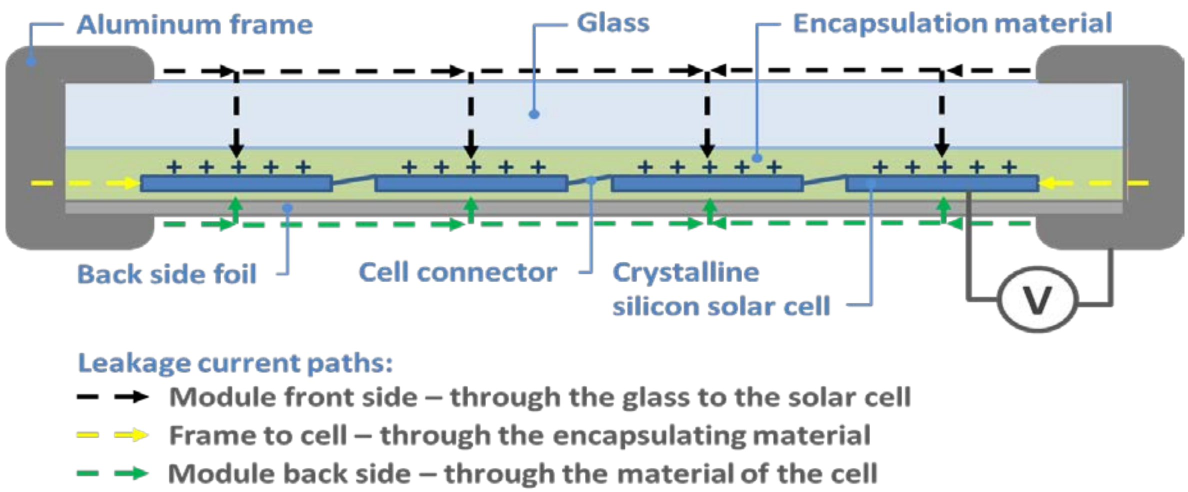

Figure 1-1
Leakage current paths in solar cells based on figure given in [4]

Various factors contribute to PID. These can be classified as environmental, system-level, panel-level, and cell-level factors. Each of these classifications is explored in the following.

Environmental Factors: Temperature and Humidity

The two main environmental factors that contribute to PID are high temperature and humidity. Conditions of elevated temperatures in combination with high relative humidity (RH) increase the leakage current between the solar cell and the ground. At high humidity, water penetrating into the solar panel increases the conductivity of the encapsulant, thereby increasing the leakage current, which reduces the module's performance [5].

Research conducted at the Fraunhofer Institute for Solar Energy Systems (ISE) in Germany and the Institute for Technology in Spain to determine the effect of temperature and humidity on PID found that humidity increases leakage current significantly [6]. The study found that leakage current exhibits ohmic behavior with respect to voltage variations. The leakage current also varied with temperature and followed an Arrhenius relation with activation energy of 75 kJ/mol. It showed considerable dependence on humidity, and the relation was modeled using a sigmoidal growth function that showed that the current grows significantly with increase in RH beyond 60%, as shown in Figure 1-2. In addition, outdoor testing showed that though leakage current increased with high RH, high temperatures reduced the RH on the surface of the panels, thereby reducing leakage current. However, there was a significant increase in leakage current on rainy days, which shows a high correlation between high RH and leakage current. This study also concluded that leakage current was a strong indicator of PID but that other factors need to be investigated.

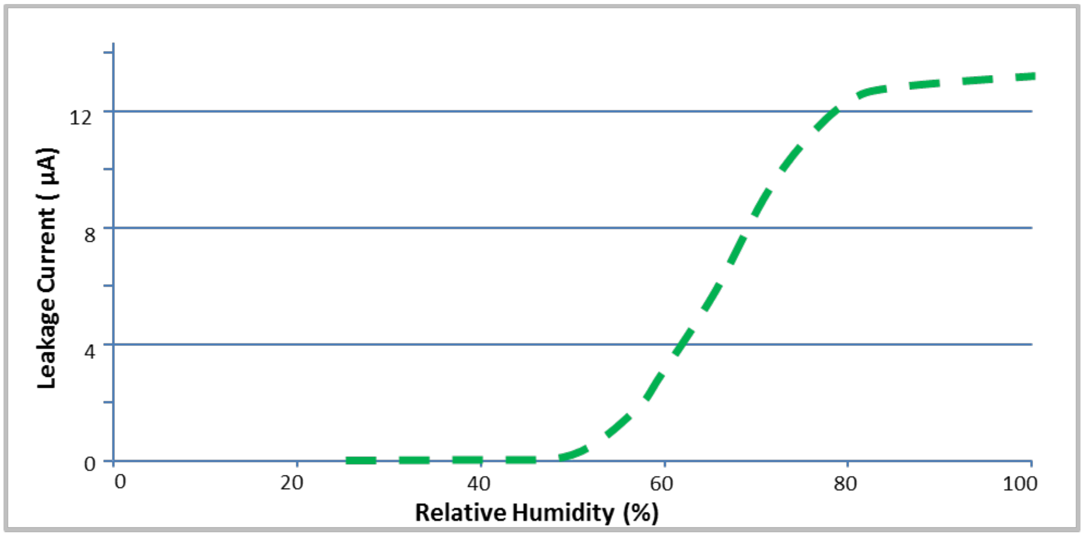

Figure 1-2
Plot showing the dependence of leakage current on relative humidity at 85°C and -300V bias, based on the image in [6]

Because leakage current is one of the crucial factors resulting in degradation, it is necessary to understand the mechanisms that facilitate it so that they can be addressed to reduce PID. The type of encapsulant used as well as the materials used for back sheet, front sheet, and the frame affect the paths for leakage current; thus, the design of the cell and panels plays a crucial role in avoiding PID. This will be covered in detail in the following section.

System-Level Factors: Voltage

One of the most important causes of PID is a large potential difference between the ground and the cells. The standard dc voltage for installed PV systems in the United States used to be 600 V as stated by the National Electrical Code (NEC). However, there has been an increase in PV systems that are being installed at voltages of 1000 V and higher, up to 2000V [7]. Several companies are partnering to launch a 1500-V utility-scale PV power plant [8] as there is a shift towards 1000-V and higher-voltage PV power plants. Systems of 1000 V have been commonly used in Europe but are becoming increasingly prevalent in the United States, too; it is one of the important changes in the NEC 2014. The 2014 version of the NEC code has revised the threshold voltage for high-voltage systems in Article 490 from 600 V to 1000 V [9]. Consequently, such high-voltage systems that are being deployed now have resulted in a high potential difference between the PV system and the ground, which has led to increasing occurrence of PID.

The potential of the cells with respect to the ground can be positive or negative if one of the poles is grounded. However, if none of the poles is grounded, the two different parts of the string have opposite potentials toward the ground. This is called *floating potential* [5]. The magnitude of the voltage depends on the number of panels connected in series as well as the total incident irradiation with higher voltages increasing the probability of PID occurrence.

Panel-Level Factors: Encapsulant Material and Module Design

The encapsulant material is the most important factor at the panel level, which contributes to PID in PV modules. A study [5] comparing three different encapsulant materials showed that one of them resulted in drastically high PID compared to the other two. Experiments conducted at Photovoltaik-Institut (PI) Berlin's lab compared three different encapsulant materials under the standard damp-heat conditions (85% RH, 85°C) required by IEC 61215. Initial results showed that EVA (ethylene vinyl acetate) and PVB (polyvinyl butyral) exhibited polarization effects as the output power decreased by more than 90%, whereas silicone did not exhibit PID. However, even silicone displayed reduced performance, with a 90% reduction in power output after 240 hours of testing [10]. This experiment revealed that EVA, which is widely used in the solar industry today, can be highly susceptible to degradation. Hence, appropriate encapsulation materials causing less leakage current should be used on the panel level to reduce the effect of PID. Though alternative materials that do not affect PID are available, there is a tradeoff in terms of cost, overall performance, and stability. Thus, a better approach would be to optimize the cell design to reduce PID, as explained in the next section.

In addition to the encapsulant, the glass front sheet plays a significant role in causing PID because the sodium ions from the soda lime glass support conducting the leakage current, and further studies revealed that any ions would increase conductivity of leakage current [11]. Soda lime glass is a commonly used front sheet cover in solar cells, and the sodium ions from the glass migrate through the encapsulant and accumulate in the antireflective coating (ARC) or the transparent conductive oxide in the case of amorphous silicon cells. Besides sodium, other metal ions that are present in the glass also migrate toward the surface of the cell under an applied voltage [3]. Hence, new types of glass technologies are being developed that aim to minimize leakage current and prevent PID. However, it is the combination of glass front sheet, encapsulant, back sheet, and foil that creates paths for leakage current to flow between the ground and the solar cells, as depicted in Figure 1-1. An extensive study showed that the commonly used combination of soda lime glass, EVA encapsulant, and ARC in photovoltaic modules results in PID.

Cell-Level Factors: ARC, Emitter Sheet Resistance, and Type of Base Doping

The main factors affecting PID on the cell level are the chemical nature of the ARC used and the types of base doping and emitter doping [12]. For PID in back contact cells, the ARC was found to play an important role. Experiments conducted at the labs of PI Berlin to determine if silicon nitride (SiN) antireflective coating played a role in PID revealed that cells with the silicon nitride ARC showed considerable degradation after being tested for only 48 hours at 85°C and 20% relative humidity, whereas samples without an SiN ARC did not exhibit PID even after 48 hours [10]. This PID effect was also observed in conjunction with a higher concentration of sodium ions on the cell, but further investigation is required to determine how the SiN ARC promotes PID. Most silicon solar cells are coated with an ARC of SiN, and it was observed that PID might be affected by the relative composition of the coating as well as its thickness. Research [5] indicated that a higher ratio of nitrogen to silicon in the SiN coating was associated with higher PID. Moreover, a thicker coating was also associated with higher PID sensitivity. Hence, higher Si/N ratio ARCs with reduced thickness would facilitate PID mitigation.

The other factors analyzed were base doping and emitter sheet resistance. It was observed by comparing wafers with different base doping that higher base resistivity was associated with lower PID effects. It was also observed that emitters with higher sheet resistance had higher sensitivity toward degradation [4]. This is one explanation for PID in solar cells in recent years because methods to optimize cell processes have used higher emitter sheet resistances, which increase a cell's susceptibility to PID. Figure 1-3 shows the effect of emitter diffusion in the silicon wafer on PID, and it can be observed that increasing the sheet resistance increases the sensitivity of the cell to PID [4]. Moreover, some manufacturers perform edge isolation by emitter back etching, which results in localized high sheet resistance and can result in degradation when a large potential is applied.

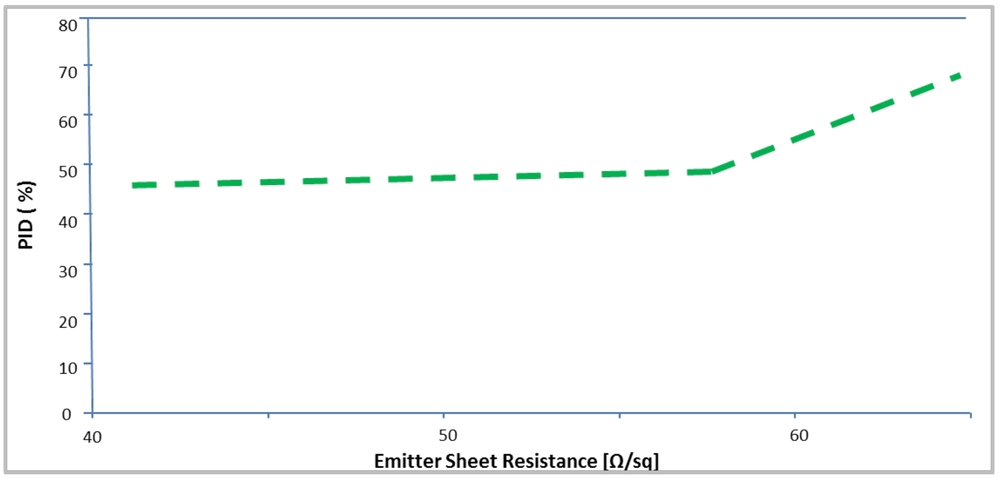

Figure 1-3
Dependence of emitter sheet resistance on PID based on figure given in [5]

One of the main causes for PID is hypothesized to be the migration of sodium ions from the glass front sheet to stacking faults in the emitter region, which will be further explored in the next section. Various methods can be employed to prevent the sodium ions from reaching the emitter of the cell, such as increasing the emitter depth. However, this would increase production costs and decrease the efficiency of the cells [13]. Hence, there is a greater focus on improving the ARC properties of solar cells to reduce the occurrence of PID.

2 PID MECHANISMS

Studies [14], [3] have determined two main failure mechanisms that result in PID—polarization and electrochemical reactions. The process of polarization occurs as a result of charge accumulation in the encapsulant (caused by the leakage current), which degrades cell performance by reducing the parallel resistance and the fill factor. As covered previously, the leakage current depends on the environmental temperature and RH. This process is reversible and does not affect the cell as severely if the stress is applied intermittently, in which case the cell has time to recover. However, the application of constant voltage bias, along with stress and humidity, can damage the cell.

The other failure mechanism is an electrochemical reaction occurring in the cell and is irreversible [14]. The application of a voltage potential can result in a chemical reaction that results in the degradation of the encapsulant, ARC, and the solar cell. In this process, the applied voltage causes the flow of current between the cell and the frame, which are analogous to the anode and cathode in an electrochemical cell, with the humidity acting as the electrolyte, thereby causing electrolytic corrosion.

Polarization

This effect was observed by SunPower in their back contact cells with n-type base doping and p-type emitter doping. With this failure mechanism, the leakage current causes ions from the front glass to migrate through the encapsulant to accumulate as trapped charges over the solar cell. These charges can also cause delamination of the cell. Modules fabricated using materials such as quartz showed very little leakage current and no degradation when subjected to tests with high voltage bias. Polarization effects have been observed in crystalline silicon technology; Solon SE demonstrated the occurrence of PID in mono- and polycrystalline modules. Moreover, research conducted by PI Berlin also showed polarization in CIGS modules [10].

Electrochemical Reaction

An electrochemical reaction occurs when the sodium ions from the glass migrate into the transparent conductive oxide, owing to a negative potential set up in the cell with respect to the ground. In this mechanism, the modules act as an electrolytic cell, with the active cell and the frames acting as the anode and cathode, respectively. The water vapor present due to humid conditions forms the electrolyte solutions, enabling the transfer of ions and leading to degradation of the cell material [14]. The potential relative to the ground enables a reaction in the modules, which results in electrolytic corrosion and degradation of materials, such as the ARC, EVA, or the active solar cell.

Most crystalline silicon cells undergo degradation by polarization caused by the migration of sodium ions from the glass to the cell surface, which results in shunting and reduced module performance. The main PID mechanisms observed in crystalline silicon cells and thin film cells are described in the following sections.

PID in Crystalline Silicon Cells

The exact PID mechanisms are still not entirely known, although research [11] has revealed that a combination of sodium ions from soda lime glass (front cover) along with EVA (encapsulant) and SiN or other antireflective coatings are necessary for PID to occur. All of these elements form the basic components of most solar cells today.

There are two main mechanisms that can occur during the migration of ions from the encapsulant to the cell surface. The charged ions reaching the cell surface can accumulate there and contribute to an electric field that would negate the passivation provided by the ARC, thereby increasing surface recombination. The ions can also diffuse into the silicon and increase the concentration of sodium ions in the emitter, resulting in inversion of the n+ emitter region [10]. Standard multicrystalline silicon solar cells were investigated to reveal that PID is associated with the formation of microscopic ohmic shunts that cause the emitter to invert [11]. A single multicrystalline silicon cell was used for testing, and it was covered with a metal foil to ground the frame and cause PID by leaving a small portion uncovered. The cell was exposed to -600 V bias under conditions of 85% RH and 85°C to induce PID. During the process, it was found that the measured parallel resistance decreased drastically, thereby decreasing the cell performance.

In order to investigate the underlying cause, electron beam–induced current (EBIC) measurements were performed, which revealed the formation of various microscopic shunts. One model proposed that the sodium ions migrated from the glass toward the ARC on the application of the potential, leading to a leakage current. These positively charged sodium ions (Na+) create a corresponding layer of negatively charged ions, and if the field of the charge double layer is strong enough, it would result in the inversion of the n+ emitter region. Thus, the cell is shunted because the current can flow directly to the p-base through the tunnel junctions created [11]. Hence, the PID observed in crystalline solar cells is due to the formation of these microscopic shunts, as proposed by this model. However, PID mechanisms are still undergoing further investigation.

PID in Thin-Film PV Modules

Similar to PID in crystalline silicon cells, thin-film amorphous silicon solar cells showed degradation of performance when an electric field was applied due to the corrosion and metal ion migration between the cell and the frame of the module. In the case of thin films, those using a sodium-containing substrate, such as soda lime glass, showed significant degradation when subjected to PID inducing tests. A study [15] compared samples with different Na content under PID test conditions of 85°C with an applied bias of 50 V. After 50 hours of testing, samples with high Na content showed significant degradation; however, the Na-free sample and the ones with low Na content did not undergo any degradation. The degradation was also associated with appreciable Na accumulation in the CIGS and CdS layers of the samples, which exhibited high degradation. However, on measuring the samples six months after the test, it was observed that the efficiency of the samples—which had dropped to nearly 0% after PID testing—recovered to 14%. This indicates that the degradation is reversible to some extent. Therefore, the test shows that PID is largely due to the migration of Na ions from the substrate into the cell, and PID can be mitigated by using glass with very low Na content or high resistivity [15].

3

DETECTING PID IN THE LABORATORY AND FIELD

Numerous tests and methods have been developed to detect PID in the laboratory and in the field. PID can take place over a long period; thus, accelerated tests in the laboratory have been developed that aim to reproduce the outdoor conditions that cause field failures. However, it is hard to establish a correlation between the time over which failure occurs in the field and module degradation under accelerated lifetime testing [16]. The main stress factors that act on the modules in the field and which need to be replicated are those of high system voltage, temperature, and humidity.

There are two main approaches being employed in the industry at present to replicate PID in the laboratory. One method uses an environmental chamber with high RH and temperature settings and an applied voltage bias to induce PID. The other method is to cover the front side of the modules in a conductive foil (such as aluminum foil) before applying the bias.

Various indoor and outdoor test results [3], [16] have indicated that the applied voltage should be the nameplate voltage because it is the voltage that a module experiences in the field. Most modules that are susceptible to PID show degradation within 100 hours of voltage application. The modules are usually placed in saline water baths and tested under humid conditions in an environmental chamber, or a conductive material is applied to ground the module properly. Preliminary experiments used a temperature of 85°C with 85% RH, the same conditions as the IEC 61215 damp-heat test. JPL had previously shown that factors associated with PID, such as encapsulant conductivity and leakage current, increase with RH and temperature [3]. These conditions vary from those observed in the field because the humidity on the outer surface of the modules changes with varying weather conditions, but the internal humidity changes very slowly in well-packaged modules. Modules in the field are often subjected to RH greater than 85% along with periods of dryness.

Humidity is the most important factor in inducing PID in modules because leakage current and conductivity of glass increase with humidity up to 100%, which the modules do experience due to rain and snow. However, 100% RH is not used in lab tests due to limitations on using the environmental chamber, which could cause uneven condensation and induce higher stress in modules. Hence, 85% RH has been selected as the standard level for indoor lab testing [3].

On the contrary, research has shown that high temperatures increase the hydrolytic degradation of the modules and the water content, whereas in the field, this does not occur because the module dries under the sun and the humidity within the packaging is lowered. Hence, a standard temperature to maintain the humidity required for PID still needs to be determined. Different organizations have used different temperature conditions for testing the modules for PID. For instance, NREL carried out acceleration testing in their environmental chamber at temperatures of 50°C, 60°C, and 85°C [16], though others have conducted PID tests at temperatures ranging from 25°C to 85°C [3]. Further investigation is required to determine a standard temperature or range of temperatures for PID testing in laboratories.

Various tests conducted as a part of round-robin testing during the drafting of IEC 62804 revealed the need to lower the chamber temperature from 85°C. This was because the modules showed series resistance losses at high temperatures coupled with high humidity due to corrosion, which would not be representative of field conditions [17]. Moreover, it was shown that testing at 85°C, 85% RH, and -1000 V resulted in irrecoverable degradation within 44 hours, whereas the PID occurring in the field is recoverable in most cases. Hence, the necessity to reproduce outside conditions within the chamber led to lowering the test temperature to 60°C.

The IEC 62804 draft is being designed for qualification testing of system voltage durability of crystalline silicon modules [18]. According to IEC 62804, voltage durability tests are conducted in an environmental chamber at 60°C ±2°C temperature and 85% ±5% RH conditions with a voltage bias of -1000 V or the nameplate rated voltage if different, over a period of 96 hours. This test was designed to give a pass/fail criterion as to whether modules will experience PID in the field. After performing the test, the modules' power would be measured along with electroluminescence imaging and visual inspection. A module fails the test if power degradation is more than 5%.

One other method for creating high voltage conditions in PV modules is to cover the front side of the modules in a conductive foil (such as aluminum foil) and apply a potential between the cells and the module frame [19]. In this case, the voltage bias is applied uniformly across the entire front of the module and, therefore, applies the same potential to each cell. Such a setup is representative of outdoor conditions, such as during rainfall or early in the morning, when there is dew on the modules. By contrast, the environmental chamber method is representative of highly humid environments.

Various studies using different modules in varying locations have reported different results in terms of the time-scale for PID to occur as well as the PID pattern observed. Hence, depending on the environmental conditions and locations, the appropriate test should be used. Most of the modules showing PID in the field show degraded cells near the frame, which is similar to the results obtained when the modules are tested in an environmental chamber. Therefore, this test approach may be more representative of what occurs in the field [19]. However, modules in marine environments would be better represented by the aluminum foil test. A study by UL International, Germany, also suggests using the aluminum foil tests for crystalline silicon modules and the environmental chamber test for thin-film modules [19].

These tests are being used to replicate PID inducing conditions in the lab to test modules for their susceptibility to PID. PID is detected in the lab and the field by using various detection techniques. These are the topic of the next section.

Techniques for PID Detection

PID has been detected in labs using various characterization techniques to detect degradation in the modules by analyzing the optical, electrical, and material properties. Techniques used for PID detection include electroluminescence imaging, current-voltage (I-V) testing, lock-in thermography (LIT), time-of-flight secondary ion mass spectroscopy (ToF-SIMS), secondary electron microscopy (SEM), and light beam induced current (LBIC). However, the most common methods for solar cell are electroluminescence, LIT, and LBIC. Meanwhile, ToF-SIMS and SEM are mostly used for characterization of the semiconductor material.

Electroluminescence Imaging

Electroluminescence is a technique used to characterize solar modules by applying a forward bias to inject excess carriers into the cell, which results in a unique emission spectrum. These carriers have different concentrations in different regions, depending on the presence and type of defects [20]. The cells emit infrared light under the applied forward bias, which is captured using a silicon-charge-coupled device (Si-CCD) camera. The image thus obtained shows the distribution of the minority carriers [21]. Light areas show regions with high concentration of high lifetime minority carriers, whereas darker areas illustrate the presence of defects. A PID-free module would produce an electroluminescence image with uniform cell brightness, whereas modules affected by PID would have dark cells. Electroluminescence is widely used in the characterization of solar cells because it is nondestructive and efficient and provides information on series and shunt resistances. Figure 3-1 shows the pre-PID and post-PID test images of two modules tested as part of the round-robin in 2011 to establish a standard for PID testing. As can be observed from the images, both modules have been affected by PID, although the degradation is more severe in module 1 because there are more dark areas as compared to module 2. There was a 50% and 11% reduction in the output powers of module 1 and 2, respectively, after being subjected to PID tests [22]. It is difficult to differentiate between the optical, electrical, and resistive effects [23] and further tests need to be conducted to determine failure mechanisms.

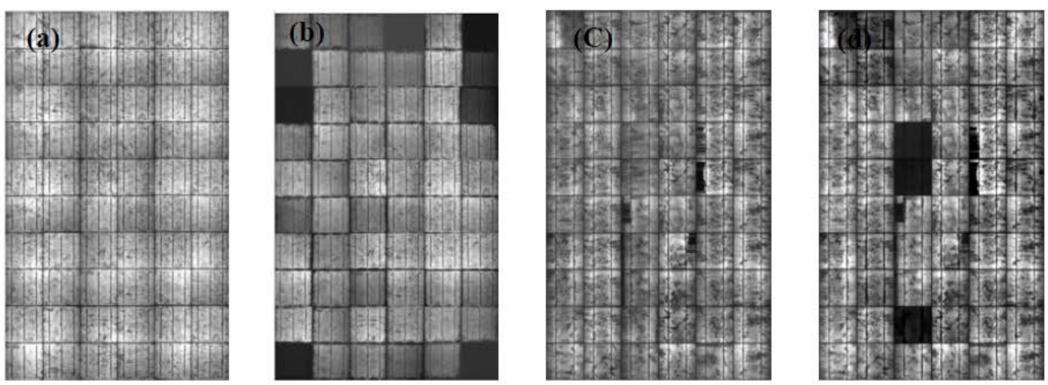

Figure 3-1
Solar modules showing electroluminescence images (a) before PID testing for module 1, (b) after PID testing for module 1, (c) before PID testing for module 2, and (d) after PID testing for module 2 [22]. Reprinted with permission from [22].

I-V Tests

I-V measurements are the typical characterization technique used by the industry to determine module performance. Deviation in the shape of the I-V curve can indicate the presence of PID. There are other factors that can influence an I-V curve. Research has shown that PID has a bigger impact on module efficiency under low irradiation conditions. Hence, dark I-V tests are used to detect PID in solar modules [24].

LIT/Infrared Thermography

LIT is a method that maps the leakage current of a cell. The technique analyzes dynamic temperature changes due to modulating thermal waves, and hence it is also called *thermal wave imaging*. The main principle of LIT is based on applying oscillating energy waves to an object, resulting in an interference pattern in the local surface temperature that is averaged and evaluated to determine the internal structure of the object [25]. The input wave is amplitude-modulated with a particular frequency called the *lock-in frequency* because the main aim of this technique is to extract signals from statistical noise and evaluate the oscillating ac in the detected signal [25]. The averaging nature of this technique, along with the use of a unique lock-in frequency, improves the sensitivity of the camera significantly. Lower lock-in frequencies are preferred because they sample a greater depth. Moreover, the high sensitivity of the camera results in accurate detection of small changes in the infrared radiation and is used to detect shunting in areas with large currents or determine the electron concentration by analyzing the infrared energy emitted or absorbed by the electrons [26].

LIT is a technique for nondestructive testing of electronic devices and performing failure analysis. Research conducted at a Max Planck Institute [27] indicates that LIT can be used for failure analysis in solar cells. Various defects that occur in the cell—such as cracks and scratches—lead to leakage currents and result in shunting. Because the excess currents at these sites generate more heat, they can be detected thermographically using LIT.

LIT can be categorized as illuminated LIT and dark LIT [28]. The experimental setup for LIT is shown in Figure 3-2.

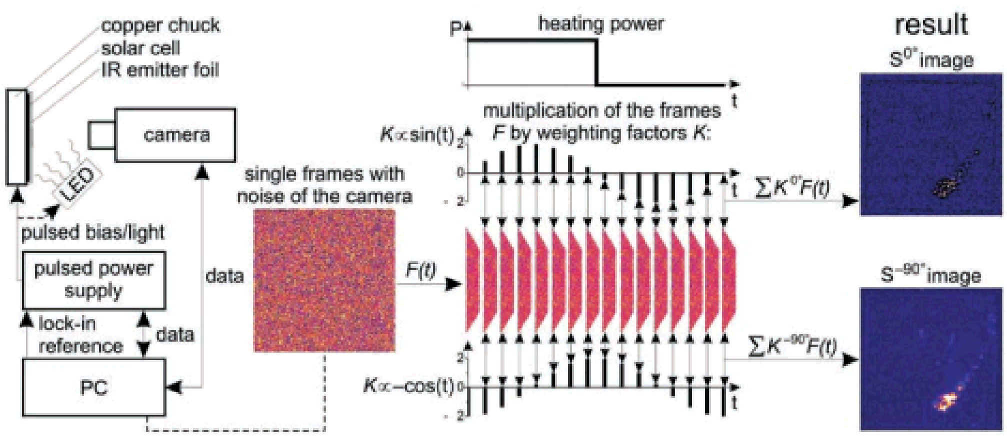

Figure 3-2
Measurement setup for lock-in thermography [27]. Reprinted with permission.

Dark LIT is the method of applying pulsed voltage to the solar cells at a lock-in frequency, without any illumination. This results in the flow of a dark current that causes heating at the shunts. This method is useful for detecting different types of shunts as well as differentiating between linear and nonlinear shunts.

Illuminated LIT is the method where pulsed light is used to illuminate the solar cells, as shown in Figure 3-3. This is a noncontact LIT technique, and the cell is under open-circuit voltage conditions. This method is used for detecting nonlinear shunts.

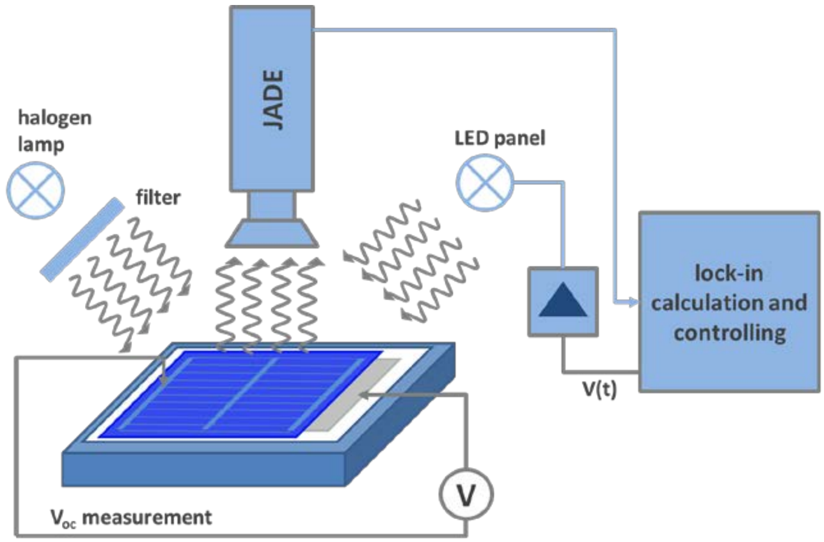

Figure 3-3
Illuminated LIT test method based on the test set-up used in [29]

Secondary Ion Mass Spectrometry

SIMS is used in the semiconductor industry for molecular and elemental analysis because it can detect dopants and impurities even at low concentrations [30]. The common SIMS techniques include Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS), Dynamic Secondary Ion Mass Spectroscopy (D-SIMS), and Distance-of-Flight Mass Spectrometry (DoFMS). The SIMS technique has high specificity and sensitivity and provides detailed characterization of solar cells at a length scale of 1 nm or less. It is especially used for thin-film PV [31].

ToF-SIMS is used for tracing molecular analysis and detecting elements below the parts-per-million level [32] and has been used in both thin films and crystalline silicon solar cells. The principle of this technique is to use pulsed primary ion beams to desorb and ionize molecules that are then accelerated into a mass spectrometer, where their time-of-flight measurements are used for analyzing the mass [33]. The technique is capable of three-dimensional (3-D) analysis. Resolution (M/ΔM) of this technique is greater than 10,000 [31]. However, SIMS is a costly technique, requires ultrahigh vacuum (UHV) conditions, and the measurement time is considerably longer than other techniques such as EL or LIT.

ToF-SIMS has been used by Fraunhofer Center for Silicon Photovoltaics (CSP) to determine the cause of PID in crystalline silicon solar cells through depth profiling. Sodium ions are considered to play an important role in PID; this was also proven by using ToF-SIMS to detect significant concentrations of Na ions in the silicon nitride and silicon interface in cells exhibiting PID [34].

Light Beam–Induced Current

Beam-induced current is a microscopy technique used to detect defects in solar cells and consists of two techniques—electron beam–induced current and LBIC. The basic principle of the LBIC method is to measure the nonuniformities of a solar cell through a point-by-point scanning process across the cell surface using laser light microscopy. This technique detects defects due to the influence of short circuit current and quantum energy. The LBIC system as shown in Figure 3-4 takes a measurement in a specific position before moving to the next point [35]. A drawback of the LBIC method is that it takes longer than other techniques, such as electroluminescence or LIT. The LBIC measurement is performed in the order of hours instead of minutes, as is the case for electroluminescence or LIT [28]. Thus, LBIC is not as practical as other techniques in the industry [35].

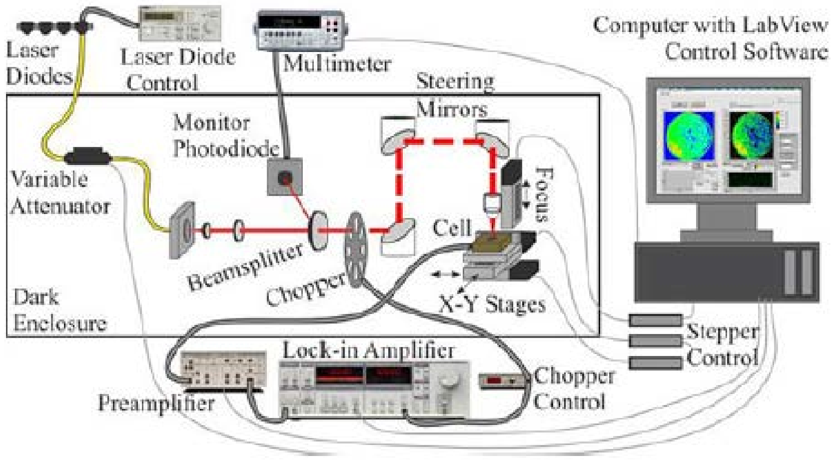

Figure 3-4
General measurement equipment set in LBIC [35]. Reprinted with author's permission.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) is similar to LBIC, but instead of using laser light, it uses an electron beam to capture the image or profile of a solar cell through an electron microscopy or optical system. SEM provides high resolution and a large range of magnification for a detailed examination of samples' surfaces using an exceptionally focused electron beam. It applies a small amount of mass and short wavelength (approximately 0.007 nm) at 30 kV in order to increase its resolution [36]. A general set-up for SEM has been shown in Figure 3-5 below.

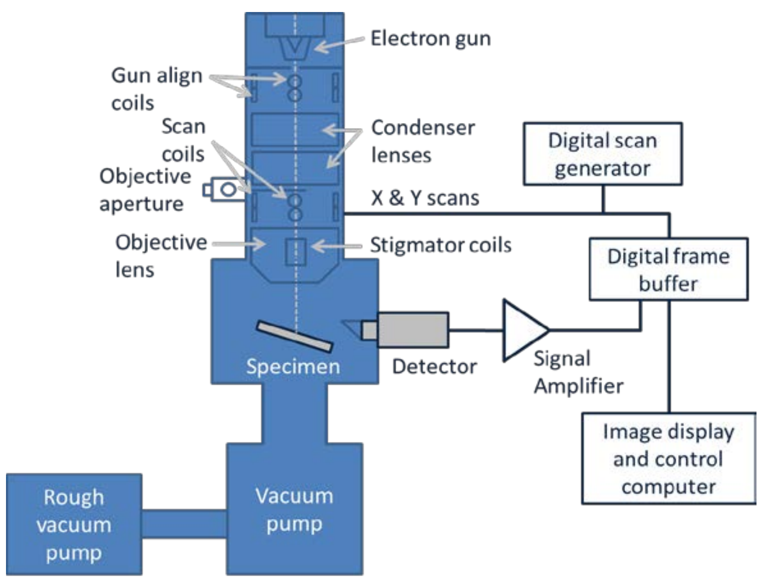

Figure 3-5
A general SEM measurement set-up based on the setup used in [36]

An electron probe is formed by an electron optical system. It enables a horizontal scanning process of solar cell surfaces, as shown in Figure 3-5. An electron gun produces the electron beam. It is directed to the sample, in which it excites atoms on the sample's surface. Electrons emitted from the surface are detected to provide an image result. Magnification of the result is determined by the ratio between the length of the image result line and the actual line of sample [36].

4
PID IN PV INSTALLATIONS

Effect of PID on the Performance of PV Installations

Commercial and utility-scale PV installations often have operating system voltages in the range of 500–1000 Vdc, with some systems operating as high as 1500 Vdc. Such high voltages result in higher module degradation due to polarization, electrolytic corrosion, and electrochemical reactions, collectively known as *PID* [37]. In order to determine the impact of varying system voltage on PID, an experiment was conducted by NREL and PI Berlin [38] where the modules were tested under the same temperature and RH conditions but with voltage increasing from -100 V to -1500 V relative to ground. The modules were tested by applying negative voltages of 100 V, 300 V, 1000 V, and 1500 V with the frame grounded. The modules were subject to each voltage level for 240 hours, followed by electroluminescence imaging. The results from the electroluminescence imaging show more defects in the cells at higher system voltages as compared to lower voltages over the same period. Figure 4-1 shows the performance and electroluminescence images of modules at different system voltages. It can be observed that there are darker regions indicating many defects at 1000 V and 1500 V as compared to lower voltages that are in agreement with the reduction in module performance.

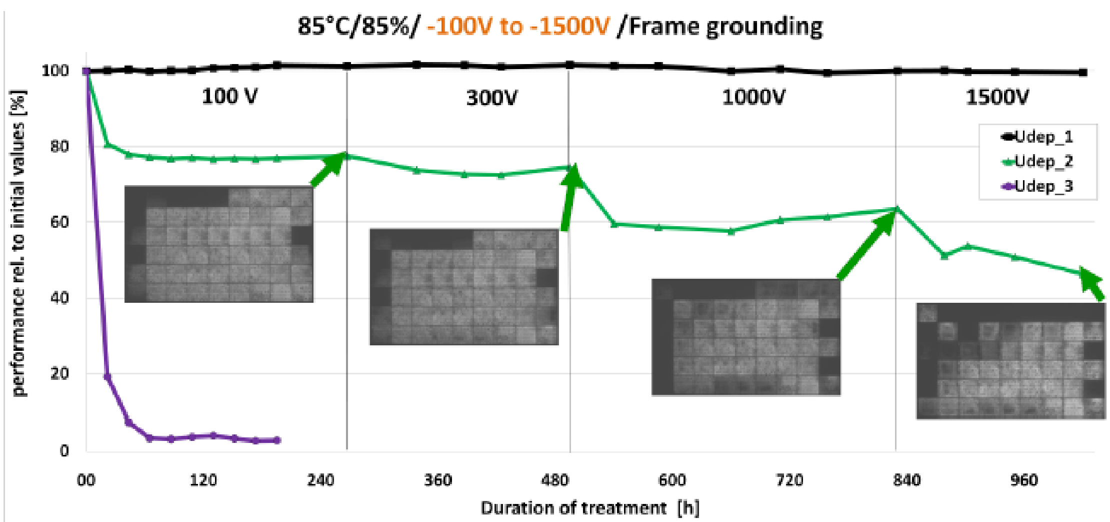

Figure 4-1
Module performance with increasing voltage bias based on results obtained by NREL and PI Berlin published in [38]. Reprinted with author's permission.

Hence, large PV installations that operate at high voltages are more susceptible to PID. However, one or a few short-circuited cells would not have a significant impact on the overall output of the system. The problem arises when many cells undergo degradation, which is usually the case. For instance, in an installation consisting of 24 60-cell modules in a string, there are approximately 1400 cells, and large potential differences can thus result in losses of 80% or higher [4]. This would reduce the overall performance of the system drastically. Presently, module manufacturers incorporate bypass diodes in modules to prevent shading or malfunctioning of one or a few cells from affecting the overall performance of the module. Though it is not practical to have a bypass diode across every cell, modules usually have bypass diodes connected in parallel to a few cells or a string of cells. Most modules being manufactured currently have at least one bypass diode connected across it to avoid the malfunctioning of the module from affecting the entire array [39]. Hence, a significant performance drop due to PID across one or a few modules in an array will not affect the overall performance of the system by much. However, if many modules in a system undergo PID, the overall power output will decrease considerably. Although the exact effect on a system is not yet known, if we assume a linear relationship and the power of each module decreases by 20–80%, the overall system yield losses can also be 20–80% in a system affected by PID. Cells damaged by PID reduce the total output of the system as well as the total string voltage. Hence, inverters will switch on later in the morning as higher irradiation is required to exceed the inverter’s switch-on voltage, and then they switch off earlier in the evening [4]. The inverter’s efficiency will also be affected, which would add to the total system losses.

Time-Scale for PID to Occur in the Field

The exact time for PID to occur is not known because it varies with module design, type, and various other factors previously mentioned. However, the effects are usually not immediate and are noticeable only over a period of several months to a few years [40].

The IEC 62804 standard that is being developed to test the modules for failure in the field due to PID have proposed test conditions of 60°C at 85% RH in the chamber for a period of 96 hours, which corresponds to testing the modules in the field for 28 months in a hot, humid, subtropical environment, such as Florida [41]. However, the time to degradation in the field varies considerably depending on location, seasonality, and irradiation conditions because the modules’ time to failure has been found to reduce by 28% under low irradiance as compared to those measured under high irradiance [41].

SunPower observed the PID effect in their modules and developed PVLife, a model of module performance, degradation, and failure [42]. The results from the model were compared to a study on a set of modules bought from 20 different manufacturers. Degradation was observed after an average of 6.7 years. SunPower also purchased and analyzed the performance of a relatively good-quality module, which showed an average age of 4.6 years before degradation [42]. However, this field-induced degradation was due to various mechanisms, not only PID. PVLife was used to calculate the effect of polarization on module performance, and it was observed that only 1% of the annual fluctuation in the total degradation was contributed by PID. Thus, the relative effect of degradation due to polarization in SunPower modules is relatively low as compared to other failure mechanisms. SunPower has since improved its module design and is producing polarization-resistant modules.

While these modules showed PID relatively early in their lifetime, some systems might take years to be affected by PID; others might not be affected at all. Hence, given the limited availability of data on this topic, it is hard to predict the period in which PID is most likely to occur. Further research is required in this area.

Long-Term Impact on Operations and Revenue

One of the key benefits of PV systems is low maintenance and their potential to last more than 30 years with minimal degradation. However, with the utility-scale deployment of PV systems over the past few years, there has been a considerable increase in system voltage, with 1000-Vdc systems in Europe and 600 V trending to 1000-Vdc systems in the United States. Additionally, high-voltage systems operating at 1000 V and up to 1500 Vdc are now being explored. This has resulted in increased PID. It has been found that susceptibility to PID can decrease the yield by more than 20% in PV modules [43]. PID is one of the biggest concerns associated with large systems installed since 2006 because it can cause yield losses of up to 80% in modules if not corrected [24]. An anonymous module manufacturer reported module output reduction of 40% resulting from PID [44] after a few years of installation.

PV plant owners and investors are concerned about the overall profitability of the system. PID can have unforeseen consequences because the return on investment from a PV system depends greatly on the annual yield. A reduction of 40% in system performance (as has been reported) will lower revenue considerably. Performance losses due to PID have been reported after only a few years in the field, and if many modules are affected, the entire string power will be reduced. This will result in a longer payback period and a drastically reduced profitability index and return on investment. However, because PID is a recently observed effect, not enough data are available to determine the exact impact of degradation on the annual yield output of large PV systems. Although laboratory tests can determine PID modes and rates under accelerated testing conditions, a better alternative is to monitor the data in real time to evaluate the long-term performance of a PV system and determine annual losses—investors' two primary concerns.

One such analysis was performed by Solarpraxis Engineers for four PV plants in Brandenburg, Germany [45]. The plants were monitored, and real-time data were collected over two years, from 2011 to the end of 2012. The results indicated a considerable degradation rate for two of the plants employing thin-film technologies. Degradation is a worrying factor from an economic as well as operational point of view. A PV plant design is based on the maximum system voltage of the modules and inverters, which need to match, along with the optimal number of modules connected in series in a string. A string initially designed to operate within the maximum system voltage might fall out of the inverter's maximum power point (MPP) range due to degradation after a few years. In addition to affecting the modules, PID would affect the inverter indirectly by increasing the inverter losses. Moreover, hotspots in the modules resulting from PID can reduce the overall system output drastically. Thus, the unexpected yield losses compound module yield losses due to degradation reducing the overall output of the PV system. Moreover, mitigating this effect by rewiring the dc strings or increasing the MPP voltage range of inverters would result in additional costs that were not accounted for during the initial system design [45].

PID causes reduction in shunt resistance at the cell level, which subsequently reduces modules' MPP and open-circuit voltage, as can be seen in Figure 4-2.

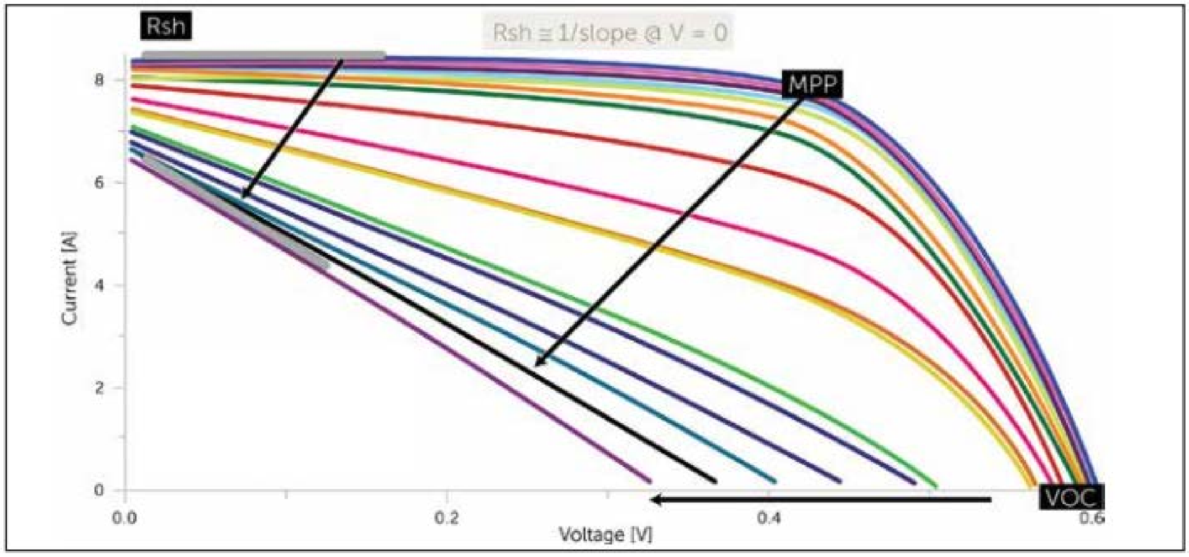

Figure 4-2: Effect of reduction in shunt resistance due to PID on a module's performance [1]. Copyright 2011 by IEEE. Reproduced with permission from [46].

In some cases, PID has reduced the electricity yield of solar panels by 80% within the first two years after installation [47]. In a large PV system, the effect of PID is much stronger in modules that are closer to the negative pole of the PV array due to the high voltage difference [40]. Though PID is caused by interactions within the PV system, the failure modes take place only in the modules, and not all modules are affected. Depending on the system configurations, some modules might undergo drastic power loss up to 80%, whereas the yield losses due to PID in others might be 20% or zero. Losses due to PID in many modules or strings in a PV system can result in overall potential losses of 20% or more in solar power plants [48]. PI Berlin reported PID in 20 German power plants located near the coast. However, the actual impact of PID on large PV power plants is yet to be determined because there is no current research quantifying the effect of PID on a PV system's performance. A survey by PHOTON International revealed the lack of reliable and comparable data that can help determine the extent of PID [49]. Various PID tests are being conducted by different labs globally; however, these tests show only the susceptibility of modules to PID. There are no simulation models available yet that forecast the performance of a module in the field. PI Berlin is one of the organizations that are currently working on collecting field data and determining indoor/outdoor test correlations for PID [38].

PI Berlin's study on measurement of PID on a photovoltaic plant's performance revealed significant string-level reduction of power at the MPP due to considerable reduction in the MPP voltage of the affected panels. A power plant with 12 strings of serially connected modules showed 10–15% losses in power output in 39% of the strings, and 23% of the strings showed a reduced output power by 15–20% [50] as is shown in Figure 4-3. Moreover, the analysis of a 10.7-MW plant in Spain showed that 41% of the modules in the plant were affected by PID, on average.

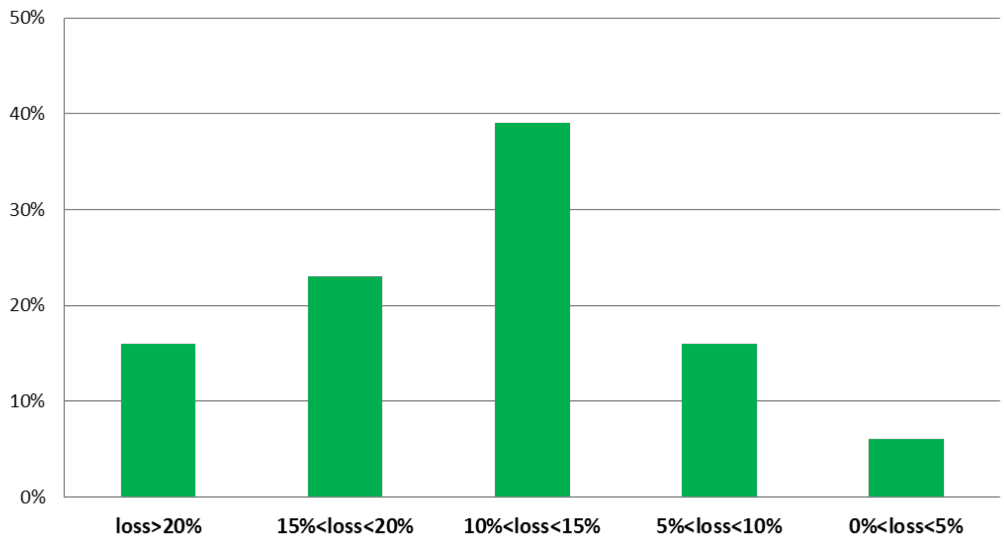

Figure 4-3
Distribution of power loss at MPP for all strings in a PID-affected photovoltaic plant [50]

vPID can impact the operations and financing of PV plants adversely because reductions in the performance of panels affects the overall performance of the system, which implies lower output and, therefore, lower revenue and a longer payback period. Moreover, employing preventive measures to mitigate PID can also increase the initial systems costs [1].

Various metrics have been developed to characterize the profitability of the PV system economics [51]. The payback period is a useful parameter for analyzing the economic performance of residential and small-scale commercial systems, whereas the larger commercial and utility-scale systems use return on investment to analyze the financial viability of PV systems.

The simplest method to characterize profitability is to calculate the simple payback period of the system, which is given by [52]:

$$\mathrm{PB} = \frac{\mathrm{CC}}{\mathrm{E_{ideal}}(1-\epsilon)}$$

where CC is the capital cost of the system, E_{ideal} is the cost of the ideal energy output of the system in the absence of PID losses, and ϵ is the loss due to PID as a percentage of total energy yield. Hence, for a system with 40% output power loss due to PID over the lifetime of the modules, the payback period is increased by:

$$\mathrm{PB_{new}} = \frac{\mathrm{PB_{old}}}{(1-\epsilon)} = \frac{\mathrm{PB_{old}}}{(1-0.4)} \approx 1.677\mathrm{PB_{old}}$$

Thus, there will be considerable loss in revenue because the system would take longer to recover the initial cost. Moreover, the system would also lose any additional revenue it would have generated after the system reached the breakeven point. However, it should be noted that the payback period does not take into account the time value of money and is used here only to estimate the loss in revenue due to PID. In order to be more precise, the return on investment needs to be calculated using the net present value as well as the revenue generated from the system, taking into consideration the annual losses from PID. However, because the PID phenomenon has been observed only recently, the information and data generated to date are insufficient to perform a detailed financial analysis.

5
METHODS TO REDUCE PID

As previously covered, there are two types of PID—reversible (polarization) and irreversible (electro-corrosion), though most cases of PID in silicon modules in the field are reversible. This section covers the various methods being employed to reduce or eliminate PID at the system, panel, and cell levels.

PID Reduction at the System Level

At a system level, reversible PID occurs when the modules are subjected to conditions of high temperature and high RH intermittently with periods for the modules to recover their performance, unlike modules that are continuously subject to PID inducing conditions. Therefore, PID can be reversed in the laboratory almost completely by applying high voltages of the opposite polarity. In large-scale systems with high system voltage, the PV modules often have a negative potential relative to the earth. This results in a high voltage difference between the cells and the grounded frame, resulting in a leakage current. One of the methods to prevent PID is by grounding the negative pole of the system.

However, this is not possible in modules with transformer-less inverters, which are becoming increasingly common. In these cases, PV offset boxes can be used [12]. A PV offset box—a product developed for module output regeneration [48], which applies an inverse voltage to the PV array during the night, resulting in discharge of the charged module [53].

PID Offset Box Technology

The PV offset box is one of the commercially available technologies to reverse the effect of PID in modules. A voltage that contrasts with the grounded potential of the solar module is provided from the box. Thus, it will be able to diminish the reduction of power due to gradual PID [53] [54].

The box is operated and connected separately from the solar system, as shown in Figure 5-1, and is connected in parallel with the inverter. The PV offset box can be used for PID prevention for systems in the voltage range of 400–1000 Vdc. Note that the number of inverter strings must be taken into account and connected differently, as shown in Figure 5-2. In the case of multi-string inverters, the negative PV input should be connected internally before connecting to the PV offset box. However, only one box should be connected to an inverter, unless the inverter is connected to multiple inputs that have not been connected internally [53].

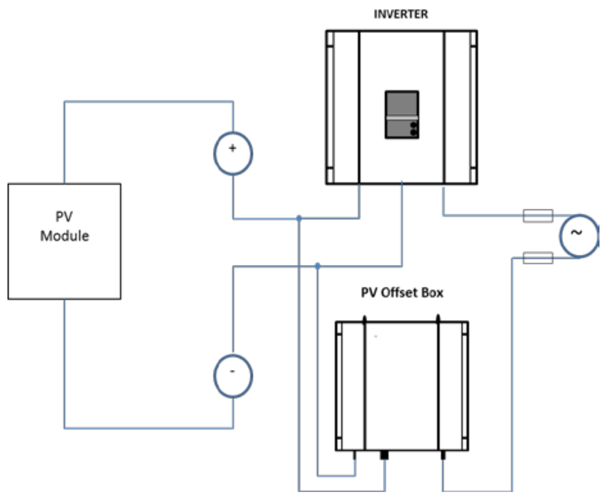

Figure 5-1
SMA Solar Technology PV offset box connection to solar system with a single string of inverter based on SMA's PV offset box shown in [53]

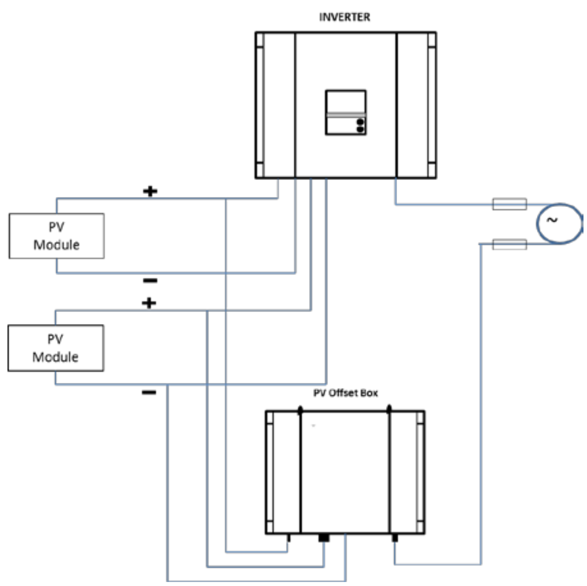

Figure 5-2
PV offset box connection to solar system with multiple strings on inverters based on SMA's system set up given in [53]

The main advantages of using PV offset boxes are low cost, ease of installation, and their wide compatibility with various PV plant designs and different inverter manufacturers.

PID Reduction at the Panel Level

At the panel level, PID can be minimized by changing the design to incorporate PID-resistant materials. These include an encapsulant that reduces leakage current (see Section 2, Panel-Level Factors: Encapsulant Material and Module Design) as well as PID-resistant ARCs, front sheets, and back sheets.

PID-Resistant Encapsulants

Based on a study on the resistance of EVA to PID, it was recognized that some encapsulants are more PID resistant than others [5] and some EVA materials might contribute to PID significantly while others don't, as can be seen in Figure 5-3.

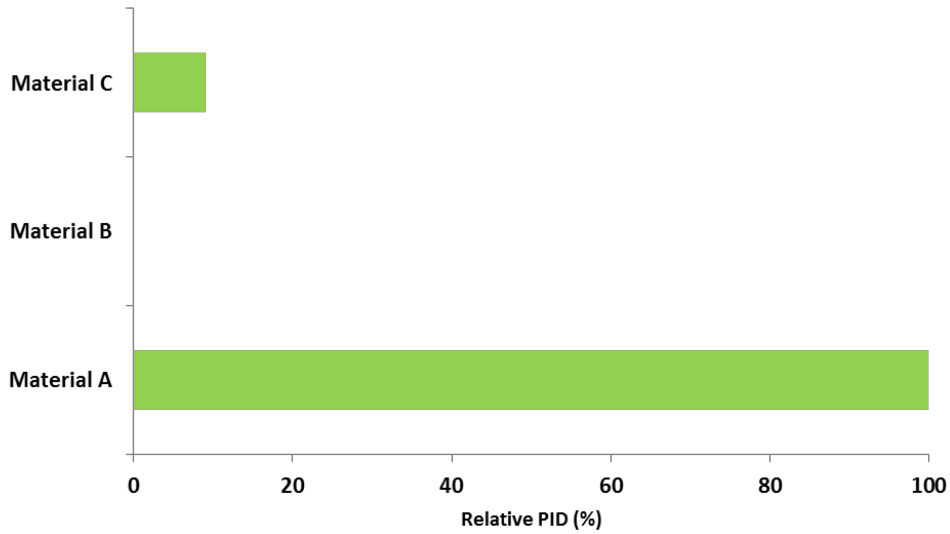

Figure 5-3
Three different type of EVA and its effect to the occurrence of PID based on the results plotted in [5]

A new PID-free encapsulant material has been created, which is an olefinic encapsulant and has been proven to show zero degradation when subject to PID testing by several laboratories such as Fraunhofer Center for Silicon Photovoltaic (CSP) and Photovoltaic Institute Berlin (PI-Berlin) [55]. An experiment compared the olefinic encapsulant and an EVA encapsulant by subjecting them to a damp heat test (85° C and 85% RH) for 5,500 hours and it was observed that the EVA based module turns yellowish while the olefinic encapsulant module remains unaffected. The results obtained after testing both the encapsulants for 10,000 hours [56] [57] indicated that the PID-free encapsulant module has more stable performance under longer term damp heat. Electroluminescence testing did not show any degradation and the results conclude that the new encapsulant has approximately 5 times better PID resistance than the EVA based module [56].

Another PID resistant encapsulant is Ionomer. Ionomer films reduce the leakage current significantly and hence, do not undergo PID. These films can also be used in conjunction with EVA to reduce the cost while preventing PID as it has been shown that a thin Ionomer film of 50 microns thickness when placed adjacent to 450 microns thick EVA can prevent PID and has the same performance as a 400 micron Ionomer film used by itself [58]. A study [58] compared the performance of different encapsulant materials after being tested for PID over a period of 500 hours. It was observed that Ionomer films showed resistance to PID even after 500 hours while PID resistant EVA underwent significant loss in power after 100 hours.

Chemically Strengthened Glass

Another way to prevent PID is by using a glass cover that is chemically strengthened [59]. This is achieved by creating a cover glass for the solar module, which contains less sodium than the typical glass. This type of glass is identified as chemically strengthened and is very effective against any sodium-ion induced PID.

Kambe et al. prepared a cover glass with reduced Na content and used it in small modules that were then subject to a continuous -1000-V voltage bias. The modules were then given a PID test for 2 hours under 85°C. The results showed that these modules with chemically strengthened glass have identical I-V curves before and after the accelerated PID test, as shown in Figure 5-4.

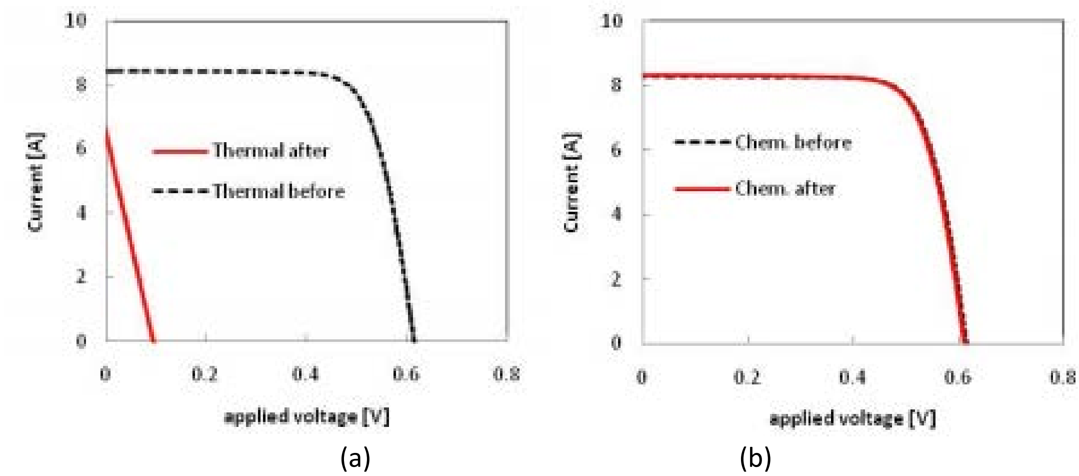

Figure 5-4
Characterization profile after two cover glass modules had an accelerated 2-hour PID test with -1000-V bias and 85°C. A typical module cover glass [a] and a module with a chemically strengthened cover glass [59]. Copyright 2011 by IEEE. (Reproduced with permission.)

PID occurring in most crystalline silicon solar cells is reversible when the module is subjected to PID-inducing conditions intermittently and not continuously over a long period. In this case, there are various mitigations, as previously described. However, PID caused by electrochemical reactions, which are often seen in thin-film PVs due to transparent conductive oxide corrosion, is irreversible. Because PID is a relatively new issue that has arisen in the past decade, considerable research still needs to be done to fully understand the causes and to develop techniques to mitigate it.

PID Reduction at the Cell Level

At the cell level, PID can be prevented by using PID-resistant ARCs or by modifying the emitters by doping. PID can be prevented by adding a higher concentration of impurity atoms to the emitter. However, this process will result in higher production costs; therefore, employing an anti-PID ARC is a better alternative [49].

Anti-PID Technology

To eliminate PID from their cells, some manufacturers are developing cell technology by optimizing various parameters, such as the cells' metallization, the emitter design, and doping, in addition to the cells' ARC [60]. These cells and 13 other modules were tested at Fraunhofer CSP for PID but did not show any degradation after the tests, whereas nine of the thirteen modules showed an average output reduction of 56% [60].

Various module manufacturers are using PID-resistant technologies at the cell, module, and system level to prevent PID from occurring in the field. The best solutions seems to be the ones at the cell level because manufacturers can integrate them into the cell production process with only a few changes [49]. However, some of these technologies are relatively expensive, and there is a tradeoff between employing these preventive technologies and risking module degradation due to PID, which could occur.

6 CONCLUSION

This report presents a literature review on the phenomenon of PID, an issue of rising concern in the PV industry and one becoming more prominent as we move toward high-voltage systems. PID can range from mild degradation affecting a few modules to severe PID that can reduce the overall performance of the system significantly. Accordingly, there is a need to mitigate PID to ensure the profitability and durability of PV systems.

The primary cause of PID in the field is high potential on a system relative to ground, which results in various degradation-causing mechanisms in the modules. The main factors facilitating PID in modules susceptible to degradation are environmental in nature—high temperature and humidity. High RH is a major factor contributing to PID in high-voltage systems because it induces high leakage currents in PV panels that reduce the performance of the panels. The location and the corresponding environmental factors play an important role in determining if the system would be susceptible to PID, but PID can also be attributed to other factors at the panel and cell level. On the panel level, the panel design and materials used can contribute to PID significantly. The main panel-level factors contributing to PID are the encapsulant material and the front cover used because the sodium from the glass front sheet used in most commercial modules facilitates the conduction of leakage current. At the cell level, the ARC would be the main factor affecting PID because it can result in accumulation of sodium ions, which needs to be avoided.

The two main mechanisms of PID are polarization and electrochemical reactions. Most cases of PID in crystalline silicon modules have been due to polarization, which is a reversible mechanism and caused by the migration and accumulation of charged ions in the encapsulant due to high leakage currents. This results in creation of shunts that reduce the system's output power. Shunting is mainly attributed to sodium ions in the glass that can migrate easily from the glass to the cell surface in the presence of moisture and a negative electric field and facilitated by EVA degradation. PID can also be caused by electrochemical reactions that result in the corrosion of the encapsulant or transparent conductive oxide, an irreversible process.

The literature review also presents a study on various methods and techniques being used to detect PID in the lab and in the field. PID effects have been replicated by many organizations, such as Fraunhofer ISE, PI Berlin, NREL, and TUV Rheinland that have developed testing procedures to determine modules' susceptibility to PID in the field.

Various tests conducted as a part of round-robin testing have led to the development of the IEC 62804 standard, which is still in its drafting stage. IEC 62804 aims to provide a standard qualification testing procedure and proposes testing conditions of 60°C temperature, 85% RH, and a nameplate voltage bias for 96 hours in an environmental chamber to determine a module's susceptibility to PID. PID in modules is detected mainly by conducting electroluminescence imaging and lock-in thermography (LIT), though various other methods can also be used.

An issue reviewed in this report is the effect of PID on PV systems' durability, their operations, and revenue. PID can affect a system at any point during its life cycle and can take a few months to several years to be detected. The time-scale for PID to occur is not known accurately because the effect has been observed only in the past decade and the susceptibility to PID varies across PV systems. PID has been observed within the first two years of installation in some cases, whereas other large-scale PV systems have not been affected over their entire life. Hence, further research is required to be able to accurately predict the time period for PID to occur in PV systems.

It has been observed that the likelihood of PID increases as the system voltage increases. PID may not affect an entire system uniformly, and some modules might undergo severe degradation while others remain unaffected. PID can reduce a module's yield by 20–80%. In this case, the overall system performance would not be affected by a few modules with PID. However, if many modules or strings of modules experience PID, the overall yield losses can range from 20% to 80%. Moreover, the inverter's losses might also increase because the PV strings' maximum voltage might fall out of the inverter's maximum voltage range. A case was reported where the electricity yield of solar panels reduced by 80% within the first two years because of PID. Hence, if PID is not detected and corrected, it can impact the operations and financing of PV plants adversely.

A study by PI Berlin on a 10.7-MW plant in Spain revealed MPP power loss of 41% on average in the strings of the system. Such high losses at the string level will reduce the overall performance of the system drastically. Lower output will consequently result in lower revenue generation and a longer payback period. This is a cause of great concern to PV plant owners and investors because unforeseen reduction in the annual yield due to PID can affect the overall profitability of the system and its return on investment drastically. However, the actual impact of performance losses from PID on the profitability and return on investment is yet to be determined because there is lack of reliable data quantifying the effect of PID on a system's operation and finances.

Finally, a literature review of various techniques to mitigate and prevent PID was performed. PID can be prevented at the system level by grounding the negative pole of the system. This might not be possible in some systems, in which case a PID offset box can be used to provide voltage of reverse polarity to reverse the effects of PID. However, in some cases, PID is irreversible and needs to be prevented by incorporating changes at the panel and cell level. Various anti-PID techniques have been developed that aim at improving the front sheet, encapsulant, and ARC designs to reduce leakage current and mitigate PID.

It can be concluded that PID can result in severe losses in system performance and revenue generation if left undetected and uncorrected. However, numerous technologies are being employed by companies to mitigate PID. Adapting PID-minimizing processes at all levels will help optimize the energy output and performance of the system over its entire life of 25 years. Nevertheless, PID has only recently come to light, and considerable research is still required to determine the exact causes, effects, and timing of PID as well as its impact on system operation and finances.

7
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