Article

Defects Impact on PV System GHG Mitigation Potential and Climate Change

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Abstract: Solar photovoltaic (PV) systems are widely used to mitigate greenhouse gases (GHG), due to their green renewable nature. However, environmental factors such as bird drops, shade, pollution, etc., accommodation on PV panels surface reduce photons transmission to PV cells, which results in lower energy yield and GHG mitigation potential of PV system. In this study, the PV system's energy and GHG mitigation potential loss is investigated under environmental stresses. Defects/hotspots caused by the environment on PV panel surface have unknown occurrence frequency, time duration, and intensity and are highly variable from location to location. Therefore, different concentrations of defects are induced in a healthy 12 kWp PV system. Healthy PV system has the potential to avoid the burning of 3427.65 L of gasoline by 16,157.9 kWh green energy production per annum. However, in 1% and 20% defective systems, green energy potential reduces to 15,974.3 and 12,485.6 kWh per annum, respectively. It is equivalent to lesser evasion burning of 3388.70, and 2648.64 L of gasoline, respectively. A timely solution to defective panels can prevent losses in the PV system to ensure optimal performance.

Keywords: PV system; defects; GHG; hotspots

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1. Introduction

Solar photovoltaic (PV) energy systems are widely used as green renewable energy sources across the globe. PV systems have a combustion-free nature, i.e., no burning of fossil fuels such as oil, gas, coal, etc., in the running phase. Hence, there are no production and emissions of greenhouse gases (GHG) such as CO₂, NO_x, water vapors, etc. GHGs are the leading cause of global climate change [1–3]. Moreover, fossil fuels are limited energy resources and are depleting fast [3]. However, across the globe, a major portion of energy production is based on conventional thermal power plants. For example, Pakistan's energy production is heavily based on fossil fuel technology [4]. In contrast, the PV system offers a green solution because of its 1500–50,000 EJ per year, which is direct free solar energy potential across the globe [1]. PV systems have the advantage that small-scale PV systems can be installed on load sites, i.e., on rooftops of end-energy users. It reduces transmission and distribution losses; hence, GHG emissions reduction [2]. As a result, PV system energy production capacity was increased to 117 GW in 2019 [3].

Despite the tremendous potential, PV system efficiency varies depending upon geographical location and natural parameters. These factors in turn affect PV system output [2,5]. PV systems like other power system components such as insulators are exposed to environmental stresses. Environmental stresses include ultraviolet radiations, inert and active pollution, rain, snow, etc. [6]. These factors reduce the PV system's performance [7]. Moreover, hotspots/defects that arise in the PV system due to the environment such as bird drops [3], shading effect [8], dust [9], etc., are responsible for energy losses and affect

PV system output as well [3,10]. In addition, bypass diodes may not bypass the defective cell/part effectively, which results in energy loss and accelerated aging of panels [11]. The literature reports up to 18.9% annual power loss [7] and a reduction of PV output of up to 50% [3] due to PV system issues. Other issues may include wiring issues, aging, maximum power point tracking errors, manufacturing faults, etc. [3].

The PV panel suffering due to environmental issues brought on by shadow, bird drops, dust, etc., results in localized heating of PV panels. Issues, if they remain undetected, damage the PV module, which results in system permanent degradation [9]. Shaded PV cells operate in the reverse region, blocking the normal flow of current by healthy PV cells due to its series connection [3,12]. For instance, light dust particle accommodation on PV systems reduces light transmission up to 11%. While particle size may vary between 1 and 50 microns [5]. This gives a temperature rise at reverse-biased PV cells, which forms localized heating or the creation of hotspots [13]. These hotspots affect the PV systems in the short term and long term, which includes performance, efficiency, health, and reliability of PV systems [8,14]. The literature suggests that almost 50% of the overall fault is the hotspot [15]. However, PV system overheating may arise due to aging, cracks, snail tracks, etc., as well other than hotspots [3]. Bypass diodes provide an alternative path to avoid additional power loss due to PV cell(s) reverse-biased operation; however, the PV system still suffers from efficiency loss [14].

Some PV issues can be seen through the naked eye such as broken cells, burned cells, corrosion, etc. [16]. However, extensive analysis on PV panels condition/health monitoring for hotspots formation due to environmental issues is very much important specifically in large scale PV systems. Monitoring approaches include a non-invasive image-based approach, such as infrared (IR) thermographic images [3,17], electroluminescence images [18], etc. Moreover, the performance of PV panels can also be monitored using electrical signals, voltage, and current characteristics curves [19]. In IR images, hotspots and defective parts are brighter in appearance compared to the rest of the body [20]. Therefore, some PV panel hotspots and defects are identifiable in IR images [12]. PV issues such as bird drops, string, block, etc., are identifiable through infrared images. More detail of defects and possible identification through visuals of IR images is provided in [12,20]. PV panel issues such as bird drops, string, block, etc., have different concentrations on PV panels surface; hence, their impact is different, as shown in Figure 1. Importantly, the occurrence of these environmental issues is purely natural, and its impact (time duration and intensity) is highly variable. Therefore, their impact on energy production and GHG mitigation potential varies from case to case. IR thermographic experimental approach is provided in [17].

Figure 1. Environmental stresses (hotspots/defects) on PV panels.

PV systems due to their green nature are capable of mitigating GHGs [1]. GHGs are one of the primary causes of climate change. Climate change has a devastating impact on the environment and creates unanticipated health threats [21]. Climate change has affected air quality, human health, food, and water supplies, i.e., social, and natural resources. It

has affected sectors such as tourism and agriculture due to their linkage with weather and climate [21,22]. In a nutshell, climate change has affected human health, illness, air quality, the occurrence of extreme events, vector-borne diseases, water-related illness, food safety, nutrition and distribution, mental health, well-being, etc. More details are provided in [21].

Concisely, PV systems have tremendous green energy potential. Therefore, across the globe, PV systems are used to mitigate the GHGs. However, PV systems suffer from lower efficiency and output due to multiple issues. In this study, the PV system's GHGs mitigation potential under environmentally induced hotspots/defects are investigated. Environmental issues may involve bird drops, shadow, pollution, etc., and accommodation on PV surface. Moreover, hotspots/defects occurrence and concentration are highly variable. For this purpose, different percentages of losses are added in the healthy PV system to investigate the drop in the energy production of a 12 kWp PV system. Afterwards, green energy output by the PV system and equivalent GHG production under mixed fuel combustion in conventional power plants are used to calculate the GHG mitigation potential in different defects/hotspots concentrations. However, this study is generic, but the geographical parameters of Pakistan's capital, Islamabad, are considered.

The rest of the paper is structured as follows: Section 2 discusses the defects concentration on PV panels surface; Section 3 presents the research approach, while Section 4 focuses on the results; afterward, Section 5 discusses research significance, whereas the conclusion is presented in Section 6.

2. Defects Concentration on PV Panel Surface

The PV panel defects can be seen through the brighter areas due to high temperature/hotspots on the PV surfaces [20]. However, it is difficult to identify exactly how much area of PV panel is suffering. For this purpose, defects/hotspots covering PV panels surface are shown in Figure 2 by the white area and the healthy surface through the black surface. Initially, defective PV panels infrared images, i.e., presented in Figure 1 were converted to grayscale images. Afterward, IR images contrast was improved, and a filter was applied to reduce the noise and improve visibility on the PV surface image. Finally, images were binarized using Otsu's method (string and block). Otsu chooses the threshold value to minimize the intraclass variance of the threshold black and white pixels [23].

Figure 2. Defects covering PV panel surface (white defects, black healthy).

However, birds' drop image after filter was binarized by calculating locally adaptive image threshold using local first-order image statistics around each pixel. MATLAB 2020a was utilized for binarized defects investigation on solar PV panels surface. Moreover, it is important that the binarization approach, filters, etc., play a pivotal role. These techniques need careful selection, and results may greatly vary as a result.

3. Research Approach

Environmental issues' impact on PV system energy and GHG mitigation potential are carried out in RETScreen Expert software. RETScreen Expert is developed by the Ministry of Natural Resources, Canada. RETScreen is utilized for various analyses, financial, investment, GHG, etc., for power plants, industries, individual households, etc. [24]. The study is generic. However, Islamabad, Pakistan, is considered to analyze the performance of PV systems with different defects/hotspot concentrations.

After location selection, 12 kW PV system orientation angles are optimized to maximize the annual average daily solar radiations potential. Moreover, the PV system's minor losses due to geographical constraints and aging issues are defined. Since PV system defects/hotspots frequency, severity, and time are purely unpredictable, PV system output energy with different percentages of defects is calculated for a year. Finally, PV systems' energy production potential and GHG mitigation potential under different concentrations of defects are calculated. The proposed research approach is provided in Figure 3.

Figure 3. Proposed research approach.

3.1. Location

The capital of Pakistan, Islamabad, was considered to be an appropriate location for the PV system. Islamabad's geographical parameters are provided in Table 1, which were fetched from NASA meteorological data using RETScreen Expert Software. Geographical parameters greatly affect the PV system output in terms of solar radiations intercept and ambient temperature.

Table 1. Geographical data of Islamabad.

Latitude	33.62 N
Longitude	73.1 E
Air temperature	21.6 Celsius
Relative humidity	62.0%
Precipitation	30.52 inches
Annual average daily solar radiations	4.02 kWh/m ² /d
Atmospheric pressure	91.1 kPa
Wind speed (10 m height)	2.4 m/s
Earth temperature	20.1 Celsius

3.2. PV System

PV cell's proper selection plays a crucial role in PV system performance by extracting energy from intercepted solar radiations. PV system grid tied topology is used in this research to utilize maximum PV system potential. Grid-tied scheme transmits surplus energy to the fossil-fuel-based main grid after fulfilling local load demand. PV system details are provided in Table 2.

Table 2. PV system technical data.

PV Panel (Pmax)	300 Wp
Module efficiency	18.05%
Operating voltages	32.5 V
Operating current	9.24 A
Output	25 years, linear
PV System	12 kWp
Inverter	12 kW
Inverter efficiency	99%

Islamabad's annual average daily solar radiation is 4.02 kWh/m²/d at the horizontal surface. The optimization of PV system orientation (tilt and azimuth) angles increases the PV system electricity production potential. Optimized orientation angles expose the PV surface to most solar radiations without additional investment, operation, and maintenance costs [1]. PV system orientation angles are adjusted to −34 tilted and 180 azimuth angles after careful consideration. This increases the annual average daily solar radiation to 4.38 kWh/m²/d.

3.3. PV System Losses

PV systems mainly comprised of PV panels, and inverters have manufacturing limitations defined by the manufacturer on the respective component's datasheet [25]. Moreover, component performance declines over time due to the aging effect [6]. Additionally, the PV system based on geographical location may suffer from yield limitations. Limitations are due to very minute inert pollution accommodation on the surface of PV panels daily. This pollution layer on PV panels highly varies from location to location. Therefore, considering a real-time scenario, a 13% total loss in a PV system is considered right from the first year to tackle the minute uniform distributed pollution layer, which arises due to location and the aging phenomenon of electrical components.

4. Results

In this section, firstly a 12 kWp PV system output without any operational defects caused by any environmental stress (bird drops, shadow, etc.) or internal issues (wiring, manufacturing faults, etc.) is calculated as a reference. Afterward, 0.5 percent loss in the PV system may arise due to a minor defect/hotspot, such as birds drop, is considered, since it covers a very small part of the PV panel, reflected in Figure 1. Afterward, defect/hotspot-like vicinal objects' shadow covers a considerable amount of PV cells. A

1% loss is considered in the PV system for a year. Finally, multiple hotspots or major fault/defect such as a block covering one third of PV panel surface [12] in the PV system is considered as a 20% loss. However, defects and their occurrence frequency, time span, and causes in the PV system may vary. Since these are purely unpredictable natural events. It is not necessarily a minor loss in the PV system due to bird drop or having the same concentration and loss percentage. It may have other reasons; the details of defects are provided in [20]. Moreover, due to the cleaning of the PV panels, the potential formation of hotspots decreases. However, in this study, the average concentration of hotspots and defects is added for a whole year due to their unpredictable nature and duration. However, their timely monitoring may prevent PV panels from greater and permanent issues [3]. Table 3 provides comparative details of healthy and different percentages of losses in PV system due to defects.

Table 3. PV system energy output in the presence of defects/hotspots.

Location	33.62 N, 73.1 E				
Orientation angles	−34 tilt, 180 azimuths				
Ambient air temperature per annum average	21.6 Celsius				
Defect/hotspot Concentration					
PV output per month average (kWh)	Daily Solar Radiations (kWh/m ² /d)	Healthy	0.5%	1%	20%
January	2.90	981.310	975.735	970.159	758.285
February	4.11	1225.732	1218.768	1211.803	947.157
March	4.17	1334.896	1327.311	1319.727	1031.510
April	4.55	1357.484	1349.711	1342.058	1048.965
May	4.85	1447.077	1438.855	1430.633	1118.196
June	5.04	1430.101	1421.976	1413.850	1105.078
July	4.35	1295.885	1288.522	1281.159	1001.366
August	4.46	1342.288	1334.661	1327.035	1037.222
September	4.66	1380.110	1372.269	1364.427	1066.449
October	5.52	1743.688	1733.780	1723.873	1347.395
November	4.55	1449.648	1441.411	1433.174	1120.182
December	3.47	1169.652	1163.006	1156.361	903.822
PV output per annum average (kWh)	4.38	16,157.871	16,066.065	15,974.259	12,485.6278
System efficiency (%)	-	100	99.43	98.86	77.27
Energy Loss (%)	-	0	0.57	1.14	22.73
Common Loss	Aging and very small layer of inert pollution				

PV system green output per annum in presence of different defects/hotspots concentration is used to calculate the GHG production under mixed fuels energy production technology using RETScreen Expert software. PV system energy output drops due to defects/hotspots directly relate to the PV system's GHG mitigation potential. Detail of GHG mitigation potential in terms of CO₂ equivalent, of PV system under different losses condition, and equivalent cases for better understanding are provided in Table 4. For GHG analysis, losses in Pakistan's transmission and distribution (T&D) sector are considered to be 17.136% [26]. In addition PV system T&D losses are considered as zero, considering the case of a household rooftop.

A 12 kWp PV system located in Islamabad has the potential to mitigate approximately 8 t of CO₂ equivalent GHG emissions per year, which reduces to 6.16 tonnes of CO₂

equivalent GHG emission in case of 20% loss in green renewable energy production due to defects. In the worst-case scenario, 25 years life span of the PV system, if the same percentage of loss persists, limits approximately 45.33 tonnes of CO₂ equivalent GHG emissions, which highly compromises the true potential of the 12 kWp PV system. In terms of energy production capacity, it is approximately 91,806.1 kWh lesser production in PV system life span.

Table 4. PV system GHG mitigation potential with different defects/hotspots conditions.

Equivalent Cases	GHG Reduction Potential (per Annum)			
	Healthy	0.5% Loss	1% Loss	20% Loss
Annual GHG emissions reduction	7.9774 t CO ₂	7.932 t CO ₂	7.8867 t CO ₂	6.1643 t CO ₂
Cars and light trucks not used	1.4611	1.4528	1.4445	1.129
Litres of gasoline not consumed	3427.6479	3408.1726	3388.6974	2648.637
Barrels of crude oil not consumed	18.552	18.4466	18.3412	14.3356
People reducing energy use by 20%	7.9774	7.932	7.8867	6.1643
Acres of forest absorbing carbon	1.813	1.8027	1.7924	1.401
Hectares of forest absorbing carbon	0.7337	0.7295	0.7254	0.567
Tons of waste recycled	2.7508	2.7352	2.7196	2.1256

5. Research Significance

A defect can be simply defined as a cause of energy loss in a PV system. A defect/hotspot caused by environmental factors such as bird drops, vicinal objects shadow, and impurities accommodation on the PV surface reduces the efficiency of absorbing incident solar energy. It forces the PV cells to operate in the reverse region. Hence, dissipating energy and resulting into localized heating. A 20% defect in a healthy 12 kWp PV system reduces the production of 91,806.1 kWh, which is equivalent to 19,475.3 L of gasoline or 105.41 barrels of crude oil burned for the lost energy production, in PV 25 years lifetime.

However, the impact of a household rooftop PV system on GHG emissions mitigation is very limited on a global scale but has equal importance, as conducted in [1,2] studies. Since the reduction in PV output forces energy users to depend on fossil-fuel-based main grid. It results in the production of GHGs. The impact of hotspots and defects, especially if they remain undetected in multiple PV systems or in a large-scale PV system, will have more prominent consequences. For this purpose, multiple PV-equipped rooftop households (single end energy users) scenario equivalent to 1 MW PV system is considered. It illustrates the impact of the defect on large-scale PV system with two cases, without defect and with 20% defect. Defects impact on the energy production capability of the 1 MW PV system is shown in Figure 4. A 20% defective PV system GHG emissions mitigation potential with equivalent cases is shown in Table 5.

Figure 4. 1 MW PV system energy loss due to 20% defective PV system.

Table 5. 1 MW PV system GHG mitigation potential loss due to 20% defective PV system.

Equivalent Cases	GHG Reduction Potential (per Annum)		Difference
	No Defect	20% Defective	
Annual GHG emissions reduction	664.9126 t CO ₂	513.7961 t CO ₂	151.1165 t CO ₂
Cars and light trucks not used	121.7789	94.1019	27.677
Litres of gasoline not consumed	285,694.4523	220,763.895	64,930.5573
Barrels of crude oil not consumed	1546.3085	1194.8747	351.4338
People reducing energy use by 20%	664.9126	513.7961	151.1165
Acres of forest absorbing carbon	151.1165	116.7718	34.3447
Hectares of forest absorbing carbon	61.1547	47.2559	13.8988
Tons of waste recycled	229.2802	177.1711	52.1091

6. Conclusions

PV systems due to their huge potential, renewable and green nature are widely used across the globe. However, PV systems suffer in efficiency, performance, output, and effective GHG mitigation potential because of hotspots and defects. These defects in the PV system arise due to internal issues (manufacturing, etc.) and external/environmental issues (bird drops, shadow, etc.). In addition, environmental issues such as concentration, time, occurrence frequency, etc., are unpredictable and vary from location to location. Therefore, the losses in the PV system specifically due to environmental issues reduce green output, hence lowering GHG mitigation potential.

The 20% environmentally induced defects on the 1 MW PV system in Islamabad reduce the energy output by 306,081.5 kWh in a single year. Moreover, to meet the energy demand gap due to losses in a PV system using mixed fuels combustion, thermal power plants emit approximately 151.12 t of CO₂ equivalent GHGs with 17.136% transmission and distribution losses in Pakistan energy sector. This is equivalent to the burning of 64,930.6 L of gasoline or combustion of 351.4 barrels of crude oil. It requires 34.3 acres of forest to absorb the emitted equivalent CO₂.

Timely identification of PV system issues restrains from green energy loss and dependence on fossil fuel-based main grid. Future works include the practical verification of defects impact on PV system output and identification of PV panel defects and hotspots using machine-learning approaches through noninvasive image processing techniques.

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