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A Review on Degradation of Silicon Photovoltaic Modules

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ABSTRACT Photovoltaic (PV) panels are generally treated as the most dependable components of PV systems; therefore, investigations are necessary to understand and emphasize the degradation of PV cells. In almost all specific deprivation models, humidity and temperature are the two major factors that are responsible for PV module degradation. However, even if the degradation mode of a PV module is determined, it is challenging to research them in practice. Long-term response experiments should thus be conducted to investigate the influences of the incidence, rates of change, and different degradation methods of PV modules on energy production; such models can help avoid lengthy experiments to investigate the degradation of PV panels under actual working conditions. From the review, it was found that the degradation rate of PV modules in climates where the annual average ambient temperature remained low was -1.05% to -1.16% per year, and the degree of deterioration of PV modules in climates with high average annual ambient temperatures was -1.35% to -1.46% per year; however, PV manufacturers currently claim degradation rates of up to -0.5% per year.

Key words Photovoltaic modules, Degradation of crystalline photovoltaic module, Types of PV module degradation, Year on year degradation

Subscript

PV : photovoltaic
YoY : year-on-year degradation
EVA : ethylene vinyl acetate
RH : relative humidity
PR : performance ratio

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1. Introduction

The energy issue remains an important part of the social and economic factor for the progress of the society. The impact of the environment using nonrenewable fuel resources poses problems. Nowadays, various types of renewable energy sources in different technologies suggest high reliance and sufficient dependability to minimize the load-shedding due to increased demand. Photovoltaic power generation has an important place in today's market of renewable energy resources. In fact, the photovoltaic system is utilized for industrial and residential needs. The market of solar power systems has seen remarkable improved by the development in PV technology.[1] A solar PV system can only effectively function for sufficient energy requirements if the fixing of solar setup is enhanced its design and maintained accordingly. For this purpose, it is essential to comprehend the dependability and longevity of this type of setups. Investors want clear answers about their reliability, especially the useful life of PV systems, to analyze the practical and commercial reliance. Observing the degradation of photovoltaic systems is significant because elevated decomposition rates lead directly to the loss of energy production and reduce the profit on speculation,[2] due to deficiency of accurate knowledge on the degree of decline and rise of economic risk.[3] The dependability and lifespan of PV systems rely mostly on the efficiency of the PV system and its various degradation patterns.[4,5] PV module failure information has been available since the early 1970s.[6]

The National Renewable Energy Laboratory (NREL) assessed the yearly production of polycrystalline and monocrystalline PV panels to decrease by 0.7% in 2002.[7] Jordan[8] states that in the first decade of the 21st century, the average reduction rate measured by individual units was 5%. Insufficient long-lasting research on the decline of photovoltaic modules has been available by Skoczek et al. (2009). They estimate the working efficiency of 204 PV modules output based on the aging of Si crystals (53 module type).[9]

The Collaborative Research Center in Northern Italy report in 1983 that a 90% early high capacity performance of PV system achieved after 10 years and an 80% performance guarantee after 25 years, where only 17.6% of the installed units would fail has been found. This high power loss (>20%) is associated with fill factor loss due to high resistance. Moderate power loss (<20%) may be associated with short circuit current loss due to degraded visual effects. Enduring failure is limited to 0.2% to 1.0% per year. However, little information is available regarding the degradation patterns of photovoltaic modules regarding the incidence, degree of expansion, and extent of their influence on module lifespan and dependability.[10~14]

Figure 1 summarizes the main photovoltaic silicon module decomposition or degradation modes described in this review paper.[28] Table 1 shows the several modes of degradation rate reported in various countries in which most of the degradation cause by the environmental condition like high humidity, extreme ambient temperature and exposure time more than 10 years.

Table 1. Degradation rate reported of various countries

Country	Module type	Degradation rate	Cause of degradation
Spain[15]	Multi-Si solar cell	-0.8% to -1.1%/year	Wind speed
Italy[16]	Multi-Si solar cell	-0.8% to -1.1%/year	PV cell shading
Cyprus[17]	Multi-Si solar cell	-0.8% to -1.1%/year	Solar irradiance & cell temp
Greece[18]	Multi-Si solar cell	-0.9% to -1.13%/year	Ambient temp, solar irradiation & wind speed
Poland[19]	Multi-Si solar cell	>-0.9%/year	Elevated air temperature
India[20]	Mono-Si solar cell	-1.4%/year	High cell temp & humidity
Southern India[21]	Multi-Si solar cell	-1.3%/year	Air temp & high irradiance
Thailand[22]	Multi-Si solar cell	-1.5% to -4.9%/year	Humidity & moisture
Northern Thailand[23]	Multi-Si solar cell	-1.5%/year	Delamination of EVA sheet
Japan[24]	Multi-Si solar cell	-1.15%/year	Ambient environmental factors
Singapore[25]	Multi-Si solar cell	-2.0%/year	Ambient temp
Republic of Korea[26]	Multi-Si solar cell	-1.3%/year	Corrosion & discoloration
Scotland, UK[27]	Multi-Si solar cell	-1.05% to -1.16%/year	Extreme low temp & humidity
Australia[27]	Multi-Si solar cell	-1.35% to -1.46%/year	Extreme high temp & moisture

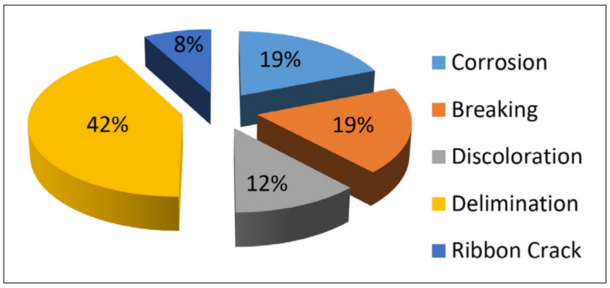


Fig. 1. Silicon PV modules: representativeness of degradation modes[28]

2. Year-on-year (YoY) degradation investigation technology

Meanwhile, data of the PV system is random; a process of normalization is needed to convert the information into a standard dissemination mode. In the present stage, a unit less performance index (PR) with small changes is calculated from the total energy production data. Generally, the resistance level depends on the nominal resistance of the photovoltaic system, the measured photovoltaic power and the irradiance of the location (measured by the weather station). Use the following equation for normalization performance ratio (PR):[8]

$$PR = \frac{P}{P_{STC} \times \frac{G_s}{G_r} \times (1 + \gamma(T_{PV} - T_r))}$$

(P) is the real-time calculated DC or AC power of the photovoltaic system in watts, (P_{STC}) is the nominal DC or AC power of the photovoltaic system in watts, and (G_s) is the radiation on-site, (G_r) is the reference radiation 1000 W/m^2, (γ) is the coefficient of temperature for the maximum power in percentage/℃, (T_{PV}) is the temperature of the photovoltaic system in ℃, (T_r) is the reference temperature of the photovoltaic system that is 25℃.

Information on filter-photoelectric data used to eliminate data points that represent unacceptable information, cause analysis deviation, or introduce a lot of noise. Due to the activation of PV modules such as the MPPT unit of PV modules, low irradiance conditions are usually related to data or night-time errors, an illustration of filtered data yield is presented in Fig. 2.

Data of the PV system is collected by a weighted average of temperature and irradiance. This process minimizes the influence of prodigious erroneous information facts in the early time and afternoon. The collection time is determined during the day; therefore, the final effect data is accurate to 1 day. An instance of product composition is revealed in Fig. 2.

The Procedure for analysis of the degradation phase for the remaining data is to calculate the rate of degradation based on an annual measurement procedure. The exchange percentage is intended at one time among two facts in succeeding years. By manipulating the change rate of all data points and all years, a graph of the exchange rate (as shown in Fig. 2) can be obtained, and the central trend represents the overall performance of the system.[29~32]

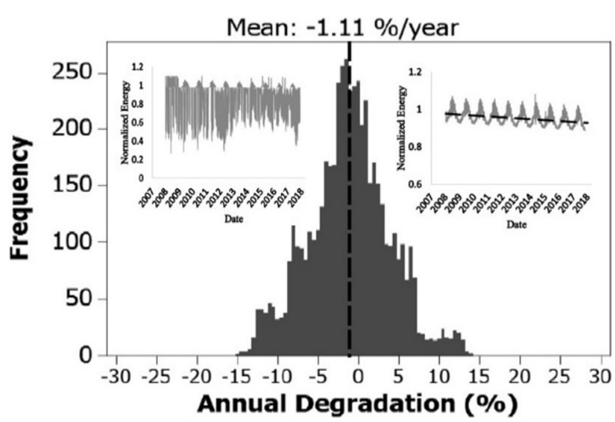


Fig. 2. Illustration of the year-on-year (YoY) degradation process: (a) data filtration; (b) daily aggregation procedure; (c) the result of the degradation rate[29]

3. Photovoltaic module degradation

3.1 Major PV module degradations

Degradation refers to the steady decline of the performance of a constituent or arrangement, that might disturb its capability to perform across the qualified standard, and is the result of operating conditions.[33] The degraded photovoltaic module can continue to perform its most important function, that is, it can produce power from the light of the sun still if it is no extensive to utilize. Moreover, when the degradation exceeds the critical threshold, the state of degradation may cause more problems.[5] As stated by Wohlgemuth et al. (2005), industrialists believe that when the energy is less than 80% of the original capacity, the quality of photovoltaic modules will decrease.[34] The performance of PV modules will be reduced as a result of various aspects, such as humidity, radiation, temperature and external impact.[6,35] Anyone of these factors mentioned can cause one or more types of parameters to degrade, for example:[36~38]

- Delamination
- Corrosion
- Breakage
- Cracking
- Discoloration

NREL and IEA PVPs[39~41] provides a record of the main recognized degradation of the crystalline silicon solar modules as describe in Table 2 and plotted in Fig. 10.

3.2 Corrosion of PV module

Moisture entering the equipment through the edge of the plate can cause corrosion.[45] When moisture remaining in the module encapsulant that will significantly increase in the electric conduction of solar cell with frame. In fact, deterioration will affect the metal contacts of solar cells, resulting in performance is reduced due to increased leakage current.[46] Deterioration also declines the bond among the solar cell and the metal frame. Fig. 3 demonstrates the photovoltaic module pretentious by oxidization of the flange and connection case.[36]

Table 2. Various means of crystalline silicon modules degradation[38~44]

Various degradations modes	
Failure of the bypass diode	Delamination
Interconnections broken	Defect back sheet
Delamination of the encapsulant	Defect junction box
Corrosion	Junction box detached
Broken glass	Discolouring of pottant
Discoloration of the encapsulant	Cell cracks
Broken cells	Burn marks
Failure of the weld ribbons	Potential induced shunts PID
Disconnected cell of string	Potential induced corrosion
Defective bypass diode	Corrosion / abrasion of AR coating
Isolation failure	CdTe: back contact degradation
Failure due to hail	Failure due to snow load
Failure due to storm	Failure due to direct lightning stroke
Animal: bite/ corrosion/ dirt	Dust soiling

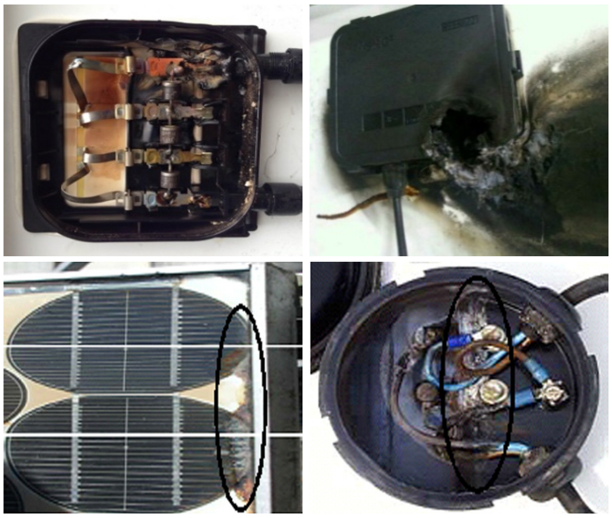


Fig. 3. Photovoltaic module pretentious by the deterioration of the border frame and the connection case

3.3 Photovoltaic module delamination

Due to adhesion loss (termed as delamination) happens among the encapsulation polymer and the solar cell or amid the solar cell and the windshield. This is a key problematic condition because it has dual properties: increased sunlit consideration and diffusion of water into the equipment housing.[36] Skoczek et al. (2008) deliberate the degradation of photovoltaic panels linked to the decoding module based on the test based on the standard IEC 61215.[47] When the discharge occurs at the edge of the device, the discharge will be more serious because it not only reduces energy consumption but also causes electrical hazards to the device and the entire device. In warm, humid climates, spills are more common. It allows moisture to enter the equipment and often causes many physical and chemical damages, for example, corrosion of metal for the equipment assembly, Fig. 4 shows photovoltaic module delamination with a drain flange. Jansen and Delahoy (2003) pointed out the discharge might be instigated by the buildup of salt and the saturation of moisture into the photovoltaic module. In addition, it is believed that

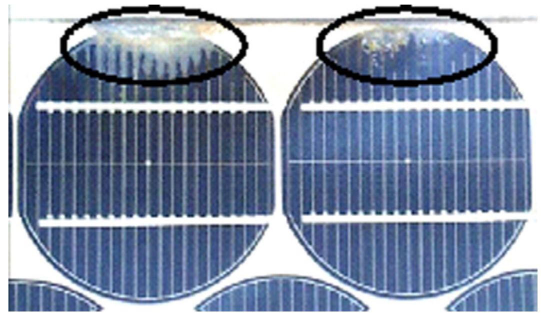


Fig. 4. PV Module with a delamination[48]

the interface might be corroded by hydrofluoric acid made from fluorine and tin oxide in photovoltaic modules.[49]

3.4 Photovoltaic module Discoloration

Color changes typically cause deprivation of the packaging unit, ethylene–vinyl acetate (EVA), or the glue sandwiched between the photovoltaic cells and glass. Modulus color change is a color alteration in which a considerable becomes brown and occasionally yellow. When solar radiation falls on the module which have change in color of cell, by this means the output power is reduced by that PV setup. Oreski and Wallner (2009) pointed out to the chief cause of EVA deprivation is the ultraviolet radiation produced by water at a temperature higher than 50℃.[50] The color change may occur in a different area, rather than next to the photovoltaic module. That might be, by reason of the dissimilar properties of the polymers used. This may mean that the color comes from the polymer of the encapsulation, rather than the color that usually comes from viscous elements such as EVA. Moreover, EVA fails to disseminate in the same method in all cell parts in the same way.[44] The discolored photovoltaic cell is exposed in Fig. 5.

Kojima and Yanagisawa (2004) are concerned about the yellowness of EVA utilized in photovoltaic setup.[51] In the trial, artificial radiation is exposed to the

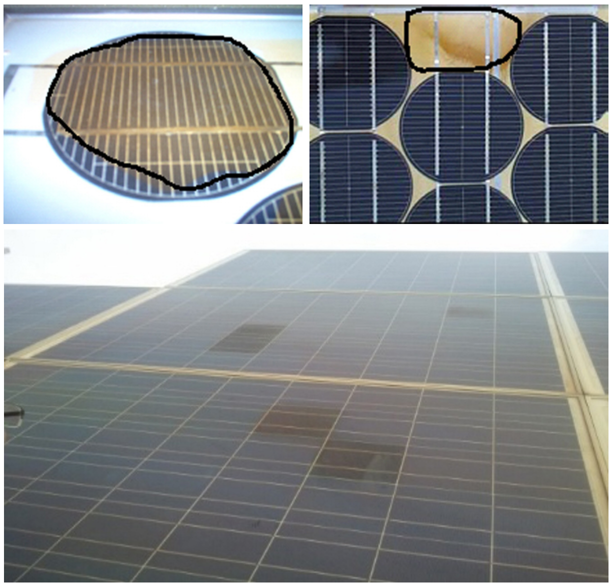


Fig. 5. Solar cells discolored[48]

photovoltaic modules to evaluate the color of the photovoltaic cells to check the influence of ultraviolet light (wavelength range from 280 nm to 380 nm). When an irradiance of 4000 W/m^2 is applied, the photovoltaic cell degrades rapidly, and the photo-sensitivity increases and the transmittance between 280 nm and 380 nm increases after 400 hours of exposure. It happens mostly by reason of reduced absorption of ultraviolet radiation that can defend solar cells from color transformation. In addition, the low yellowness of EVA film leads to the power loss of PV modules.[52] However, for irradiance of 1000 W/m^2, after 500 hours of exposure, the wave-length range does not change between 280 nm and 380 nm. Wohlgemuth and Kurtz (2011) conducted tests for UV effect on photovoltaic modules at 60℃ and conclude that only when the total UV radiation reaches 15 kWh/m^2 and does not exceed 250 W/m^2 in the wavelength range between 280 nm and 385 nm. The color change of the coating material only occurs when the amount is measured.[53] Osterwald et al. (2002) believe that the less effective and long-lasting deprivation of photovoltaic modules has a linear

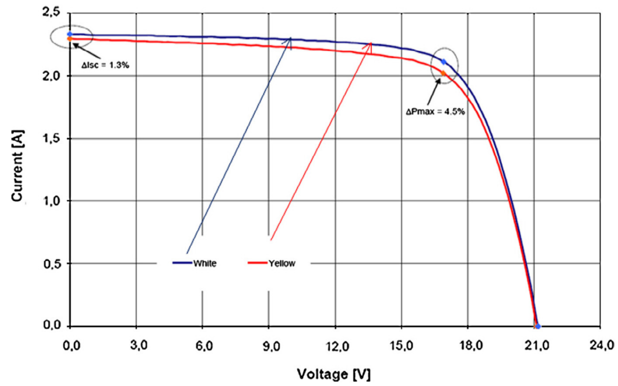


Fig. 6. A comparison of IV (current vs voltage) curve pro-perties of the photovoltaic solar module in between new and discolored[57]

relationship with the exposure of PV modules to ultraviolet radiation.[7] In recent years, most of the works on the degradation of crystalline silicon photo-voltaic modules have focused on the degradation of EVA.[54~56] Realini (2003) conducted research in between 1982 and 2003, in which permissible him to show a relationship between the electric features of the device with the color of the housing.[57] The color change will cause the short circuit current (I_{sc}) of the photovoltaic module to deteriorate; for partial changes to the surface of the PV module, the I_{sc} decomposition range can be lower than the nominal value by 6% to 8%, and for complete discoloration, it can be 10% to within 13%. The maximum power (P_{max}) of the photovoltaic module is correspondingly reduced due to the color change of the module, as shown in Fig. 5 and 6.

3.5 Cracks and breakages of PV modules

Breakage of glass is a significant degrading influence for photovoltaic modules. Most of the time, this happens when installing and maintenance of the PV module, specifically when transporting the equipment to the installation location.[53] Damaged or broken equipment can still operate normally. Cracked poly-crystalline PV module runs for several years deprived

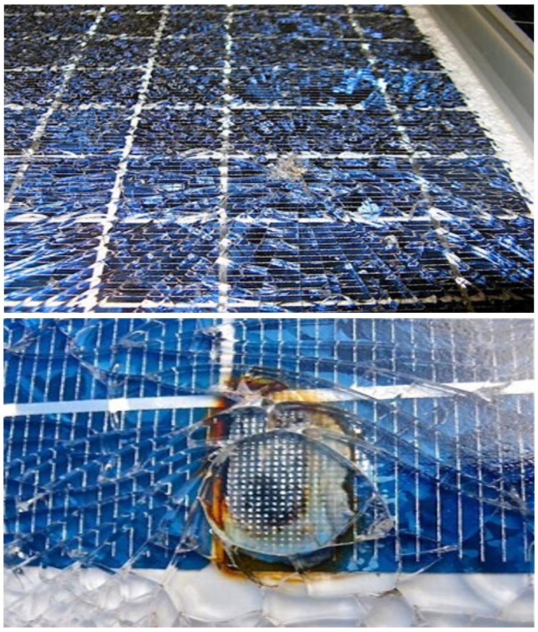


Fig. 7. PV module with broken glass and cell burn

of a significant drop in energy shown in Fig. 7. However, this increases the risk of electric shock and moisture penetration. Fractures and flaws are typically accompanied by different kinds of degradation, just like wear, change in color and cracks.[6] With the purpose of providing silicon and decrease the production cost of solar photovoltaic power generation, in recent years, manufacturers have changed the thickness and area of cells. The thickness of silicon PV has been reduced from 300 microns to less than 200 microns, sometimes less than 100 microns. Further-more, to reducing the thickness of the photovoltaic cell, the cell area is also improved to 210 × 210 millimeter.[58] This makes the photovoltaic device more fragile and breaks faster through management (storing and rolling). It is usually difficult to identify with the naked eye a crack in a PV module that is already in operation. It can be detected by optical methods.[59]

3.6 Additional influences of PV modules degradation

3.6.1 Potential Induced Degradation (PID)

In photovoltaic systems, PV modules are usually connected in series sequence to upsurge the voltage of the system output. Therefore, the output voltage of this series circuit could reach sometimes hundreds of volts.[60] To protect people from electric shock, all-metal structures of the equipment are usually grounded. Due to the potential between the photo-voltaic module and its structure, once the protection among the structure and the high voltage layer is not ideal and leakage current occurs, the electrons in the photovoltaic module material may escape through the soil structure.[61] Due to this phenomenon, polarization affects the electrical performance of PV cells. This occurrence is called PID (Induced Potential Degradation), and it is characterized by the gradual degradation of the performance of the crystalline silicon PV module due to the current induced in the module.[62] Hack et al. (2011) presented the PID is further suitable in moist weather than in warm and dry climates.[63] Shchütz et al. (2011) confirmed this view by proving that leakage current upsurges with moisture.[60] In their research, a voltage was applied among the structure of metal and the contacts of the 60-cell PV module. The applied voltage changes from −600 volts at sunrise to 0 volts at sunset.

3.6.2 Hot spots

Hot spots are areas of photovoltaic modules with high temperatures that may damage the cells or other parts of the unit as shown in Fig. 8.[64] The cause of hot spots may be a diversity of cellular interferences, comprising fractional shadows, cell mismatches, or interrupted connections between cells.[65] The short-circuit current and the open-circuit voltage are applied by the photovoltaic cell with the lower-

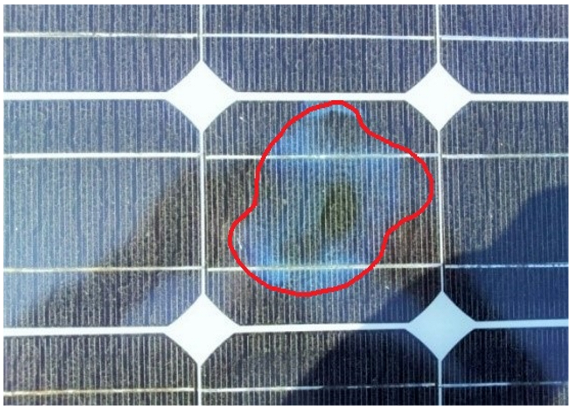


Fig. 8. PV module with hotspots

most photoelectric efficiency, which is connected in series and parallel respectively. In the event of a short circuit, if the PV cell fails, the voltage will reverse and become equal and opposite to the other cells in the series. This faulty solar cell will place a burden on other batteries and relatively high heat dissipation positions, thereby forming hot spots.[66,67]

3.6.3 Bubbles

In this kind of deprivation is comparable to delaminating, nevertheless herein the situation, the detriment of EVA sticking affects solitary a minor part and joint with the external part of an expansion that affects the grip. The bubbles are usually the result of a chemical reaction, releasing the gas stuck in the PV module. Once this happens on the rear side of the unit, mobbing occurs in the encapsulated polymer or the back of the unit, causing air bubbles. This made it harder for solar cells to dissipate hotness, increase temperature and shorten life span.[68] Fig. 9 shows a photovoltaic module with a lot of bubbles on the back and front. They typically seem in the midpoint or corner of the solar cell, possibly because of poor cell bond due to high temperature. Making a photovoltaic call in front of the device can reduce the radiation entering the device that separates light and increases its reflection.[36]

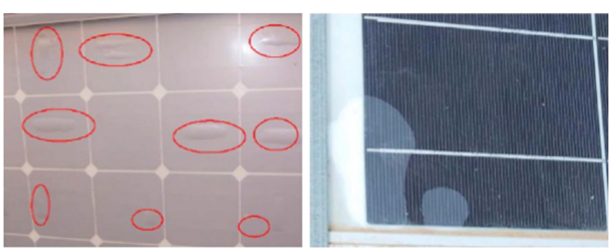
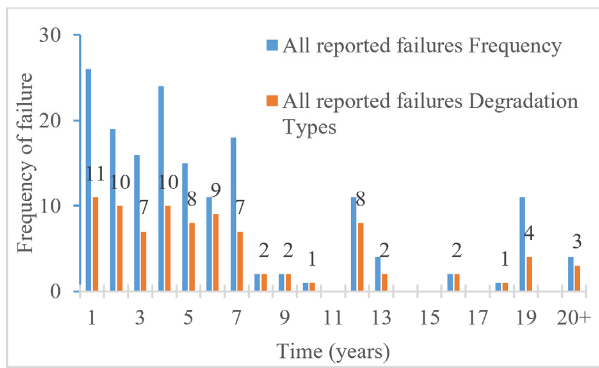


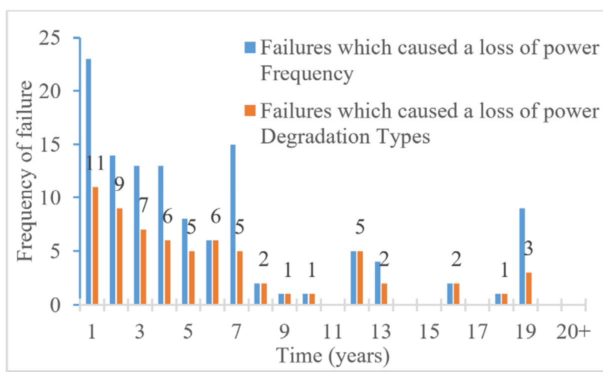
Fig. 9. Bubble in photovoltaic module[36]

3.7 IEA-PVPS report for field failure assessment of photovoltaic module degradation

Figure 10 present an estimate of the rate of deter-ioration, shows the presence of failures during years



(a)



(b)

Fig. 10. Distribution of the presence of failures over the years of operation of the PV system. The existence of a fault is divided into a degrading fault and a sudden fault. Graph of Fig. 10a indicates the presence of a total error of all errors found. The graph in Fig. 10b detects fault detection that results in loss of measured power[41]

of service. Figure 10a shows the presence of all reported failures and Figure 10b shows only the failures which caused a loss of power. Each number is divided into degraded and sudden faults. Both types of disability occur in the first 7 years, focusing on specific types of failures. Cell crack failures are reported primarily in the early stages of PV system operation from year one to year two. These are mainly systems where PIDs failures were reported in years 3 and 4. If the chain of cells or modules is separated, it will be split after 4 years of operation. Although the potential for cancellation has grown in recent years, the energy-related color spacing process begins after 3 years and builds up strongly after 18 years of system operation. Defective bypass diodes are distributed during the first decade of operation.[64]

4. Effect of degradation rate on different weather regions

It should be noted that the rate of decline of PV power system in different climatic regions is mainly influenced by cold and hot weather conditions. The results showed that the deprivation rate per year in cold places is low. Larger damage is observed for solar power plants installed in areas with warmer climates where deprivation rate per year is high. Moreover, due to the rapid changes in ambient temperature and uneven solar radiation affecting the solar cell module, it has been found that the solar system in hot climates has many defective solar bypass diodes. However, in cold climates, bypass diodes were not damaged during the more exposure period. In addition, several hot spots of the cells have been observed in cold zone areas. It has been found that there are fewer PV modules with hot spotted PV panels in the cold zone area than in the hot zone PV system installed site.[38~43]

5. Solutions to minimize degradation rate

Corrosion can be managed by numerous methods like "Coatings, Corrosion inhibitors, Selection of materials", it is deliberated the highly prominent tool for restraint against corrosion. These are constituents that minimize the scale of corrosion for the atmosphere when sited in this situation and have a great endurance to deteriorate. So, employing these resources will enhance the working period of solar cells.[69] Control of corrosion for the photovoltaic system will be utilized by eradicating corrosion for internal components and external structures. The subsequent techniques can also be applied to reduce corrosion rate, for example, Ethyl Vinyl Acetate (EVA) provides isolation from the flow of electrons, structural strength, and protection from dangerous and critical atmospheric situation to the photovoltaic cells.[70]

EVA is a polymer that can defend the external face by substantially avoiding water accumulation at its joining parts. Stainless steel or other corrosion-resistant alloys to be used in photovoltaic cells due to the high prevention of corrosion so the frames of solar modules could be manufactured from these materials.[71]

The incorporation of nanomaterials into the solar panel can not only enhance the mechanical properties of the polymers but also endows polymers with some other functional capabilities, in addition, that, it has a high resistivity against water vapor and corrosive gases.[72]

For long-lasting constancy of photovoltaics cells, plasma activation becomes its potential to fabricate weather-resistant solar modules with the use of a strong bonding agent that is very dependable and waterproof.[73]

The front glass made of low iron glass that transmits in the UV (no cerium oxide), large enough to restrict oxygen. It is critically important that PV module manufacturers be observant of the performance of their products in the field.[74]

Solutions to decrease the propensity for crack dissemination or the influence of open cracks on module operation are located at the solar cell, module, and system levels. Although, certain results are achieved with progressive cell construction. To minimize the cracks at the cell level the following solution could utilize to minimize these creaks, i.e. manufacture thicker wafers, multi-busbars/interconnect-wires, wires placed closer to the cell edges, rectangular or half-cut cells, uniform power dissipation, and with reverse "breakdown" at low voltages. Also, reduce the creaks at module level by deploying the following methods i.e. optimized soldering materials, equipment and quality control, glass module construction, back-sheet constituent that makes compressive force into the cells, cells wired in parallel, strings wired in parallel, stiffer modules, solder with more flexible materials, increased number of bypass diodes.[75]

6. Conclusion

Different modes of PV module degradation rate have been overviewed in this article. Corrosion, discoloration, deformation, destruction, delamination, breakage and cracking are the main deprivation causes of photovoltaic modules. On the other hand, the chief reason of PV module degradation is corrosion and discoloration, according to the literature describe in section 2 and 3. Environmental factors such as temperature, humidity and ultraviolet radiations are the main factors behind the dilapidation of PV modules. This article also presents an analysis of degradation rates for different PV sites mainly affected by cold weather and affected by warm weather. It is reviewed that at the regions where the average annual ambient temperature remains very low the degradation rates of solar cells ranges from −1.05% to −1.16% per year and on the other hand, solar power plants installed in the regions where the average annual ambiaent temperature remains high have a significant decline from −1.35% to −1.46% annually but the PV technology have developed enough now-a-days the PV manufacturing companies claimed degradation rate is up to −0.5% per year. Thus, surprisingly noted that, the monthly average PR of PV systems installed in the cold and hot region sites was 88.81% and 86.35%, respectively. The outcomes confirm that the annual degradation rate in the cold region is lower than that in hot region sites. Also, various types of degradation rate of solar cell at several countries worldwide is reviewed related to sun exposure time, ambient temperature, humidity or moisture in air and solar radiation as described in table 1 and 2. Also provide some solutions to minimize the degradation rete of solar cell in chapter 5 that could help for manufacturer to optimize their production to enhance the cell quality and provide long-term warranty period to the customers.

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