एनटीपीसी
NTPC

एनटीपीसी लिमिटेड
(भारत सरकार का उद्यम)
NTPC Limited
(A Govt. of India Enterprise)

Date: 14.03.2024

The Secretary
Central Electricity Regulatory Commission,
3rd & 4th Floor, Chanderlok Building,
36, Janpath,
New Delhi-110001

Subject: NTPC submission on Draft CERC (Terms and Conditions for Tariff determination from Renewable Energy Sources) Regulations, 2024.

Sir,

Hon'ble Commission has published Draft CERC (Terms and Conditions for Tariff determination from Renewable Energy Sources) Regulations, 2024 and has invited comments from various stakeholders on the draft regulation.

In this regard, please find enclosed submissions of NTPC on Draft CERC (Terms and Conditions for Tariff determination from Renewable Energy Sources) Regulations, 2024

Thanking you,

Yours sincerely

Ajay Dua
ED (Commercial)

NTPC Submission on Draft CERC RE Tariff Regulations 2024

1. Clause 2(c) of the Draft Regulations provides that:

"'*Biomass'* *means wastes produced during agricultural and forestry operations (for example, straws and stalks) or produced as a by-product of processing operations of agricultural produce (e.g., husks, shells, deoiled cakes); wood produced in dedicated energy plantations or recovered from wild bushes or weeds; and the wood waste produced in some industrial operations;"*

Submission:

It is submitted that municipal solid waste can be converted to "Torrefied charcoal" which can be co fired with fossil fuel in the boilers. It's a proven technology by which Charcoal produced from MSW can be utilized for generating electricity. Additionally, these projects will have huge indirect benefits as garbage free city which will help in achieving the objectives of **Swachh Bharat Mission**. Apart from that, it will also reduce the methane gas emission that would otherwise occur from the decomposition of MSW.

Hence in order to promote such projects it is requested to include torrefied charcoal also in the definition of biomass and accordingly definition may be modified as follows:

"'Biomass' *means wastes produced during agricultural and forestry operations (for example, straws and stalks) or produced as a by-product of processing operations of agricultural produce (e.g., husks, shells, deoiled cakes); wood produced in dedicated energy plantations or recovered from wild bushes or weeds; wood waste produced in some industrial operations* ***or produce such as charcoal made from municipal solid waste."***

2. Clause 2(z) of the Draft Regulations provides that:

"***Renewable hybrid energy project*** *means a renewable energy project that produces electricity from a combination of renewable energy sources connected at the same inter-connection point."*

Submission:

It may please be noted that the TBCB Guidelines provides that:
"The solar and wind projects of the hybrid project may be located at same or different locations."

Therefore, the definition of Renewable hybrid energy project may be revised to incorporate the provisions of TBCB guidelines as follows:

"Renewable hybrid energy project' means a renewable energy project that produces electricity from a combination of renewable energy sources connected at the same ***or different*** *inter-connection point."*

3. Provision for the Solar panel degradation:

Submission: it is submitted that in the draft RE Regulation no provision has been provided to account for reduction in generation due to Solar panel degradation.

Solar panel degradation comprises a series of mechanisms through which a PV module degrades and reduces its efficiency year after year. Aging is the main factor affecting solar panel degradation, which can cause corrosion, delamination and also affecting the properties of PV materials. Other degrading mechanisms affecting PV modules include **Light-Induced Degradation (LID), Potential-Induced Degradation (PID), outdoor exposure, and environmental factors etc**.

The relevant extracts of the two studies conducted on Solar panel degradation is submitted for the ready reference:

(i) In one of the published papers "Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management" published in Energies 2023,16,3706 provides impact of various parameters on performance of solar modules. The important extract from the paper is as mentioned below:

Table 2. Recent studies and findings of the main causes of PV degradation.

Reference	Country	Cell Type	Key Findings	Cause of Degradation	Degradation Rate
[44]	Australia	Multi-Si solar cell	Comparatively, a smaller number of hotspots were seen in hot weather conditions than in cold weather.	High temperature and humidity	−1.35% to −1.46%/year
[45]	Thailand	Multi-Si solar cell	One of the major degradation factors is moisture.	Moisture and humidity	−1.5% to −4.9%/year
[46]	India	Multi-Si solar cell	The main defects observed in PV modules after 28 years of exposure are encapsulant discoloration, delamination, oxidation of front grid fingers and anti-reflective coating, glass breakage, and bubbles in the back sheet.	Humidity and high cell temperature	−1.4%/year
[47]	Poland	Multi-Si solar cell	Up to 850 MW of rooftop PV can be installed in the city, which has the potential to reduce electrical-energy-related emissions by almost 30%.	Elevated air temperature	>−0.9%/year
[48]	Singapore	Multi-Si solar cell	Greenhouse gas emissions of 0.0811 kg CO_2-eq/kWh would decrease the annual emissions from campus electricity use by 27%,	Ambient temperature	−2.0%/year
[49]	Republic of Korea	Multi-Si solar cell	Low degradation in hot climates can be achieved for Al-BSF technology if properly installed to reduce heat transfer to thermally decouple the modules from the roof. They also found that monofacial and bifacial passivated emitter and rear contact (PERC) modules reduced degradation.	Discoloration and corrosion	−1.3%/year
[49]	Spain	Multi-Si solar cell	Regarding the total system efficiency of the power plants, the range for all years is between 10% and 12%.	Wind velocity	−0.8% to −1.1%/year
[50]	Greece	Multi-Si solar cell	The PV efficiency was found to be about 18% lower than that under standard laboratory test conditions and similar operating conditions. The mean annual PV efficiency was 8.7%.	Ambient temperature, solar irradiation, and wind speed	−0.9% to −1.13%/year
[51]	Cyprus	Multi-Si solar cell	The average efficiency was found to be 5.17% for a-Si, 15.40% for heterojunction with intrinsic thin-layer (HIT) cells, and 10.78% for multicrystalline silicon (mc-Si) modules.	Solar irradiance and cell temperature	−0.8% to −1.1%/year

Table 7. Degradation rates of various aging factors.

Aging Factors	Degradation Rate	Area of Degradation
Dust [60]	5.88%	Efficiency
Discoloration [13]	24.6%	Maximum output power
Delamination [4]	9.50%,	Output power
Hotspot [77]	1.45%	Output power
Crack [89]	2.5%.	Performance ratio
Temperature [96]	0.5%	Efficiency
Humidity [61]	36.22%	Output power

The copy of published paper is attached as ***Annexure-A*** for reference.

(ii) NTPC and its JVs/subsidiaries are implementing various floating solar projects. The water on which floaters are to be placed is brackish in nature and the salinity varies during different months of the year due to seasons. As on date there are no experiences available and precedence to know the impact of saline water on the life of the floaters and degradation of modules.

The study was carried out on degradation analysis and the impacts on feasibility study of floating solar PV system published in *Sustainable Energy, Grids and Networks 26 (2021) 100425 by A. Goswami and P.K. Sadhu.* The conclusion of the study is as extracted below:

"Scarcity of open lands combined with increasing land prices has led to the emergence of FSPV systems for electricity generation in recent times. This paper examines the degradation rate of FSPV module under real outdoor conditions. An experiment was performed to determine the performance and degradation rate of FSPV module and compare it to land-based PV system. Results show that the FSPV module remains cooler than the land based PV system, the average temperature difference is 6 ^{0}C. The temperature difference increases to 22 ^{o}C in the summer months and deceases in the winter time. The performance of the FSPV system is also higher, it generates 10.96% power more than the land-based PV system. The efficiency of the FSPV system is 10.06%more than the land-based counterpart. The lower temperature of the FSPV modules attributes to the higher performance. From the 17 months of ***experiment it was found that the FSPV module had undergone 4.4% higher degradation than the land-based PV module****. The reasons for degradation are explained by analyzing the parameters of the PV modules under real outdoor conditions. The results showed that the increment in series resistance for the FSPV module was 4.1% more than land-based PV system. On the contrary, the shunt resistance of the FSPV module also displayed 4.86% additional reduction. Similarly, the FSPV module displayed higher increment in ideality factor compared to the LBPV module while the saturation current displayed opposite trend.* ***Visual inspection also revealed higher degradation in the FSPV module due to water-based corrosion and moisture ingression.***

On the basis of experimental results, it is seen that FSPV module has higher degradation than land-based modules. *Considering the degradation rates obtained from the experiment, a feasibility study of 5 MW FSPV power plant is also done in the paper. The plant is designed with 5 units each having capacity of 1MWand itis spread over a total water surface area of 60,000 m^2. The power generated by the plant in its lifetime of 25 years by considering1.18% degradation rate is 187,238 MWh, which is 2.06% lower compared to the power output considering standard degradation of 1%. The LCOE calculated is also 2.5% higher considering the actual degradation rate.*

From the results it is concluded that proper estimation of degradation is very important before performing feasibility study of FSPV projects as degradation rate impacts the performance and financial parameters of the project*. FSPV systems also have environmental benefits, the proposed 5 MW system will save 105,000 kL of water from evaporation annually. The FSPV plant will also save 183,493.24 mt of CO2 in its lifetime."*

A copy of published paper is attached hereto and marked as **Annexure B.**

It is submitted that based on the insolation level available at project location, the EPC contractor commits the generation for the first year of operation only and thereafter, Module manufacturers provides a warranty for output wattage in the range which is not less than 90% at the end of 10 years and 80% at the end of 25 years, which is a linear degradation of 0.7% per annum. **Thus, the value of 0.7% annual degradation needs to be considered for considering the generation from the plant year on year basis.**

By considering the degradation factor of 0.7% per year, the power output after 10th year will reach by 93.22% and after 15th year by 90% and after 25th years by 83.89% as represented in the table below:

	Degradation factor	**0.70%**
Year of Operation	**Power Output**	**Power output after degradation**
1	100.00	99.30
2	99.30	98.60
3	98.60	97.91
4	97.91	97.23
5	97.23	96.55
6	96.55	95.87
7	95.87	95.20
8	95.20	94.54
9	94.54	93.87
10	**93.87**	**93.22**
11	93.22	92.56
12	92.56	91.92
13	91.92	91.27
14	91.27	90.63
15	**90.63**	**90.00**

	Degradation factor	0.70%
Year of Operation	**Power Output**	**Power output after degradation**
16	90.00	89.37
17	89.37	88.74
18	88.74	88.12
19	88.12	87.51
20	87.51	86.89
21	86.89	86.28
22	86.28	85.68
23	85.68	85.08
24	85.08	84.49
25	**84.49**	**83.89**

It is pertinent to mention that considering degradation factor in TBCB Projects, following provision exists in the Standard Bidding Documents of SECI:

"The bidders will declare the Annual CUF of the Projects at the time of submission of response to RfS and the SPDs will be allowed to revise the same once within first year after COD. Thereafter, the CUF for the Project shall remain unchanged for the entire term of PPA. The declared annual CUF shall in no case be less than 17%.

*The SPD shall maintain generation so as to achieve annual CUF within +10% and **-15%** of the declared value till the end of **10 years** from COD, subject to the annual CUF remaining minimum of 15%, and within +10% and **-20%** of the declared value of the annual CUF thereafter till the end of PPA duration of **25 years**………"*

Hence the degradation has also been considered in Standard Bidding Documents.

It is pertinent to mention that in case loss of generation due to degradation is not considered and accounted for, then the developer shall require to put additional panels in a time span to compensate for the generation loss occurred due to degradation. Hence developer needs to be provided additional capitalization in subsequent years to recover the cost incurred due to technical phenomenon of solar panels.

In view of above, it is submitted that to take care of the degradation either a **degradation factor of 0.7 per year may be provided** or the generator is allowed **additional capitalization to re-power the solar PV project within the contracted useful life**, to overcome the module degradation and to meet the contracted generation.

4. Clause 16(2) of the Draft Regulations provides that:

"The normative Return on Equity for renewable energy projects other than small hydro projects shall be 14%, and that for the small hydro projects shall be 14.5%. The normative Return on Equity shall be grossed up by the latest available notified Minimum Alternate Tax (MAT) rate for the first 20 years of the Tariff Period and by the latest available notified Corporate Tax rate for the remaining Tariff Period."

Submission:

I. It is submitted that Sections 115BAA and 115BAB were inserted in the Income Tax Act of India through the Taxation (Amendment) Ordinance 2019 to give benefit of reduced Corporate Tax Rates to companies.

Certain RE developers like NGEL have opted for availing the concessional tax rate @ 25.168% as per section 115BAA of Income Tax act 1961. The companies opting for payment of tax u/s 115BAA are not required to pay Minimum Alternate Tax (MAT) under section 115JB of the Act.

It is pertinent to mention that Section 61 (d) of the electricity act also provides that *the Appropriate Commission shall, subject to the provisions of this Act, specify the terms and conditions for the determination of tariff, and in doing so, shall be guided by the following, namely: -*

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safeguarding of consumers' interest and at the same time, recovery of the cost of electricity in a reasonable manner.

In view of the above, it is submitted that for the projects specific tariff being determined on cost plus principles, the ROE needs to be grossed up based on actual tax rate applicable, to ensure the recovery of actual tax expenses incurred by developer.

II. Explanatory memorandum in regards with small hydro projects provides the following:

It imperative to highlight that, in contrast to certain other renewable energy (RE) technologies, Small Hydro Projects (SHPs) typically have a longer gestation period. The elongated gestation period in small hydro compared to other RE technologies signifies a substantial investment timeframe with delayed revenue realization, thereby elevating inherent risks. As such, the Commission proposes a 14.50% Return on Equity for SHP projects, which is 0.50% higher than what is proposed for other RE project.

It is requested that in order to promote small hydro projects and considering their long gestation period, Hon'ble commission may please provide a RoE of 17% for small hydro projects instead of 14.5%. The increase in RoE shall provide an incentive to developers to take elevated risk to harness the renewable source. It is worthwhile to mention that an increased RoE of 17% has also been proposed for run-of-river generating station with pondage in draft CERC Tariff Regulations 2024.

In view of above clause may be modified as:

"The normative Return on Equity for renewable energy projects other than small hydro projects shall be 14%, and that for the small hydro projects shall be 17%. The normative Return on Equity shall be grossed up by actual tax rate applicable."

5. Clause 17(4) of the Draft Regulation provides that:

"Interest on Working Capital shall be at an interest rate equivalent to the normative interest rate of three hundred and twenty-five (325) basis points above the average State Bank of India Marginal Cost of Funds based Lending Rate (MCLR) (one-year tenor) prevalent during the last available six months."

Submission:

It is submitted that in the computation of "Working Capital requirement", receivables equivalent to 45 days of tariff for the sale of electricity is considered on the normative Capacity Utilisation Factor or Plant Load Factor, as the case may be.

It is worthwhile to mention that a generating company raises the bill to the buyers only after receipt of energy accounts issued by RPCs or the state load despatch centre, which is generally received on 5th or 6th day of the subsequent month.

This leads to non-servicing of carrying cost of around five to six days however, same is being met from interest on working capital. Any further reduction in interest rate on working capital shall put additional financial burden on generators.

In view of the above, it is suggested that the existing provision of rate of interest on IWC of **SBI-MCLR +350** basis points may be retained clause may be provided as follows:

"Interest on Working Capital shall be at an interest rate equivalent to the normative interest rate of three hundred and fifty (350) basis points above the average State Bank of India Marginal Cost of Funds based Lending Rate (MCLR) (one-year tenor) prevalent during the last available six months."

6. Clause 20 of the Draft Regulation provides that:

*"**20. Rebate***

(1) For payment of bills of the generating company through revolving and valid letter of credit on presentation or through National Electronic Fund Transfer (NEFT) or Real Time Gross Settlement (RTGS) payment mode within a period of 5 days of presentation of bills, a rebate of 1.5% on bill amount shall be allowed.

Explanation: In case of computation of '5 days', the number of days shall be counted consecutively without considering any holiday. However, in case the last day or 5th day is an official holiday, the 5th day for the purpose of rebate shall be construed as the immediate succeeding working day.

(2) Where payments are made on any day after 5 days within a period of one month from the date of presentation of bills by the generating company, a rebate of 1% shall be allowed."

Submission:

The Draft Regulations provide, the rebate of 1.5% for prompt payment of bills within 5 days from presentation of bills and 1% from payment done from 6th day to within a period of 30 days of presentation of bills and no rebate thereafter up to 45th day.

This dispensation provides for rebate of 1% for 15 days of advancement in payments from 45th day to 30th day from date of presentation. Further, 0.5% increment in rate of rebate is provided for advancement of payments from T+30 days to T+5 days, where T is date of presentation of bills. However, if same rate (i.e., 1% for 15 days) is maintained for advancement in payment from 30 days to date of presentation (i.e., by 30 days), rebate that needs to be provided on presentation would be as high as 3%.

In view of the above, it is submitted that rebate of 0.5% may be allowed on 30th day from date of presentation considering 1.5% on presentation. This will provide a uniform rebate without skewing the rate of rebate on 30th day of presentation. Therefore, it is suggested that the regulation 79(2) may be revised as under:

"20(2) Where payments are made on any day after 5 days and within a period of 30 days of presentation of bills by the generating company or the transmission licensee, a rebate of 0.5% shall be allowed."

7. Clause 47 of the Draft Regulation provides that:

"Capacity Utilisation Factor: The Commission shall only approve capacity utilisation factors for project specific tariffs:

Provided that the minimum capacity utilization factor for solar PV power projects shall be 21%:

Provided further that the minimum capacity utilization factor for solar thermal power projects shall be 23%:

Provided also that the minimum capacity utilisation factor for floating solar projects shall be 19%."

Submission:

It is submitted that there is significant variation in the solar irradiation across the country. Due to this the CUF achieved by the solar plants across the country also varies. The CUF depends on several factors including the solar radiation, temperature, air velocity apart from the module type and quality, angle of tilt (or tracking), design parameters like cable losses and efficiencies of inverters and transformers. **There are some inherent losses which can be reduced through proper designing but not completely avoided.**

The earlier CERC (Terms and Conditions for Tariff determination from Renewable Energy Sources) Regulations, 2017 also has provided the Minimum CUF of 19% and certain SERCs like Karnataka Electricity Regulatory commission has also adopted a CUF of 19% for solar Plants in its generic Tariff order dated 01.06.2023.

Considering the above factors, it is submitted that Hon'ble Commission may please approve capacity utilisation **factors for project specific tariffs, however the minimum capacity utilization factor for solar PV projects may be considered as 19%.**

Accordingly, the clause may be modified as:

"Capacity Utilisation Factor: The Commission shall only approve capacity utilisation factors for project specific tariffs:

*Provided that the minimum capacity utilization factor for solar PV power projects shall be **19%:***

Provided further that the minimum capacity utilization factor for solar thermal power projects shall be 23%:

Provided also that the minimum capacity utilisation factor for floating solar projects shall be 19%."

8. Clause 49 of the Draft Regulation provides that:

"Auxiliary Consumption the Commission shall only approve auxiliary consumption for project specific tariffs:
Provided that the maximum auxiliary consumption for solar PV power projects shall be 0.75%.
Provided further that the maximum auxiliary consumption for solar thermal power projects shall be 10%.
Provided also that the maximum auxiliary consumption for floating solar projects shall be 0.75%."

Submission:

The APC for solar projects consists of transformer losses, line losses and other auxiliary consumption such as lighting, air conditioning load & module cleaning etc. Due to large scale Solar projects which is spread over wide area, requires longer cabling system causing additional generation losses.

It is pertinent to mention that as per the actual APC data of Solar power projects it can be observed that actual APC is much higher than the proposed maximum APC in the draft regulation. For example, the actual APC for the FY 22-23 for Bhadla (260MW), Mandsaur (250MW), Ananthpur (250MW), is 2.75%, 2.96%, 2.05%, respectively and is varying in the range of 2-3%.

Therefore, it is requested that Hon'ble Commission may approve auxiliary consumption for project specific tariffs, however the maximum auxiliary consumption for solar PV & Floating solar PV Projects may be kept at least as 2.5%.

Accordingly, the clause may be modified as:

"Auxiliary Consumption the Commission shall only approve auxiliary consumption for project specific tariffs:

Provided that the maximum auxiliary consumption for solar PV power projects shall be 2.5 %.

Provided further that the maximum auxiliary consumption for solar thermal power projects shall be 10%.

Provided also that the maximum auxiliary consumption for floating solar projects shall be 2.5%."

9. Additional Comments: Requirement of considering Grid Unavailability Factor

It may please be noted that for the recovery of annual fixed charges in Transmission system, the Central Electricity Regulatory Commission (Terms and Conditions of Tariff) Regulations, 2019 provides that:

"51. Normative Annual Transmission System Availability Factor (NATAF):

(a) For recovery of Annual Fixed Cost, NATAF shall be as under:

(1) ***AC system: 98.00%.***

(2) HVDC bi-pole links 95.00% and HVDC back-to-back stations: 95.00%:

Provided that the normative annual transmission availability factor of the HVDC bi-pole links shall be 85% for first twelve months from the date of commercial operation."

It is submitted that the solar PV project, consisting of modules, inverters, inverter transformers, cables, power transformers, switchyard etc. is a static system, analogous to a transmission system.

It is pertinent to mention that the revised TBCB Guidelines issued by Ministry of Power also provide compensation due to Grid Unavailability beyond 175 hours (=2% of 8766) only. The relevant provision is as mentioned below:

"Generation Compensation in off take constraints due to Grid Unavailability: *During the operation of the plant, there can be some periods where the plant can generate power but due to temporary transmission unavailability the power is not evacuated, for reasons not attributable to the Generator. In such cases the generation compensation shall be addressed by the Procurer in following manner:*

Duration of Grid unavailability	***Provision for Generation Compensation***
Grid unavailability beyond ***175 hours*** *in a year, as defined in the PPA*	*Generation Compensation =* *(Tariff X Solar power (MW) offered but not scheduled by Procurer)) X 1000 X No. of hours of grid unavailability.* *However, in case of third-party sale or sale in the power exchange, as price taker, the 95% of the amount realised, after deducting expenses, shall be adjusted against the Generation compensation payable, on monthly basis.*

Like any other electrical system, solar PV system is also prone to failure and has its own Availability factor. Therefore, an availability factor in line with transmission system is also required to be considered for solar PV system.

Accordingly, it is requested to consider the net generation output in a year after considering the 2% of non-availability of electrical system consisting of modules, inverters, inverter transformers, cables, power transformers, switchyard etc while calculating tariff of RE projects.

Annexure-A

energies

Review

Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management

Tuhibur Rahman [1], Ahmed Al Mansur [1], Molla Shahadat Hossain Lipu [1,*], Md. Siddikur Rahman [2], Ratil H. Ashique [1], Mohamad Abou Houran [3], Rajvikram Madurai Elavarasan [4] and Eklas Hossain [5,*]

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Abstract: The degradation of solar photovoltaic (PV) modules is caused by a number of factors that have an impact on their effectiveness, performance, and lifetime. One of the reasons contributing to the decline in solar PV performance is the aging issue. This study comprehensively examines the effects and difficulties associated with aging and degradation in solar PV applications. In light of this, this article examines and analyzes many aging factors, including temperature, humidity, dust, discoloration, cracks, and delamination. Additionally, the effects of aging factors on solar PV performance, including the lifetime, efficiency, material degradation, overheating, and mismatching, are critically investigated. Furthermore, the main drawbacks, issues, and challenges associated with solar PV aging are addressed to identify any unfulfilled research needs. Finally, this paper provides new directions for future research, best practices, and recommendations to overcome aging issues and achieve the sustainable management and operation of solar energy systems. For PV engineers, manufacturers, and industrialists, this review's critical analysis, evaluation, and future research directions will be useful in paving the way for conducting additional research and development on aging issues to increase the lifespan and efficiency of solar PV.

Keywords: solar PV; aging factors; degradation; lifespan; efficiency

Citation: Rahman, T.; Mansur, A.A.; Hossain Lipu, M.S.; Rahman, M.S.; Ashique, R.H.; Houran, M.A.; Elavarasan, R.M.; Hossain, E. Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management. *Energies* **2023**, *16*, 3706. https://doi.org/10.3390/en16093706

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1. Introduction

Utilizing solar PV to generate energy is not a simple operation due to degradation, which can result in a reduction in solar PV performance and efficiency [1,2]. According to recent studies, the rate of degradation varies between 0.6% and 0.7% per year [3,4]. Photovoltaic (PV) degradation can be both linear and non-linear depending on the underlying mechanisms causing the degradation. Linear degradation occurs when the rate of degradation is constant over time, resulting in a gradual decrease in the performance of the PV module. Non-linear degradation occurs when the rate of degradation varies over time, resulting in an accelerated or decelerated decrease in performance. There are several factors that can contribute to the linear degradation of PV modules. One of the most significant factors is exposure to sunlight, which can cause the gradual breakdown of the materials used in the PV module. This breakdown can result in a 2.8% reduction in the performance ratio of the PV module, leading to a gradual decrease in performance over time [5–7]. In general, solar PV has a 25-year expected lifespan. Solar PV modules will not survive for this long in the majority of cases. Aging is the term that is used to describe the degradation of a PV module before its expected lifespan [8,9]. The factors that underlie the reduction in the lifetime of a PV module can be defined as aging factors. The roots of this degeneration are aging-related issues. Researchers and scientists from all around the world have discovered that one of the major causes of reduced life expectancy is aging. Aging factors are among those that significantly affect both performance and efficiency. Each aging factor has its own individual impact, but when combined, they significantly affect the lifespan of PV modules.

The PV sector has been growing at a quicker rate than ever during the past few decades. When the energy crisis is at its worst, solar PV has emerged as one of the most sustainable energy sources due to its amazing attributes, including reduced carbon emissions. Solar photovoltaic energy has been viewed as the primary source of energy in many industrialized nations. The International Energy Agency predicts that by 2025, solar energy will account for 60% of the overall renewable energy capacity, making it the most important source of energy [10]. China, the world's largest producer of solar panels, has pledged to boost its use of non-fossil fuels to 25% by 2030 and has set a target to meet 27.5% of the global energy demand with solar energy by 2050 [11]. African nations such as Ghana have begun to make the greatest use of renewable energy, as has the Asian tech giant China. The Ghanaian government has adopted a master plan to increase 42.5 MW in 2015 to 1363.63 MW by 2030, with solar PV sources alone making up over 50% of the total power [12,13]. Solar highways also have tremendous opportunities in Bangladesh [14]. Solar PV has enormous potential, but it also has significant limitations, such as intermittent power supply and reduced efficiency because of radiation intensity, dust, and temperature.

Since solar PV aging is a severe concern, numerous noteworthy studies have been conducted to solve PV aging and degradation issues. For instance, Santhakumari and Sagar reviewed the environmental elements that contribute to the PV performance deterioration of silicon-wafer-based solar PV modules [15]. Although a variety of PV failures caused by environmental conditions were discussed by the authors, it was not established how these factors affect the PV module's age. Therefore, a thorough examination of the relationship between aging and environmental factors is still necessary. The effects of electromigration and delamination on PV module failure were investigated by Hasan et al. [16]. Other aging variables, such as temperature, cracks, and dust, have not been studied. Consequently, more research on all aging-related aspects is necessary for greater comprehension. The effects of soiling on the deterioration of PV modules were examined by Conceiçao et al. [17]. Unquestionably, one of the most potent aging variables that cause PV modules to age quickly is soiling. Soiling is the process through which dirt or dust gathers and deposits itself on solar panels, and the accumulation of dirt, dust, and other contaminants on the surface of a photovoltaic (PV) module can have a significant impact on the performance and aging of the module. The primary reason for this is that soiling can reduce the amount of sunlight that reaches the surface of the PV module, which in turn can lead to a reduction in the power output and an increase in the operating temperature. When soiling accumulates on the surface of a PV module, it creates a layer of material that reduces the amount of sunlight that can penetrate the underlying layers of the module. This reduction in light intensity can lead to a decrease in the overall power output of the module of 60–70%, which can impact the performance of the entire PV system [18]. In addition, the accumulation of soiling can also increase the operating temperature of the module, which can accelerate the aging of the materials used in the module. Nonetheless, other aging factors have not been investigated. Zhang et al. explored the degradation mechanisms of perovskite solar cells, where the authors showed that the deterioration of solar cells occurs over time but that the contributions of various degradation pathways to PV aging are as yet unknown [19]. Kim et al. delivered a brief review of the lifespan of solar PV, with the authors focusing on how various types of accelerated stress reduce the longevity of PV modules [20]. Even though there was extensive consideration of many aging variables, this investigation failed to establish a connection between degradation factors and PV aging. Damo et al. evaluated the effects of light, heat, and humidity and showed how the PV panel was harmed by these environmental elements [21]. While it was obvious that environmental variables contributed to the aging of PV panels, technical failures of PV modules, including cracks and other installation failures, such as glass breakage, were not investigated. Meuret et al. assessed the long-term performance and degradation of various PV modules in hot climate circumstances, in which amorphous silicon PV modules decayed more quickly than other silicon modules in various temperate climate situations [22]. However, there was no consideration of how temperature affects the lifetime or long-term degeneration of PVs. An overview of the numerous studies on PV deterioration and aging is shown in Table 1.

Table 1. Recent studies, contributions, and research gaps for different factors that affect PV degradation and aging.

Refs.	Objective/Target	Contributions	Limitations
[12]	Analyze the impact of environmental conditions on the performance degradation of silicon-wafer-based PV modules.	This paper provides a comprehensive summation of several methods for preventing PV modules from degrading owing to environmental elements such as dust, ambient temperature, wind speed, snowfall, hailstorms, etc.	Although there are numerous additional ways that PV may degrade, such as cracks, discoloration, and delamination that cause the PV modules to age, the review primarily focused on environmental variables.
[13]	Delamination- and electromigration-related failures of PV module.	This review gives a comprehensive analysis of the causes and consequences of and associations between electromigration and delamination.	The study shows a relationship between the two most common aging variables—delamination and electromigration—but further research into the relationship with additional aging factors is required.
[14]	Examine the degradation of a PV module due to soiling.	This study provides an in-depth examination of the soiling impact on PV modules over time (1942 to 2019).	Although a comprehensive overview of the literature on the soiling impact on PV modules is provided in this work, it does not show how soiling accelerates PV aging.
[15]	Degradation pathways of perovskite solar cells.	Summary of the key degradation mechanism of Perovskite solar cells.	However, the authors did not look into other aspects influencing PV aging in actual operating situations. The research concluded that artificial aging conditions are not analogous to real operational environments.
[16]	The lifetime expectancy of PV module.	This study presents a discussion of various factors that affect the aging of PV modules.	Although this article provides a broad overview of aging variables, it does not address the additional effects of these factors on variables other than lifespan expectancy.
[18]	Long-term performance and degradation analysis of different PV modules under temperate climatic conditions.	With a ratio of 0.9 0.009%/year and 0.75 0.003%/year, a-Si degrades more quickly than its equivalents, followed by m-Si (0.53 0.01%/year and 0.41 0.003%/year) and p-Si (0.36 0.01%/year and 0.28 0.004%/year).	The temperature influence was studied for degradation rates. The deterioration rate does not take into account the impact of other aging processes, such as delamination and crack hotspot discoloration.

This review offers a brief description of the factors contributing to solar PV aging and degradation to fill in the gaps left by the available studies. Additionally, this study offers a thorough analysis of aging factors, emphasizing their effects and potential future paths. The following is a summary of this review's contributions:

- A critical analysis of various degradation rates of solar PV in various countries.
- A thorough examination of several aging factors, highlighting objectives, cases, techniques, contributions, and research gaps.
- A critical investigation of how aging influences the longevity, effectiveness, and materials of solar PV.
- Improvements, opportunities, and future directions for the advancement of PV lifetime and efficiency toward sustainable energy management.

The remainder of the article is split into six groups. Solar PV degradation analysis is presented in Section 2. Several aging variables that impact PV performance are discussed in Section 3. Section 4 provides an illustration of the effects of aging variables, including material deterioration, decreased lifetime, and efficiency degradation. Section 5 presents potential areas for future improvements toward sustainable energy management. A conclusion is provided in Section 6.

2. Degradation Analysis for Solar PV

The degradation of a PV (photovoltaic) module is the term used to describe the steady decline in efficiency and output power of a solar panel over time as a result of numerous environmental influences, manufacturing flaws, and material degradation. Several mathematical models have been introduced by researchers to evaluate the performance of PV modules and analyze PV degradation. A typical polycrystalline PV cell's V-I characteristic is expressed by the following equation using the usual double-diode model:

$$I = I_{ph} - I_{s1}[e^{\frac{V+IR_s}{V_t}} - 1] - I_{s2}[e^{\frac{V+IR_s}{Avt}}] - \frac{V+IR_s}{R_s} \quad (1)$$

where

$$V_t = \frac{kT}{e} \quad (2)$$

where V and I are the terminal voltage and current of a cell, as shown in Equations (1) and (2), respectively, K is the Boltzmann constant, T is the absolute ambient temperature (°K), and e is the electronic charge. In order to approximate the Shockley–Read–Hall recombination in the space-charge layer of the photodiode, the diode parameter A is often set to 2. The following empirical correlations of Equations (3)–(8) acquired from experimental polycrystalline cell characterization, as described in other studies, are used to determine the model parameters I_{ph}, I_{s1}, I_{s2}, A, R_s, and R_p from the values of irradiance E (w/m^2) and ambient temperature T (°K).

$$I_{ph} = K_0 E(1 + K_1 T) \quad (3)$$

$$I_{S1} = K_2 T^3 e^{\frac{K_3}{T}} \quad (4)$$

$$I_{S2} = K_4 T^{1.5} e^{\frac{K_3}{T}} \quad (5)$$

$$A = K_6 E + K_7 T \quad (6)$$

$$R_s = K_8 + \frac{K_9}{E} + K_{10} T \quad (7)$$

$$R_p = K_6 E + K_7 T \quad (8)$$

Setting $I = 0$ and $V = V_{oc}$ in the double-diode model yields the open-circuit voltage V_{oc} for a single cell, as illustrated in Equation (9) below. The highest open-circuit voltage (V_{oc}) that a terminal voltage (V) can reach is zero.

$$V_{oc} = R_p \times [I_{ph} - I_{s1}[e^{\frac{V_{th}}{V_t}} - 1] - I_{s2}[e^{\frac{V_{th}}{A_{vt}}}]] \tag{9}$$

As a solar panel's performance declines over time, it is referred to as PV degradation. Solar panels are made to turn sunlight into energy, but with time, several things may cause them to deteriorate, lowering their effectiveness and power production [23]. PV deterioration can have both internal and external sources. Environmental elements such as temperature, humidity, wind, and UV radiation are examples of external influences [24]. These elements have the potential to harm solar cells or the layer that protects them, which might eventually lead to a decrease in efficiency [25]. The deterioration of the electrical connections between cells or faults in the solar cells, such as fractures or contaminants, are examples of internal issues. The solar panel's design, its operating circumstances, and the quality of the materials used in its construction all impact the rate of panel degradation [26]. Manufacturers frequently offer warranties that guarantee a specific level of performance for a set period of time, sometimes 25 or 30 years, and that might provide insight into the predicted pace of degradation [27].

High temperature is a major cause of PV degradation. When a solar panel is exposed to high temperatures, it can cause several forms of damage that reduce the panel's efficiency and overall performance [28]. Some of the ways in which high temperatures can cause PV degradation include:

- Thermal stress: High temperatures can result in thermal stress inside the solar panel, which may cause the solar cells or other components to break or delaminate [29].
- Electrical resistance: The electrical resistance of the solar cells and interconnections increases with temperature, which can lower the efficiency of the panel [30].

Moisture can also be a cause of PV degradation. Moisture can enter the solar panel through various pathways, such as through cracks or defects in the panel's protective layers or through electrical contacts between cells [31]. Once inside the panel, moisture can cause several forms of damage that reduce the panel's efficiency and overall performance. Moisture can lead to PV degradation through the following mechanisms:

- Corrosion: Moisture can lead to the corrosion of the metal solar panel parts, including the frame and electrical connections. This may result in higher resistance and lower efficiency [32].
- Delamination: The materials used in solar panels, such as the encapsulant or back sheet, can delaminate as a result of moisture. This may cause the layers to separate, exposing the solar cells to moisture or other external elements [31].
- Electrical leakage: Moisture can also result in electrical leakage between solar panel cells or other components. This may result in decreased efficiency and a higher chance of electrical fires or failures [33].

PV deterioration can also be brought on by wind speed. Strong wind speeds can put the solar panel under mechanical stress, which can result in different types of damage that lower the panel's performance and efficiency [34]. The following are some ways that wind speed might lead to PV deterioration:

- Mechanical stress and vibration: Strong winds can bend or cause the solar panel to shake, which can put mechanical strain on the solar cells or other parts. This may cause the solar cells or other components to develop micro-cracks or delaminate, reducing the panel's power output [35].
- Structural damage: Damage to the solar panel's structure, such as the bending or deformation of the frame or supports, can also result from high wind speeds. This may result in the solar cells or other components being out of alignment, which will lower the panel's efficiency [36].

While it is often not as important a factor as temperature, moisture, or wind velocity, solar irradiance can also result in PV deterioration. The quantity of sunshine that strikes the solar panel is known as solar irradiance, and it has the potential to harm the panel in a number of ways that lower its overall performance and efficiency [37]. Solar irradiation can degrade PV in the following ways:

- Hotspots: When a portion of a solar cell is exposed to more sunlight than the rest of the cell, hotspots can form on the surface of the solar cell as a result of solar irradiance. This may result in localized cell damage and heating, which lowers the panel's overall power output. Several technologies, such as drone imaging, have been demonstrated to locate hotspots [38–40].
- Light-induced deterioration: When solar cells are exposed to sunlight for a lengthy period of time, they lose efficiency. Solar irradiance may also cause this type of deterioration. This can be influenced by the type of silicon used in the solar cells or by the presence of contaminants [41].

PV deterioration can also be brought on by the cell temperature. When exposed to sunlight, a solar cell transforms part of the energy into heat and some of it into electricity [42]. The solar cell's temperature may rise as a result of this heat, which may result in a number of types of damage that lower the cell's efficiency and overall performance.

- Light-induced deterioration: Long-term exposure to sunlight causes solar cells to lose efficiency. This kind of degradation might also be brought on by solar radiation. The kind of silicon used in the solar cells or the presence of impurities may have an impact on this [42].
- Thermal stress: Sudden temperature variations can put the solar cell under thermal stress, which can cause the micro-cracking or delamination of the cell or other components. Light- and elevated-temperature-induced degradation (LETID) can cause a decrease in the efficiency of solar cells, which leads to a decrease in the power output of the PV module. This decrease in power output reduces the overall energy production of the PV system and can result in lower financial returns. Additionally, LETID can also cause physical damage to the solar cells, such as cracking, delamination, and corrosion, which can lead to a shorter lifetime of the PV module. This might decrease the cell's power output and increase existing damage [29,43].

Over the past few decades, the temperature of the Earth has notably increased. The data show that high temperature, humidity, moisture, and elevated air temperature are the main factors that cause degradation. The degradation rates vary between -0.8% and -4.9% per year. Research has also found that the average efficiency of multi-Si solar cells under various operating conditions ranges from 5.17% to 18%, with a mean annual efficiency of 8.7%. Proper installation and the use of certain technologies, such as passivated emitter and rear contact (PERC) modules, can help reduce degradation rates in hot climates. Wind velocity, solar irradiance, and cell temperature are also significant factors that affect degradation rates. Table 2 presents a summary of recent studies of PV degradation causes.

Table 2. Recent studies and findings of the main causes of PV degradation.

Reference	Country	Cell Type	Key Findings	Cause of Degradation	Degradation Rate
[44]	Australia	Multi-Si solar cell	Comparatively, a smaller number of hotspots were seen in hot weather conditions than in cold weather.	High temperature and humidity	−1.35% to −1.46%/year
[45]	Thailand	Multi-Si solar cell	One of the major degradation factors is moisture.	Moisture and humidity	−1.5% to −4.9%/year
[46]	India	Multi-Si solar cell	The main defects observed in PV modules after 28 years of exposure are encapsulant discoloration, delamination, oxidation of front grid fingers and anti-reflective coating, glass breakage, and bubbles in the back sheet.	Humidity and high cell temperature	−1.4%/year
[47]	Poland	Multi-Si solar cell	Up to 850 MW of rooftop PV can be installed in the city, which has the potential to reduce electrical-energy-related emissions by almost 30%.	Elevated air temperature	>−0.9%/year
[48]	Singapore	Multi-Si solar cell	Greenhouse gas emissions of 0.0811 kg CO_2-eq/kWh would decrease the annual emissions from campus electricity use by 27%,	Ambient temperature	−2.0%/year
[49]	Republic of Korea	Multi-Si solar cell	Low degradation in hot climates can be achieved for Al-BSF technology if properly installed to reduce heat transfer to thermally decouple the modules from the roof. They also found that monofacial and bifacial passivated emitter and rear contact (PERC) modules reduced degradation.	Discoloration and corrosion	−1.3%/year
[49]	Spain	Multi-Si solar cell	Regarding the total system efficiency of the power plants, the range for all years is between 10% and 12%.	Wind velocity	−0.8% to −1.1%/year
[50]	Greece	Multi-Si solar cell	The PV efficiency was found to be about 18% lower than that under standard laboratory test conditions and similar operating conditions. The mean annual PV efficiency was 8.7%.	Ambient temperature, solar irradiation, and wind speed	−0.9% to −1.13%/year
[51]	Cyprus	Multi-Si solar cell	The average efficiency was found to be 5.17% for a-Si, 15.40% for heterojunction with intrinsic thin-layer (HIT) cells, and 10.78% for multicrystalline silicon (mc-Si) modules.	Solar irradiance and cell temperature	−0.8% to −1.1%/year

3. Major Aging Factors of Solar PV

Scientists and academics have recently been more interested in the significance of producing electricity from solar PV for a variety of reasons, including reduced carbon emissions, long-term solutions for future energy sources, sustainable development, and industrial reliance. However, several elements influence the power generated by PV modules in such a manner that it entirely degrades with time. A visual representation of aging variables is shown in Figure 1. A solar panel generally has a 25-year lifespan. Throughout its lifespan, a solar panel's performance may be influenced both directly and indirectly by many factors. Dust, discoloration, delamination, crack humidity, and temperature are the main factors reducing efficiency.

Aging factors are technological and environmental elements that directly or indirectly contribute to the decline in PV performance. Although the rate of PV performance deterioration brought on by aging factors is extremely minimal over the short term, they can have a significant impact over the long term and can affect how long solar photovoltaic modules last. Over time, the efficiency loss rate for aged monocrystalline and polycrystalline panels is (0.7–1)% according to the Renewable Energy Laboratory (NREL) [20]. When solar panels are exposed to aging factors such as dust, delamination, discoloration, fractures, humidity, and temperature, they deteriorate much more quickly.

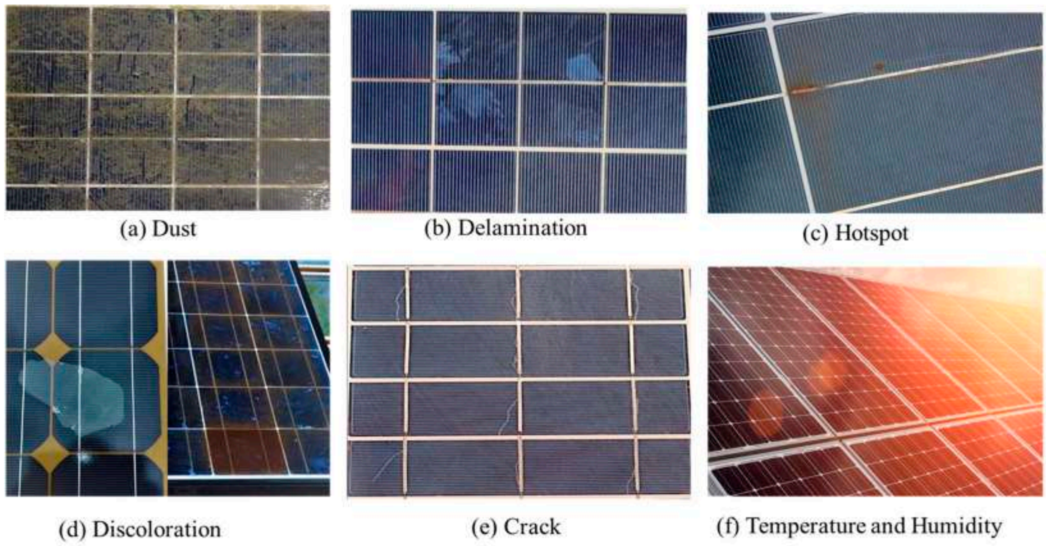
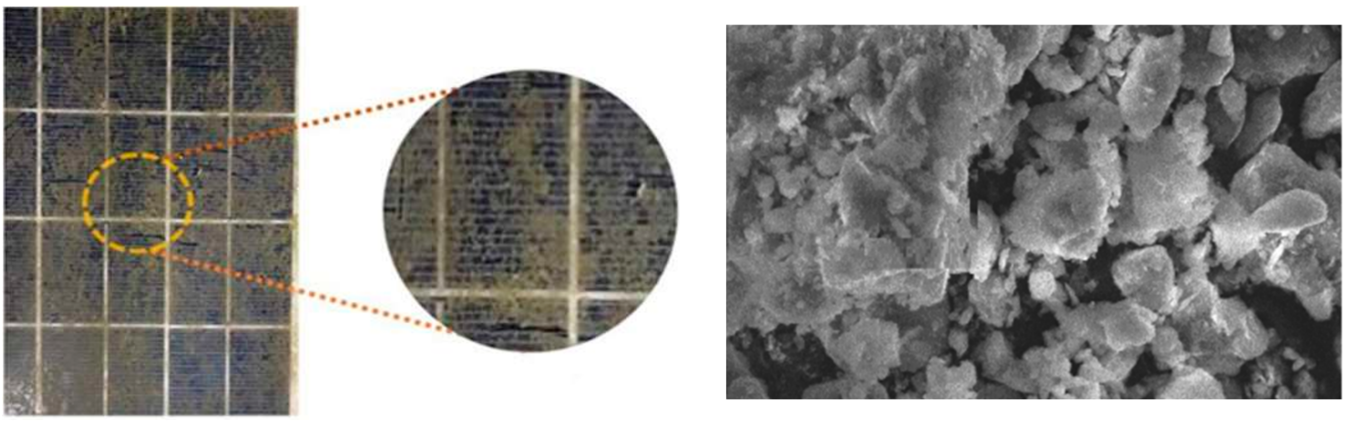


Figure 1. Key aging factors that affect the longevity of the PV module (this figure was developed from the original sample and experiments that were carried out in the laboratory).

3.1. Dust

Generally, dust is defined as small, solid particles with diameters of less than 500 μm. The particles are made up of dust in the air that originates from many environmental causes. The solar PV's output power decreases as a result of these airborne particles building up on its surface and causing shedding on the PV panel. However, the shape, size, and accumulation structure of dust may affect the shedding and its effect on both the lifetime and the efficiency of the PV module. The accumulation of dust particles on solar panels is shown in Figure 2, along with a microscopic image of these tiny particles. The significant influence that dust has on PV performance makes it one of the most critical issues confronting scientists and academics today.



(**a**) (**b**)

Figure 2. (**a**) Accumulation of dust on the PV surface and (**b**) microscopic view of the accumulated dust (this figure was developed from the original sample and experiments that were carried out in the laboratory).

Six photovoltaic modules were exposed to the elements for 6 months in a study by Adinoyi about the effect of dust accumulation on the solar photovoltaic module's output power [52]. The findings show that the output power of solar PV decreased by 50% with the accumulation of dust on a panel left uncleaned for 6 months. With time, this output decline became more pronounced, which caused the panel to permanently age. An experimental examination of the effects of dust deposition on solar PV was conducted by Aslan Gholami et al. [53]. The experiment was conducted for 70 days without any precipitation, and the rate of dust buildup was 6.0986 (g/m^2). The results indicate a 21.47% reduction in output power. Dust can form on the surface of photovoltaic (PV) panels through various mechanisms, which depend on the location and environment in which the panels are installed. Natural processes such as wind erosion, volcanic eruptions, and forest fires can generate dust particles that can travel long distances and settle on the surfaces of PV panels. Human activities such as construction, mining, and transportation can generate large amounts of dust that can be carried by the wind and deposited on PV panels. Agricultural activities such as plowing, harvesting, and livestock grazing can also generate dust that can settle on the surfaces of PV panels. A sawtooth wave shape of dust accumulation is typically seen [54,55]. Another investigation was performed by Ahmed Amine Hachicha et al. in the UAE climate, where it has been amply demonstrated that the tilt angle has a direct impact on the buildup of dust on the surface of the solar panel and that the dust density has a linear relationship with solar PV deterioration [56]. A solar panel's effectiveness decreases over time when it is dirty, and this process gradually and permanently ages the panel. Another investigation was performed by Juaidi et al. in Palestine, where a grid-connected PV plant was exposed for 7 months to determine the impact of dust on the efficiency of the entire PV plant, and the results indicate that the average rate of power reduction was 2.93% per month, which clearly shows that dust significantly influenced the power reduction in a large-scale PV system as well [57]. Kazem et al. evaluated the effect of aging on a grid-connected photovoltaic system by investigating a 1.4 KW PV plant exposed for 7 years; the results indicate that the efficiency of the PV modules decreased by 5.88%, and it is also notable that the degradation rate was severe during the summer months because of the dust density [58]. The rate of PV degradation has a linear relationship with dust density. Frost formation on solar panels can have a significant impact on the general performance of the panels. When frost forms on the surface of a solar panel, it creates a layer that reduces the amount of sunlight that can be absorbed by the panel. This, in turn, reduces the output power of the panel. The reduction in output power can be as high as 25% in a month, depending on the thickness of the frost layer [59].

Because of varying geographic conditions, the impact of dust differs from country to country. Saudi Arabia is one of the Asian desert countries where the rate of dust production is quite high and the weather is very dry. According to research, 6 months of PV panel neglect might result in a more than 50% reduction in output power [52]. Another Iranian study discovered that the tilt angle affects the amount of dust that accumulates on the PV module's surface. At tilt angles of 0°, 15°, 30°, and 45°, the dust accumulation was determined to be 33.4%, 15.8%, 12.1%, and 11.7%, respectively [60]. PV panels in a dry tropical climate, compared to mild regions such as China, are significantly impacted by dust as well. According to Chen et al., dust can lower power production by 7.4%, which is considerably less than in areas with deserts [61]. According to research conducted in Nepal, dust can reduce a PV module's effectiveness by 29.76% [62]. Scenarios demonstrating the impact of dust in Asian nations are shown in Table 3.

Table 3. Impact of dust in Asian countries on monocrystalline and polycrystalline solar PV modules.

Author	Country	Exp. Period	Panel Type	Dust Density	Experimental Conditions	Key Findings
Tafti and Yaghoubi [60]	Iran	8 months	Crystalline silicon	NA	Outdoors	The average daily energy output by PV modules was reduced by 8.6% when they were level and by 0.8% when they were tilted at angles of 15°, 30°, and 45°. Dust storms decreased the daily average energy produced by PV modules by 58.2%, 27.8%, 21.7%, and 20.7%, respectively, at tilt angles of 0°, 15°, 30°, and 45°. For PV modules with tilt angles of 0°, 15°, 30°, and 45°, the average decrease rates of daily energy output owing to dust collection were determined to be 33.4%, 15.8%, 12.1%, and 11.7%, respectively.
Adinoyi and Said [52]	Saudi Arabia	6 months	Both poly and mono	6.184 gm^2	Outdoors	Solar module output power dropped by more than 50%. A single dust storm has the potential to degrade a PV module's power output by up to 20%. When subjected to identical circumstances, polycrystalline modules' backside temperatures were marginally higher than those of monocrystalline modules. The majority of the particles were about 10 µm.
Javed et al. [63]	Qatar	2 months	Not mentioned	100 $mg\text{-}m^2/day$	Outdoors	The most abundant component in the collected dust was shown to be calcium. The collected dust's 90th percentile particle size (based on volume) was 32 µm.
Abbas et al. [64]	Pakistan	3 months	Polycrystalline	0.681 $mg\text{-}cm^2$	Outdoors	Due to dust accumulation on the PV modules' surfaces, the average output power decreased by up to 22% in June, 16% in July, and 18% in August, with an overall 3% reduction in efficiency.
Kazem and Chaichan [65]	Oman	-	Not mentioned	1 g/m^2	Laboratory	Output power decreased by 35–40%. Most particles ranged in size from 2 to 63 µm. Quartz silicates (SiO_2) and calcium oxide (CaO) made up the majority of the dust, accounting for 55.79% and 30%, respectively.
Chen et al. [61]	China	7 days	Monocrystalline	0.644 g/m^2	Outdoors	Reduced the PV output power by 7.4%. SiO_2 and $CaCO_3$ were the major components of dust.
Paudyal and Shakya [62]	Nepal	5 months	Polycrystalline	9.6711 g/m^2	Outdoors	Efficiency was reduced by 29.76%.

3.2. Discoloration

One of the key issues that contribute to the early aging of solar PV is discoloration. PV cells cause discoloration by altering the material's color. The encapsulant ethylene-vinyl acetate (EVA) corrodes as a result of this incident. EVA is a substance that transmits radiation well and degrades slowly under sunshine. This thermoplastic polymer is employed as an encasing agent in solar modules because, when heated, it creates a sealing and insulating coating around the solar cells. The aging of PET (polyethylene terephthalate) in addition to EVA (ethylene-vinyl acetate) can further cause delamination in photovoltaic (PV) modules. The aging of PET in the presence of EVA can cause delamination due to the formation of chemical bonds between the two materials, which weakens the adhesion between the layers. The aging process can be accelerated by exposure to heat, humidity, and ultraviolet (UV) radiation, which are common environmental stressors in PV applications. The delamination of PV modules can be a significant problem, as it can lead to the formation of air gaps and moisture ingress, which can reduce the efficiency of the module and ultimately result in its failure [66]. The presence of air pockets or voids between the solar cells and the EVA encapsulant layer can reduce the fill factor of a solar cell. When the EVA layer does not completely fill the gaps between the solar cells, air pockets can form, which can act as barriers to the flow of the electrical current. The fill factor (FF) is a measure of the efficiency of a solar cell, and it represents the maximum electrical power that can be obtained from the solar cell at the maximum power point, relative to the open-circuit voltage and short-circuit current. It is expressed as a percentage, and a higher fill factor indicates a more efficient solar cell. Light has multiple hues due to its different wavelengths, which are related to the fluctuating frequency and energy of the light source. Using a light source, solar cells generate electricity. As a result, the effect of light irradiance and other characteristics of sunlight, such as the frequency and photonic energy, have a significant impact on solar cells. The degeneration of solar cells is brought on by their discoloration, which can lead to irreversible cell degradation and accelerate aging [67–69]. This degradation is often seen after a prolonged period of exposure and worsens over time. Figure 3 illustrates the aging process due to discoloration.

An experimental test on how Moroccan deterioration affects PV performance was conducted by Bouaichi et al. The panel was exposed to the Mid-South Moroccan climate for two years, and the results indicate that the deterioration rate was an average of 7.56% each year [70]. This reduced the PV module's electricity output by 13.2 watts annually.

Solar panel discoloration and PV deterioration are directly related, according to a non-destructive assessment of encapsulant discoloration with crystalline silicon PV modules conducted by Sinha et al. [69]. They demonstrated that an electrical mismatch appeared to significantly speed up the encapsulant discoloration of the module. Non-uniform discoloration caused a significant loss in the fill factor, which in turn increased the series resistance of cell connections. To a lesser extent, the light reduction was directly responsible for the power degradation caused by discoloration. The electrical mismatch loss might result from encapsulant discoloration. Figure 4 shows the variation in the temperature of PV modules with and without discoloration in spatially resolved dark lock-in thermography (DLIT) pictures of two module pairs. The more brown the module is, the larger the mismatch loss [69]. When compared to similar non-brown modules (b and d) in the same module pair, the brown modules (a and c) show a larger temperature variance. By computing the standard deviation from the obtained pixel data of thermal pictures, the degree of mismatch was assessed. As they do not accurately represent mismatch-induced thermal effects, the extraordinarily hot pixels associated with severe localized faults were omitted from our calculations. The results demonstrate that, due to their discoloration, brown modules have larger electrical mismatches, which would also lead to a decrease in the FF and output power.

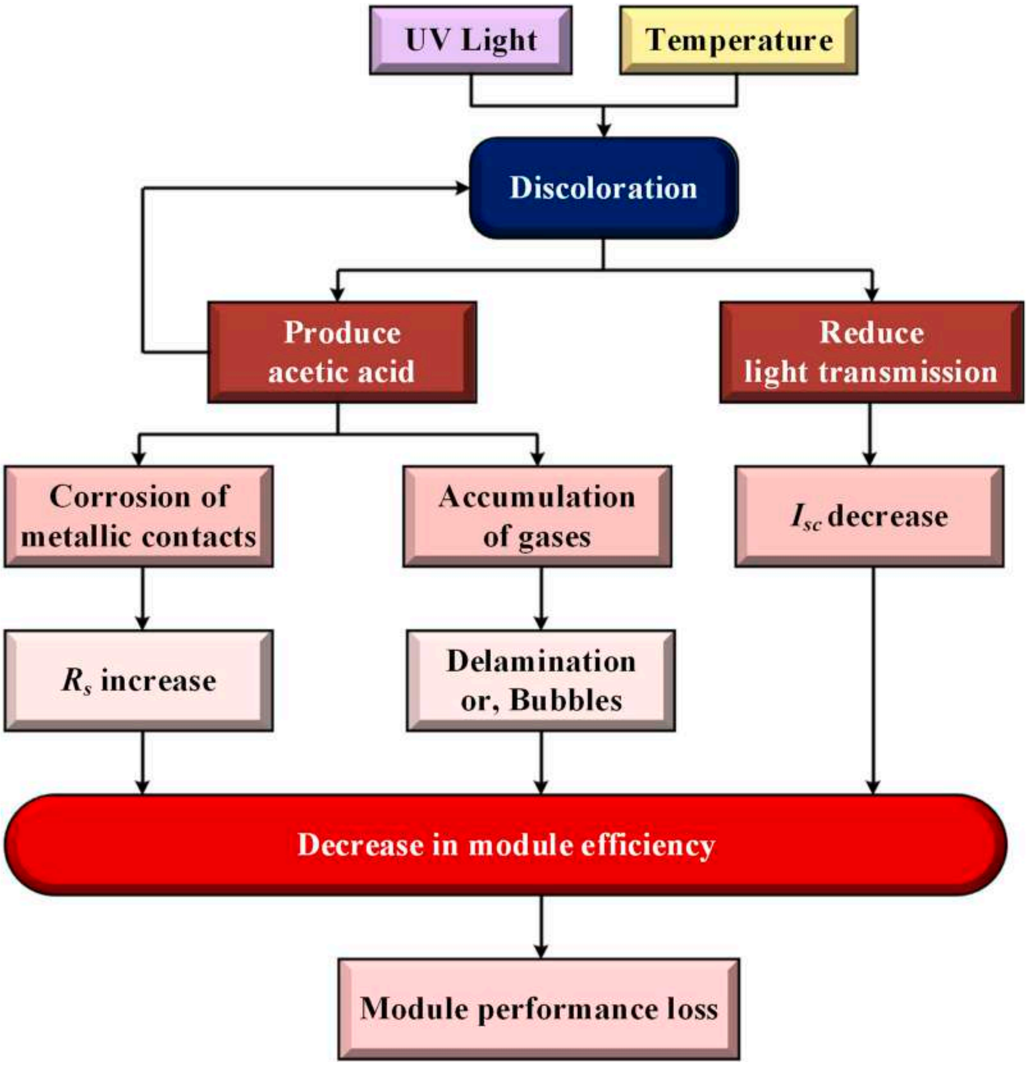
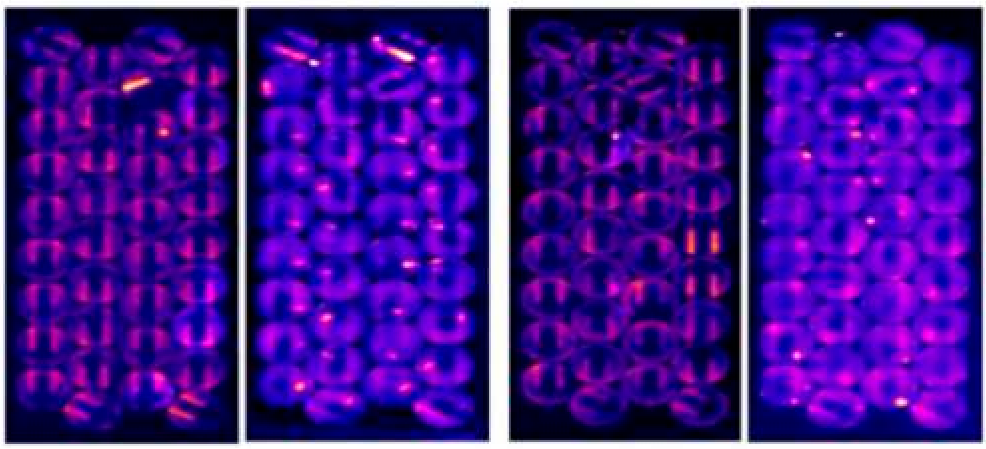


Figure 3. Flow chart of PV aging process through discoloration [69].



(**a**) (**b**) (**c**) (**d**)

Figure 4. Temperature variation in discolored and non-discolored PV modules [69].

In addition to Morocco, the deterioration and aging effects on PV performance were examined in Ghana, an African nation with a tropical climate, where 22 monocrystalline silicon modules were exposed for 16 years. The experiment was carried out by Quansah et al., who found that discoloration was a major factor in the module's maximum power being lowered by 24.6% [13]. With a growing proportion of cell discoloration, the PV cell performance degrades in terms of power output. The PV panel will eventually become completely ruined if the discoloration process continues to progress in it.

3.3. Cracks and Hotspots

The thickness of solar cells can vary depending on the specific type and design of the cell. However, crystalline silicon solar cells are typically between 150 and 200 µm (0.15–0.2 mm) thick. A hotspot is a localized area of elevated temperature on a solar photovoltaic (PV) panel that is brought on by a high resistance in one or more of the panel's cells. This can happen when a solar cell receives less sunlight than the other cells in the panel due to a shadow or other impediment partly covering a piece of the cell. Because of this, the shaded cell produces less energy than the other cells, which may result in a reverse current flow through the shaded cell, which might cause overheating and possibly irreparable harm [71,72]. When solar cells are exposed to changes in temperature, the materials they are made of can expand or contract. If the temperature changes are significant enough, this expansion or contraction can cause stress on the materials, which can lead to cracking or other forms of damage to the cell. The expansion and contraction of solar cell materials can also affect the overall integrity of the solar panel that the cell is a part of. If the solar panel is not designed to allow for thermal expansion and contraction, it can also be subjected to stress and damage. It is crucial to pick materials with great thermal stability when creating solar cells. Spotting hotspots early by obtaining infrared photos of modules can assist in boosting the power production and lifespan of the photovoltaic system. As a result, the use of focused solar radiation in photovoltaic installations can boost the specific power of photovoltaic modules while simultaneously maintaining the temperature of the solar cells within them. In silicon solar cells, hotspots can occur when a portion of the cell becomes shaded or otherwise blocked from the sun while the rest of the cell continues to generate power. This can cause the shaded area to become reverse-biased, which can lead to a buildup of heat and a potential hotspot. Hotspots in silicon cells can cause permanent damage to the cell and reduce the overall power output. In concentrating solar cells, hotspots can occur due to the concentration of sunlight onto a small area. This can cause high levels of heat to build up, leading to thermal stress and potential damage to the cell. Concentrating solar cells are particularly vulnerable to hotspots due to the high levels of concentration involved [73,74]. Hotspots can also develop as a result of manufacturing flaws or cell damage, including micro-cracks or faulty cell interconnections. These flaws might result in high resistance in the afflicted cells, which will heat up the area in question and perhaps harm the panel over the long run [75–77]. Another frequently occurring drawback of solar PV modules is cracking, which generally happens because of the expansion of the solar cell. During the day, the silicon cells, which are very thin, expand and contract because of higher temperatures, which cause small imperfections that lead to larger micro-cracks [78–80]. Cell cracks in solar photovoltaics can also occur while transporting or installing them; environmental factors such as snow, strong winds, and hailstorms can cause cracks in the solar panel as well [81,82]. Different types of cracks can occur in PV modules, including diagonal, parallel to the busbar, and perpendicular to the busbar. However, diagonal cracks cause significant degradation of the output power of solar photovoltaics over time, which can cause permanent aging. Furthermore, the number of PV panel fractures is a significant matter when the output power is reduced. The output power's deterioration is significantly impacted by only 60% of the total fractures [77]. Photovoltaic (PV) modules are subjected to mechanical and thermomechanical strains in outside settings, according to Niyaz et al., which causes the solar cells to develop fractures. Cracks can cause electrical outputs between cells to become imbalanced, which causes an uneven distribution of temperature and has a rapid impact on the performance and long-term dependability of PV modules [83]. Cracks make the solar cell uneven and serve as locations for carrier recombination that reduce EL emission. The results showed that micro-cracks in PV modules can cause power losses of 30% (Humaid Mohammed Niyaz). From the above literature, it can be stated that the classification of cracks based on their properties is the key to analyzing the effects of cracks on the temperature distribution of PV modules. Generally, cracks in PV modules are classified as micro-cracks and cracks based on UV-F (ultraviolet photoluminescence) and EL (electroluminescence) images. The foundation of UV-PL imaging is the idea that when exposed to UV radiation, damaged solar cells will produce less photoluminescence than undamaged ones. Using this method, UV light is used to ignite a solar cell, and a camera or other imaging device is used to record the photoluminescence that results. The resulting image can then be examined to find regions of decreased photoluminescence, which point to cell injury [84]. The EL imaging method is based on the idea that when a voltage is applied to a solar cell, damaged portions will release less light than undamaged ones. This method involves electrically biasing a solar cell to create an EL signal, which is then recorded by a camera or other imaging equipment. The resulting image can then be examined to find regions with a weaker EL signal, which indicates the existence of cell damage. The specific application and type of damage being identified determine the metrics utilized in UV-PL and EL imaging. The strength and dispersion of the photoluminescence or EL signal that is released, the homogeneity of the cell surface, and the presence of flaws or other irregularities in the cell structure are some frequent metrics employed in UV-PL and EL imaging. These metrics can be used to evaluate the overall performance and quality of a solar cell as well as to identify and measure the degree of damage in the cell [85]. Bdour et al. present a summary of data collected from various projects in Jordan to explain the impact of each micro-crack form on power loss and to guide decision-makers in replacing failed panels according to their terms of exchange [86]. Therefore, micro-cracks have different impacts on power loss, with polycrystalline technology having power reduction rates of 0.82–3.21%. The degradation variation depends on module conditions. For monocrystal technology, the power loss varied between 0.55% and 0.9%, except for some samples of both technologies, with effects other than micro-cracks severely affecting performance [44]. Gabor et al. showed that decomposition is largely related to recombination and shunting along cracks rather than the loss of active area [87]. Gabor et al. also presented a comparison of module efficiency and irradiance for three cases. As with single-cell coupons, after charging and cracking, the module had less irradiance than before charging, resulting in a significant drop in efficiency. An undamaged module dropped by 3.9% at 0.2 suns, while a charged module dropped by 9.2%. Interestingly, the efficiency further decreased under 1 sun after cycling, but the decrease was less severe at lower irradiances, so the module was more efficient under 0.2 suns than before cycling at 0.2 sunlight and only dropped by 5.6%. This can be explained by the fact that cyclic loading opened some cracks, effectively removing some areas of cells with internal cracks from the circuit. A shorter total length of cracks remaining in the active area of the cell results in recombination and less rapid decay at reduced irradiance, whereas a reduced active area results in lower efficiency at higher irradiances. Table 4 summarizes the crack and hotspot effects.

According to Dhimish et al., mechanical or thermal strains that partially or fully separate areas inside the solar cell are the major causes of fractures that commonly affect both solar cells in the millimeter to micron range [88]. Manufacturing, the process of transporting the module to the PV site, the installation procedure, a lot of snow, or physical damage to the module can all lead to stress. Cell tearing can be decreased by improving these procedures. Manufacturing will inevitably produce cracks. Dhimish et al. further point out that when the wafer thickness drops, the cracking issue in solar cells becomes worse. This is because the cells' lower thickness makes them more vulnerable to extra mechanical stress when they are put together into a complete PV module. In 60-cell PV modules, if the cell region is not insulated, this frequently results in cell cracking and a performance decrease of up to 2.5%. However, as fractures result in hotspots, several attempts have been made to reduce the impact of hotspot solar cells by employing power electronic devices to control the current delivered to the impacted cells. Similar to one another, these methods use a high-frequency switching component to adjust the module's current without disrupting the connection between the module and the power converter. PV module crack development is shown in Figure 5.

Table 4. Studies performed on crack and hotspot effects on solar PV.

Refs.	Objectives	Contribution	Identification Methods
[77]	Impact of a crack on PV performance	Only 60% of the total crack has a significant impact on the power deduction in the investigated PV modules	Statistical approach
[83]	Impact of cracks on crystalline silicon photovoltaic modules' temperature distribution	The temperature distribution in the PV module depends not only on the type of crack but also on the bias of cracked cells and the number of cracked cells. Shading of a cracked cell can lead to a temperature difference in the range of 10 °C to 26 °C.	Electro-thermal model
[86]	Impact of micro-cracks on PV power reduction	Micro-cracks reduce the power of polycrystalline PV modules by percentages of 0.82–3.21%. For monocrystalline PV modules, the rate varies between 0.55% and 0.9%.	EL imaging method
[87]	Impact of PV design factors on reducing the crack effect	From the cell design level to the system installation level, the authors proposed a broad range of solutions that can stop the crack's effect on PV modules, including thicker wafers, greater busbar input, parallel wiring of cells, etc.	Not applicable

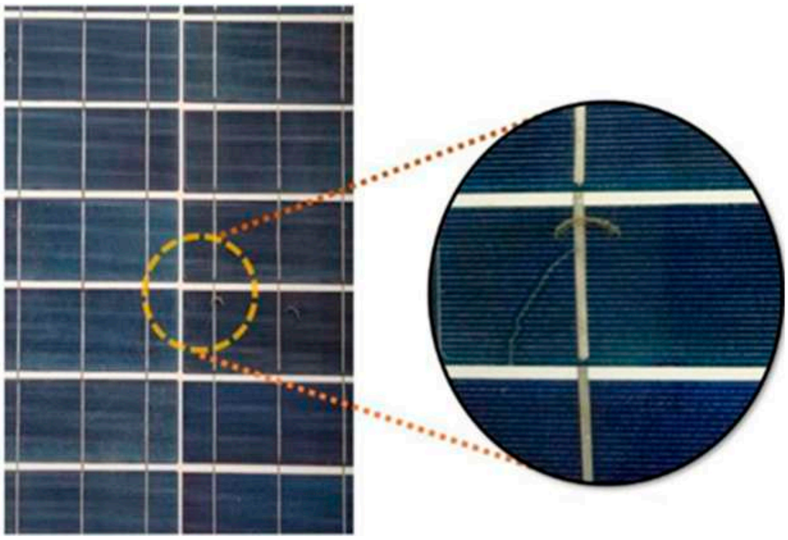


Figure 5. Formation of a crack in a PV module (this figure was developed from the original sample and experiments that were carried out in the laboratory).

3.4. Delamination

The phenomenon of delamination is the separation of laminated solar panel parts from one another. Due to delamination, the production output for the panels will considerably decrease. EVA (ethylene and vinyl acetate), glass, the back sheet, and other raw materials used to make solar photovoltaic modules can become contaminated and consequently delaminate. In addition, the delamination of panels is caused by the environment's high temperature. Other than that, a lot of evidence suggests that delamination is a sign of the solar panel manufacturer's shoddy manufacturing process. The delamination of solar panels causes degradation, which is usually seen after a long period of exposure and soars with time. Figure 6 presents the degradation process through delamination.

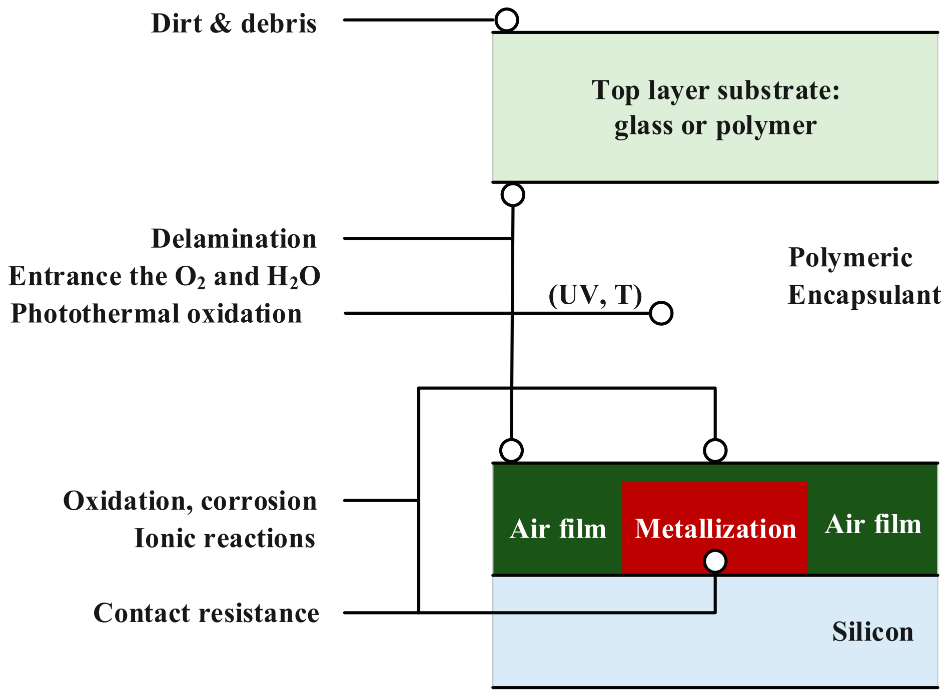


Figure 6. PV degradation process through delamination [89].

A review was presented by Oliveira et al. in which they discuss ethylene-vinyl acetate copolymer (EVA) deterioration in crystalline silicon photovoltaic modules, including its origins and consequences [89]. The generation of acetic acid and other hazardous gases is caused by the photodegradation of EVA by UV light, which also raises temperatures. These gases may result in bubble formation or delamination, which will lower the performance of the PV module. Figure 6 depicts the delamination-based deterioration process. Fonseca et al. performed a degradation analysis of a photovoltaic generator made up of 48 solar panels after it had been operating for 15 years in southern Brazil [4]. The results show that EVA darkening affected 100% of the module cells and produced a milky pattern. Twenty-four of its seventy-two cells were not functioning correctly because of a faulty internal electrical junction. The average installation power had decreased by 9.50%, or 0.7% annually, according to the electrical characterization of the I-V curve data gathered before and after the 15 years of operation for each of the 48 modules. The current decrease (9.19% and 9.12% for IMP and ISC, respectively) was mostly to blame for this power loss. In their experiment on the electrochemical processes of leakage-current-enhanced delamination and corrosion in Si photovoltaic modules, Li et al. demonstrated delamination on the metallization of an Arco Solar module after 27 years of field exposure [90]. The electrochemical reaction on cell metallization results in corrosion and delamination, which are influenced by leakage current, which can be produced by temperature, humidity, and contaminants. The ionic composition of the leakage current can trigger electrochemical reduction processes that result in hydrogen and hydroxide ions when the cell bias is negative. On the metal surface, hydrogen gas can build up, which encourages delamination and reduces the output power. Figure 7 shows a realistic representation of PV delamination.

In the western Himalayan area of India, Chandel et al. performed a degradation study of 28-year field-exposed mono-c-Si photovoltaic modules of a direct coupled solar water-pumping system [46]. PV modules visually displayed considerable cell delamination. Additionally, it was discovered that the PV deterioration rate had increased by 1.4% yearly, which is equal to India's 1.45% degradation rate for monocrystalline modules. Sequential and combined acceleration tests of crystalline Si photovoltaic modules were performed by Masuda et al. [91]. Several variables contribute to degradation when exposed to the elements outside, such as high temperatures, high levels of humidity, thermal cycling, UV rays, current flow, high voltage, salt spray, and mechanical stress. The results, however, indicated that Pmax only slightly degraded throughout the TC (thermal cycling) test, which also included the HF (Humidity Freeze) test, a delamination phenomenon frequently seen in PV modules exposed to the outdoors for an extended period. The delamination impacts are summarized in Table 5.

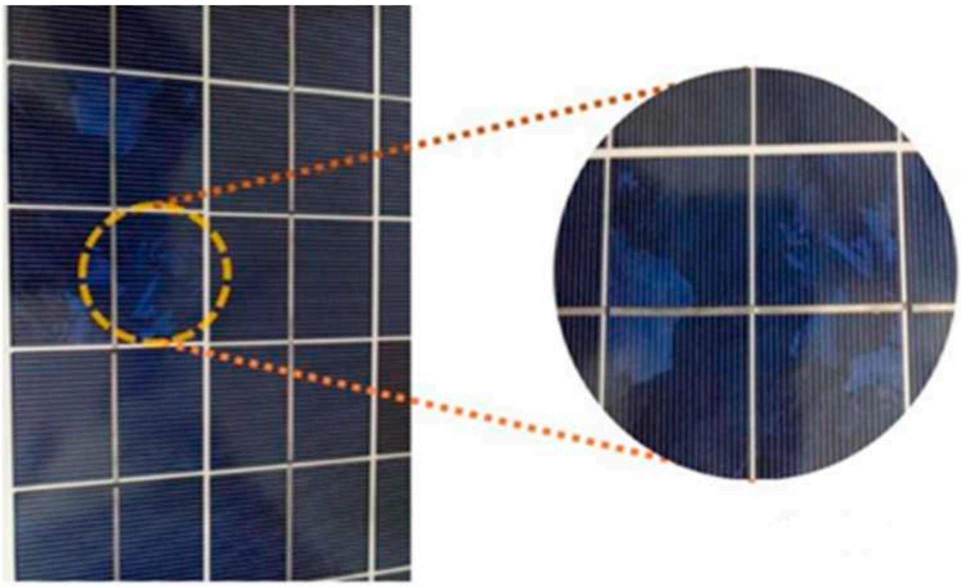


Figure 7. Delamination in solar panels (this figure was developed from the original sample and experiments that were carried out in the laboratory).

Table 5. Effect of delamination effect on PV aging.

Refs.	Objective	Contribution	Limitation
[89]	Cause and effect of EVA degradation	This study provides a thorough analysis of the research on EVA degradation and its effects.	Although aging is one of the key effects of EVA degradation, no precise rate of degradation owing to EVA failures has been determined, according to this study.
[30]	Degradation analysis of 15-year-old PV system	The most frequent defects found were browning (discoloration) and delamination. The average degradation rate was 0.7%/year.	This investigation only focused on discoloration and delamination; however, this PV system was affected by environmental factors too, which were not considered in detail in the discussion.
[90]	Electrochemical failures of Si PV modules due to delamination and corrosion	The electrochemical reaction on cell metallization results in corrosion and delamination, which are influenced by leakage current, which can be produced by temperature, humidity, and contaminants.	No specific degradation rate or relation between aging and delamination was shown.
[46]	Degradation analysis of 18-year-old PV system	Encapsulant discoloration, delamination, and oxidation were the principal flaws. The average power degradation was 1.4%/year.	This study was conducted in an irrigation field where dust is a prevalent component that affects PV modules. However, the authors failed to take this into account.

3.5. Temperature and Humidity

Kinetic energy is transferred from one thing to another through heat. Here, the heat comes from the sun, which is transferred to the PV panels and raises the temperature. Temperature is a measure used to describe how warm or cold something is. The environment's high temperature creates moisture or humidity, which is one of the main elements affecting how well the PV panels perform [92]. With the installation time, this impact grows.

Vásquez et al. experimented with the processing of global climate data and the mapping of the mechanisms and rates of PV module degradation [93]. The Köppen-Geiger-Photovoltaic (KGPV) climatic classification and the anticipated deterioration rates, according to Vásquez, have a direct association. The average rate of deterioration in Europe's hot temperate zones is around 0.5%. However, depending on the year, this figure might change. Additionally, this shows that climate change may influence the long-term effectiveness of PV systems. Another study was conducted by Dhimish et al. on the photovoltaic degradation rate affected by different weather conditions based on PV systems using the YOY (year-on-year) technique for more than 10 years (2008 to 2017) for six distinct photovoltaic (PV) sites in the UK, which is mostly influenced by cold weather conditions, and Australia, which is primarily affected by cold weather conditions. It was discovered that the UK sites' deterioration rates ranged from −1.05% to −1.16 %/year [94]. However, because the temperature is lower than in Australia, a greater deterioration of between −1.35% and −1.46%/year was seen for the PV sites deployed there [88]. Research on the effects of humidity on photovoltaic cell performance was presented by Hamdi et al. [95]. Water has an impact on photovoltaic units when it comes into contact with the cellular elements of the cell, causing its efficiency to decrease and lowering its electrical productivity. The efficiency of solar cells was significantly reduced when they worked in challenging conditions, such as high temperatures and relative humidity of more than 70%. The effects of various environmental and operational parameters on PV performance were reviewed by Hasan et al. [18]. According to their study, the PV module performance degrades with increasing module temperature. Without a cooling facility, the efficiency decreases by around 0.03% to 0.05% for every 1°C increase in temperature. They advise selecting materials carefully so that they can tolerate a humid environment since the corrosion of the PV panel is caused by moisture ingress in humid settings. Tripathi et al. evaluated the performance of solar PV panels in a humid environment [60]. The findings of the experiment show that a rise in the humidity of 50.15% caused a reduction in solar radiation of 24.05% on the panel surface. Additionally, this investigation demonstrated that a rise of 50.15% in relative humidity caused a loss of 36.22% in the panel's output power. However, when the humidity increased from 65.40% to 98.20%, the temperature of the PV panel was lowered by 11.40%, indicating an increase in output power. Table 6 presents a summary of these results.

Table 6. Effects of high temperature and humidity on PV degradation.

Refs.	Objective	Findings	Drawbacks
[93]	Global mapping of degradation and degradation rate of PV module based on temperature effect	The average degradation rate of PV modules in a hot climatic zone is 0.5%/year.	Although a great mapping of PV degradation is shown, aging factors such as cracks, dust, and delamination may have distinct effects that are not reflected in this global degradation map because the mapping is primarily based on temperature or climatic conditions.
[60]	Performance of PV module under humid atmospheric conditions	When the humidity level rises by 50.15 percent, the panel's power output falls by 34.22 percent	The experiment was conducted in a lab setting. It is still necessary to research how natural humidity will affect the results.
[95]	Impact of humidity on PV cell performance	When working in conditions of high air temperature and high humidity (above 70%), PV cells' efficiency is significantly reduced.	The temperature of the cell, which has a significant impact on PV deterioration and longevity as well, was not taken into consideration in this study, which was focused on the humidity effect on the PV cell.
[18]	Effect of environmental factors on PV degradation	Dust accumulation in humid circumstances produces sticky, adhesive mud, which lowers power output by 60% to 70%.	The technical problems with PV degradation, such as cracks, were not covered in this study's thorough analysis of PV degradation and associated mitigation strategies.

4. Impacts of Aging Factors on PV Module

4.1. Impact of Aging Factors on Lifespan

Generally, the life expectancy of solar panels is 20–30 years, and this period can be decreased by the influence of some aging factors. Aging factors influence the solar panel in such a way that it starts to slowly lose its power generation capability. The continuation of this process for a long period triggers the reduction in power generation and, after a time, the solar panel is fully degraded before its expected lifespan.

The performance of solar PV is significantly impacted by dust. The efficiency and output power of solar PV are reduced by the uniform deposition of dust on the surface. The type of dust and the length of time over which it builds depend on the solar PV system's lifetime; dust comes in many different forms, including biological dust, industrial dust, agricultural dust, and airborne dust [96]. Although the output power and efficiency of the solar panel are reduced by airborne dust accumulation, this can be improved by cleaning the PV module. However, if the panel is left dirty for an extended time, such as a year or more, this can affect the light transmission into solar cells because dust particles cause partial shedding, which causes the solar panel to mismatch and develop hotspots, which causes the PV module to age [97]. Bird droppings and other biological dust have a higher impact than airborne dust. Its increased size can result in a 31% reduction in transmittance, which leads to partial shedding and causes the panel to mismatch and develop hotspots [98]. For 15 g of dust deposition, agricultural dust such as mud, rice husk, compost, etc., can result in a maximum power loss of 51.82% [96]. On the other hand, industrial dust such as gypsum and coal can decrease a panel's efficiency by 64% and 42%, respectively [99]. Therefore, it is evident that this will decrease the PV panel's transmittance and result in partial shadowing, both of which will shorten the panel's lifespan [96]. The graph in Figure 8 was created after an in-depth study of Ref. [96], which shows the PV power loss caused by dust accumulation.

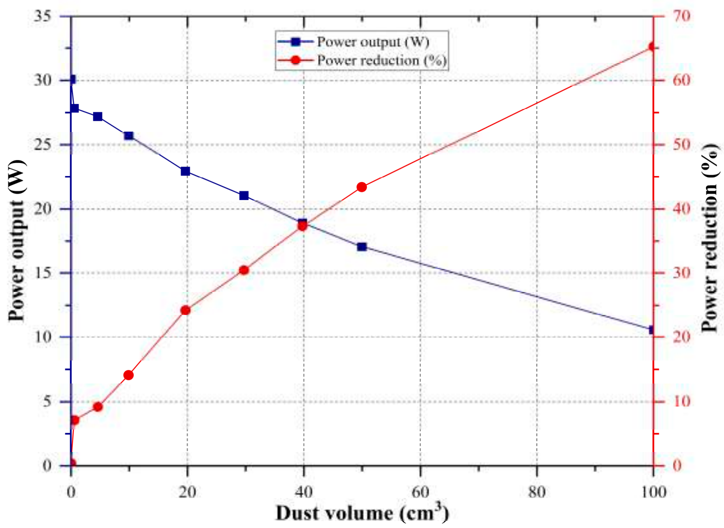


Figure 8. Reduction in PV output power due to the accumulation of dust panels.

Temperature and humidity have a variety of consequences on PV cells that can lead to cell failure and early panel deterioration. The bypass diode problems with PV panels are more prevalent in hot climates such as Australia than they are in cold climates. However, compared to hot tropical climate zones, PV panels installed in cold climate zones, such as the UK, exhibit more hotspots [100]. Rapid changes in the surrounding temperature can also lead to PV panel glass breakage. Due to thermomechanical stress, cracks in the solar cell can be seen. Solar cells with cracks in them can still produce a current, but the voltage will be lower and the output power will be reduced. With time, the percentage of cracks increases, increasing the number of damaged cells [101]. As a result, the PV panel deteriorates earlier than expected. Due to decreased light reflectance and transmittance caused by discoloration and delamination (D&D), which can cause both short-term and long-term deterioration, cell damage, and a reduction in maximum power, the PV panel degrades earlier than predicted [53].

4.2. Impact of Aging Factors on Efficiency

Age-related factors have a significant influence on the PV panel's efficiency. Dust can lower a panel's efficiency by 11.86% and the performance of the entire system by 7.4% [102]. In Nepal, the efficiency fell by 29.76% as a result of dust buildup [62]. Although other aging factors significantly contributed to the decline in solar panel efficiency, dust had a significant influence on the performance of solar PV. D&D reduced the output power by 17.9%, which had an impact on both the module's and the entire system's efficiency [103]. Temperature is one of the main environmental factors that influence efficiency and cause PV aging. The temperature may have a variety of effects on a PV panel's efficiency. Since the semiconductor is utilized to construct the PV cell, it may also result in additional PV failure concerns, including discoloration, delamination, and hotspots. The effect varies from region to region. With rising temperatures, PV panels' output current, voltage, power, and overall efficiency all drop. When the cell temperature drops below 25°C, the current decreases, while the voltage and output power rise. In general, a silicon solar PV module's efficiency can drop by 0.5% for every degree that the temperature rises. After careful analysis of Ref. [104], a graph was developed that shows the reduction in power due to dust. Some models can assess how the temperature affects photovoltaic properties. For evaluating PV performance, there are a number of cutting-edge modeling methodologies, including electrical, thermal, and coupled modeling. The dynamic electrical–thermal behaviors of PV devices can be predicted by a linked electrical–thermal model. In the coupled model, the electrical and thermal behaviors are predicted using a five-parameter SDM and a heat transfer PDE, respectively. Experimental I-V and P-V curves were used to first confirm the validity of the electrical sub-model. Based on this, the coupled model was completely validated using data from five consecutive summer days of field measurements [105].

4.3. Impact of Aging Factors on Material Degradation

A fundamental aspect of a PV cell's deterioration is material degradation or internal degradation, which may not be visible to the naked eye but affects solar PV's performance. The deterioration of solar cells is brought on by the reduction in the semiconductor band gap that occurs at increased ambient temperatures [106]. The gaps may be lowered by 1.569 eV to 1.508 eV for perovskite solar cells [107]. The reduction in PV panel output power caused by accumulation of dust is shown in Figure 9.

One of the biggest reasons why PV cells degrade is also due to the EVA encapsulant's change in color. Stress factors, including high temperatures and humidity, are significant in the case of EVA degradation, which causes cell aging to occur quicker than planned. Potential-Induced Deterioration (PID), which has a substantial impact on PV modules, is an additional cause of the significant degradation of PV modules. One of the aging variables that were significant in initiating the effect of PID is dust. The PV module's collected dust particles lower the irradiation. After 96 h of PID testing, it was demonstrated that the results are 2–4 times better at lower irradiances than at higher irradiances [108]. Table 7 illustrates the contributions of aging factors to PV degradation. In Table 8, a summary is provided.

Overall, dust accumulation on the surfaces of PV modules can reduce their efficiency by blocking sunlight and increasing the operating temperature, leading to thermal degradation. Discoloration caused by exposure to UV radiation can also reduce efficiency by absorbing less sunlight. The delamination of encapsulant layers can lead to moisture ingress, which can cause corrosion and ultimately lead to module failure. Hotspots, caused by shading or cell mismatch, can cause localized heating and material degradation, which can reduce the lifespan of the module. Cracks can also lead to reduced efficiency and material degradation by allowing moisture and other contaminants to enter the module. In addition, the mechanical stresses caused by thermal cycling and wind loading can exacerbate cracking and further reduce the module's lifespan. The degradation of photovoltaic (PV) modules due to various factors, such as dust, discoloration, delamination, hotspots, cracks, temperature, and humidity, can have a significant impact on their performance and lifespan. The following are some mitigation strategies to reduce the impact of these factors:

- Dust: Regularly cleaning PV modules is essential to prevent dust buildup, which can reduce the amount of sunlight reaching the cells. Cleaning can be performed using water or a soft brush, but care should be taken not to scratch the surface of the module.
- Discoloration: The discoloration of PV modules can be caused by various factors, such as exposure to UV radiation, extreme weather conditions, and chemical damage. To mitigate this, it is recommended to use high-quality materials with UV stabilizers and to avoid exposure to harsh chemicals. Regular maintenance and inspection can also help detect discoloration early and prevent it from spreading.
- Delamination: Delamination is the separation of layers in a PV module, which can lead to reduced performance and even complete failure. To mitigate this, it is essential to use high-quality materials and to ensure proper installation and maintenance. In the case of delamination, the affected area should be promptly repaired or replaced.
- Hotspots: Hotspots occur when a small area of a PV module generates more heat than the rest of the module, which can lead to reduced performance and even damage. To mitigate this, it is essential to use high-quality materials and to ensure proper installation and maintenance. Additionally, PV modules with bypass diodes can help prevent hotspots by redirecting the current around the affected cells.
- Cracks: Cracks in a PV module can reduce its performance and lifespan. To mitigate this, it is recommended to use high-quality materials and to ensure proper installation and maintenance. Regular inspections can help detect cracks early and prevent them from spreading.
- Temperature: High temperatures can reduce the performance of PV modules and shorten their lifespan. To mitigate this, it is recommended to use materials with high thermal conductivity and to ensure proper ventilation and shading. Additionally, PV modules with anti-reflective coatings can help reduce the amount of heat absorbed by the cells.
- Humidity: High humidity can lead to corrosion and other forms of damage in PV modules. To mitigate this, it is recommended to use materials that are resistant to corrosion and to ensure proper installation and maintenance. Additionally, regular inspections can help detect and prevent damage caused by humidity.

Table 7. Degradation rates of various aging factors.

Aging Factors	Degradation Rate	Area of Degradation
Dust [60]	5.88%	Efficiency
Discoloration [13]	24.6%	Maximum output power
Delamination [4]	9.50%,	Output power
Hotspot [77]	1.45%	Output power
Crack [89]	2.5%.	Performance ratio
Temperature [96]	0.5%	Efficiency
Humidity [61]	36.22%	Output power

Table 8. Impact summary of aging factors' contributions to PV aging.

Impacts	Reference	Effects	Contributions	Research Gaps
Efficiency	[98]	Solar PV systems' efficiency can be severely reduced by dust. Dust efficiency decreased by 64%, 42%, 30%, and 29% with various types of industrial dust, such as coal, aggregate, gypsum, and organic fertilizer, respectively.	The authors looked at many sorts of dust and discovered that of all the dust they looked into, coal had the greatest impact on efficiency loss. The authors also asserted that when the temperature rose, PV performance decreased because of heat loss caused by dust buildup.	The research noted that dust buildup raised the module's temperature, but no analysis of the effects of high temperatures or their relationship with dust accumulation was performed.
	[102]	Bird droppings, dust, and water droplets reduced the output power by 8.80% and the efficiency of solar PV by 11.86%.	Although environmental elements, including dust, moisture, and bird droppings, drastically affected efficiency, a water droplet on a PV module's surface lowered the temperature, which was able to increase the output power by 5.6%.	The influence of several environmental conditions on efficiency deterioration was demonstrated by the authors, but further research is still needed to determine how these factors affect other aging aspects in PV modules, such as discoloration or delamination.
Lifespan	[44]	Climate variables such as humidity and temperature affect how long solar panels last, and the rate of PV deterioration is higher in cold weather (UK) than it is in hot weather (Australia). For the UK and Australia, respectively, the deterioration rates range from 1.05% to 1.16%/year and 1.35% to 1.46%/year. Furthermore, the significant danger of glass breakage is brought on by the chilly climate.	The authors found that no bypass diodes were damaged in cold climatic conditions, and the number of hotspots found in cold climatic conditions (UK) was less than in hot climatic conditions (Australia).	The interrelationship between temperature and aging factors and how it affects the lifespan of PV modules is not thoroughly discussed, despite the authors' excellent investigation of PV degradation in two opposing climatic conditions, which revealed sporadic indications of various aging factors, such as hotspots and cracks.
	[101]	The possible impact of a crack and its position on output power degradation might significantly shorten the PV panel's expected lifetime.	The significance of a crack depends on the percentage of damage to a PV cell. This study found that 50% of damaged cells are cracked parallel to the busbar.	It was not thoroughly addressed how percentages of damaged cells, cracks, and crack orientation affect output power.
Material degradation	[106]	As the temperature rises, the lattice scattering worsens and the semiconductor's carrier mobility worsens. A high ambient temperature will widen the band gap on the PV surface, diminish photon absorption, and deteriorate the semiconductor.	When the temperature is increased to 30 °C and 70 °C, the electron mobility decreased from 114 $cm_2/(Vs)$ at temperature T = 0 °C to 98 °C and 82 $cm^2/(Vs)$, respectively.	Although the authors claimed that rising ambient temperatures increase band gaps, reduce electron mobility, and increase photon absorption, there is no clear evidence of how quickly materials degrade with each increase in temperature.
	[13]	The most common visibly noticeable flaws on the modules were encapsulant discoloration and junction-box adhesive deterioration.	Maximum power can be degraded by 18.2–38.8%. The annual linear degradation rate was 1.54%.	A 16-year-old PV module was studied by the authors, but further research is still needed to determine what would happen in the event of a relatively short exposure duration.

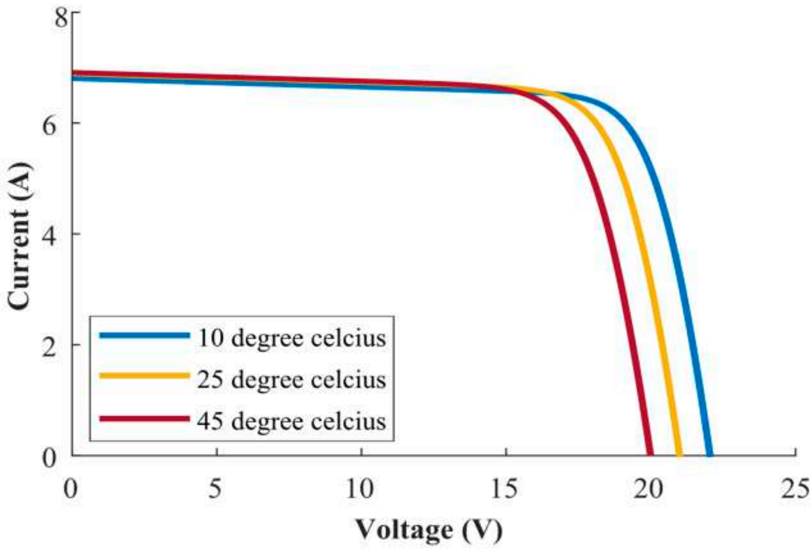


Figure 9. Reduction in PV output power due to the accumulation of dust panels.

5. Future Directions for Mitigating the Impacts of Aging Factors on PV Modules

Based on the critical discussion, information, and analysis, this study offers the following effective suggestions for sustainable energy management for solar PV.

- This study found that dust is one of the main components that accumulate on the PV module's surface and causes shedding, decreases photon absorption, and increases PV module degradation in a variety of ways, including output power reduction and efficiency degradation, which decrease the PV module's lifespan and efficiency as well. Therefore, more research is needed to understand how the form, size, and accumulation direction of dust particles impact the rate of deterioration and lifespan of PV modules.
- The encapsulant material's discoloration can reduce the module's transparency, which in turn reduces the quantity of light that reaches the solar cells and the module's total power production. Additionally, discoloration raises the module's temperature, making it more vulnerable to thermal stress, which can lead to cracking and other types of physical damage. As a result, the module's lifetime, power-generating capability, and efficiency may all decline. Hence, an in-depth investigation is necessary to prevent discoloration.
- A PV module's stability and structural integrity may be impacted by delamination, which happens when its layers split or detach from one another. By lowering the amount of light that reaches the solar cells and by raising the resistance in the module's electrical circuit, delamination can also result in a decrease in the performance of the module. This may cause the module's efficiency and power output to decline, which will lower its overall performance. To reduce the effect of delamination on the deterioration and longevity of PV modules, extensive investigation is required. It is also crucial to employ high-quality, long-lasting materials and construction methods, as well as to properly maintain and monitor the condition of the PV modules. Additionally, regular inspections and preventative maintenance can also help identify and address any delamination-related symptoms before they cause serious harm.
- The creation of fractures in solar cells because of mechanical and thermomechanical stresses causes the PV modules' electrical outputs to become imbalanced. According to this study, diagonal fractures significantly reduce the output power, efficiency, and lifespan of PV modules. The impact of cracks also depends on their direction. To reduce the effect of cracks on the deterioration and longevity of PV modules, further analysis is thus necessary. It is also crucial to employ high-quality, durable materials and construction processes, as well as to properly maintain and monitor the status

of the modules. Regular inspections and preventative maintenance can also aid in identifying and addressing any cracks before they cause serious harm.

- The materials used in the manufacturing of the module, such as the encapsulant material, solar cells, and metal frame, can experience thermal stress at high temperatures. This may result in physical damage, such as warping, cracking, and other issues. High temperatures can also slow down the deterioration of the module's materials and lower the danger of electrical failure. To reduce the effect of temperature and humidity on the deterioration and lifespan of PV modules, extensive research is required. It is also crucial to properly design and install the modules with the right ventilation and temperature control, as well as to regularly monitor and maintain the modules. The danger of degradation due to temperature and other environmental factors can also be decreased by using high-quality, long-lasting materials and building methods.
- Several variables, including climatic conditions, manufacturing flaws, and material aging, contribute to the decline in the performance of PV systems over time. As a result, it is crucial to identify and treat PV system aging to guarantee peak efficiency and lifetime. By identifying patterns in output power datasets, defect identification using sensor data analysis, and damage detection using picture analysis, artificial intelligence (AI) may play a significant role in the detection of PV system aging. For example, a solar energy company installs sensors on its PV panels to collect data on various parameters, such as voltage and current. These data are then fed into an AI-based system that uses machine learning algorithms to analyze the data and detect any anomalies or changes that may indicate the aging or degradation of the panels. The effectiveness and lifetime of PV systems, maintenance costs, and the adoption of renewable energy sources may all be improved with the application of AI in PV aging detection.
- Government policies and financial incentives can play a crucial role in preventing PV aging by encouraging the adoption of best practices in PV module manufacturing, installation, and maintenance. Governments can set minimum quality standards for PV modules and systems, which would encourage manufacturers and installers to adhere to best practices to ensure the longevity and reliability of their products. Governments can also fund research and development initiatives aiming at the development of new technologies and materials that can improve the durability and efficiency of PV modules and systems.
- Collaboration between researchers, industry stakeholders, and policymakers is crucial in preventing PV aging. Through collaboration, they can work together to develop and implement strategies for preventing PV aging, such as improving the quality of materials and construction methods, implementing regular maintenance and inspection programs, and providing financial incentives for the adoption of best practices. Additionally, collaboration can lead to the development of new technologies and innovations that can help to prevent PV aging, such as advanced materials and coatings that are more resistant to environmental factors such as dust, moisture, and temperature.
- New and emerging solar PV technologies, such as perovskite solar cells and bifacial modules, have the potential to address some of the degradation and aging issues associated with traditional solar PV modules. Perovskite solar cells are a type of thin-film solar cell that has demonstrated high efficiency and potential for low-cost production. These cells have shown promise in mitigating some of the degradation issues related to traditional solar cells, such as cracking and delamination. Bifacial modules, on the other hand, have the potential to increase the efficiency and energy output of solar PV systems. Bifacial modules can generate electricity from both sides, allowing them to capture light that is reflected from the ground or other surfaces. This can help reduce the impact of shading and soiling on the front surface of the module. Additionally, bifacial modules are less susceptible to hotspots and can help reduce temperature-related degradation.

The aforementioned analysis, critical evaluation, and constructive suggestions would be useful for conducting further exploration to overcome the concerns and challenges of the degradation and aging of solar PV toward sustainable energy management, creating a pathway to reduce global carbon emissions and achieve sustainable development goals (SDGs). By improving the efficiency and output power of PV modules, clean energy can be generated at a lower cost, making it more accessible and competitive with fossil fuels. This can help to promote the adoption of renewable energy sources and reduce dependence on non-renewable sources of energy (SDG 7). In addition, the development of the PV industry can lead to the creation of many job opportunities (SDG 8). Moreover, the need for replacement or additional PV modules can be reduced by extending their lifespan and efficiency, which will lessen their environmental impact and improve the sustainable use of resources (SDG 12). By improving the durability and stability of PV modules, the risks associated with climate-change-related events, such as extreme weather conditions, can be mitigated. This can help to combat the impacts of climate change (SDG 13).

6. Conclusions

Solar energy will be a future alternative energy source that the world realizes due to the global energy crisis and rise in carbon emissions over the past few decades. However, there are several key aspects that need to be taken into account for solar PV degradation. Due to the influence on longevity, material deterioration, and efficiency decrease, several aging elements, including dust, discoloration, delamination, temperature, humidity, fractures, and hotspots, were examined in this research. Firstly, the causes of degradation and the degradation rate were analyzed for different types of solar cells in different countries. Secondly, aging factors were introduced, followed by in-depth investigations regarding each of the aging factors. This analysis provides an overview of the current situation, the impact on performance, and the characteristics of the PV aging variables. Thirdly, a comprehensive assessment was conducted on the effects of aging variables on PV modules, including lifetime decrease, material degradation, and efficiency degradation. This investigation showed that each factor affecting aging has a distinct and varied effect on PV modules. According to reports, dust can decrease solar panels' effectiveness as it accumulates over time; nonetheless, dust's effect on the lifespan is less severe than that of other aging factors. Cracks and hotspots, on the other hand, have a significant influence on lifetime and efficiency deterioration; however, the rate of degradation is based on the proportion of afflicted PV cells. The solar PV's lifetime expectancy, material deterioration, and efficiency reduction are all impacted by both discoloration and delamination; nonetheless, delamination and discoloration caused by temperature and humidity are more severe. The effects of all aging variables were also demonstrated to linearly increase over time.

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Annexure-B

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Degradation analysis and the impacts on feasibility study of floating solar photovoltaic systems

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ABSTRACT

The constant pursuit for emerging renewable power sources has led to the development of floating solar photovoltaics (FSPV). FSPVs operate on water bodies and hence its performance is different from the land-based counterparts. Degradation and aging of PV modules severely affects the reliability and the life of PV power plants. Owners and other beneficiaries are concerned about the actual degradation of PV modules as it affects the financial outcome of the power plant. The performance analysis and the degradation of FSPV power plants over its lifetime is not well reported. This paper presents techno-economic feasibility and reliability study of FSPV power plant for long term power generation. To determine the performance of the FSPV module, an experiment was conducted and data was collected for 17 months. Results showed that the average performance ratio and the degradation rate was 71.58% and 1.18% respectively for the FSPV module and 64.05% and 1.07% respectively for land-based PV system. Feasibility study and performance analysis of a 5 MW FSPV power plant showed that with degradation of 1.18%/year, the power plant will generate 8604.5 MWh of electricity annually. Degradation also effects the financial parameters, the levelized cost of electricity (LCOE) is calculated as 0.041 $/kWh which is 2.5% higher than the LCOE calculated with standard degradation. The FSPV plant will also save 105000 kL of water per year by reducing evaporation and the total lifetime CO_2 savings will be 183,493.24 tones.

1. Introduction

From the last decade, the global energy demand is constantly on the rise. The drivers for the demand are population growth and rise in industrialization. The global energy need is estimated to increase by 50% to 7500 GW by 2040 [1,2]. A major share of the energy is obtained from conventional sources like coal and oil. To satisfy the huge energy demand, there has been an increased pressure on fossil fuels. The unsustainable extraction of fossil fuels has led to the depletion of fossil fuel reserve of the earth. Fossil fuels also have negative impact on the environment, they produce pollution and are instrumental in greenhouse gas generation. To tackle the issue of preserving the environment while satisfying the global energy demand, the policymakers are emphasizing on alternative power generation sources which are green and sustainable. Among the non-conventional sources of energy, the most common are solar energy, wind energy, tidal energy and geo-thermal energy. Solar photovoltaics (PV) have gained prominence in the recent years owing to the vast energy emitted from the Sun, which is both clean and inexhaustible. The earth receives around 3.4 million exajoules of energy. Even with 10% efficiency the solar energy potential of the earth is around 3500 GW [3,4]. As of 2018, the total solar power generation using various PV technologies is 425 GW [5]. With advancement in solar PV technologies the global solar power generation is expected to rise almost twenty times to 1.8 TW by 2050 [6]. It is estimated that by 2030, solar PV systems will deliver 25% of the total global energy need. Table 1, presents the expected rise in solar PV system in different continents.

To promote solar PV systems, the policymakers have introduced new regulations and provided subsidies. Introducing subsidies will encourage commercial and especially residential consumers to shift to independent solar power and not entirely depend on grid power supply [7,8]. Srivastava et al. [9], discussed the various factors required to set up a solar power plant. They suggested that solar irradiance, wind speed and temperature must be measured very precisely. The authors analyzed PV power plants located in different parts of the world and found that almost 27% of the energy is wasted in PV modules and accessories. Rojas et al. [10], presented the performance analysis of a hybrid power plant consisting of 4.15 MW solar power plant and 5.3 MVA diesel generator set. In the hybrid system, the renewable power penetration was nearly 46%. Due to proper designing, the system was able to supply power entirely for 10 h a day. To

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Table 1
Expected generation from solar PV systems [18].

Continent	Solar PV capacity (GW)		
	2018	2030	2050
North America	55	473	1728
South America	7	97	281
Asia	280	1680	4837
Europe	121	291	891
Africa	8	131	673
Oceania	10	25	109

maximize the power output from the PV modules, it is required to track the maximum voltage and the maximum current of the module effectively. Satsangi et al. [11], designed a grid connected 40 kW solar power plant to supply power to a university in India. The average efficiency of PV module was reported to be 9%. The solar power plant generated about 31.74 MWh of energy annually. Various maximum power point tracking (MPPT) techniques are used so that PV modules operate at maximum power point and delivers maximum power output [12,13]. Solar PV module's efficiency and power production depends on the weather conditions. The power output from the solar modules depends on amount of solar irradiance falling on the module. The output of a solar power plant is also impacted by the presence of cloud in the sky [14,15]. Presence of dust, shadows and other obstruction causes partial shading of solar modules. Partial shading has a detrimental effect on the efficiency of PV modules. Mostefaoui et al. [16], discussed the issue of partial shading of PV modules in the Saharan region. The power output of the PV modules reduced by 30% due to partial shading. Timely cleaning and proper sun tracking system could be effective to counter partial shading. Chandrasekaran et al. [17], employed sine-cosine technique to solve the problem of partial shading. The proposed technique effectively tracks the maximum power point even during shading. They developed a 2 kW PV system and the algorithm tracked the MPP with 96% efficiency.

The feasibility of developing a PV power plant depends on the long-term performance and the economic considerations. For a PV power plant to be economically sustainable, it is important to determine the financial outcome of the plant, the payback period and the LCOE [19,20]. Generally, PV power plants are expected to work for at least 25–30 years. With time, the PV modules face degradation due to UV exposure, thermal cycles and wear and tear [21]. Proper estimation of the PV module degradation is essential as the performance, power output and hence the LCOE is affected. Kumar et al. [22] studied the degradation of 200 kW roof top solar system situated in Northern India. They found that, for tropical region the solar modules operate with a performance ratio of 77.27% and the degradation rate is around 0.5% per annum. Honnurvali et al. [23] reported that for hot and arid conditions the PV degradation rates are higher. According to the study, multi-crystalline modules degraded at 2.54% annually and thin film modules had an annual degradation rate of 0.8%. Bouaichi et al. [24] reported the degradation of PV system in harsh climate. They analyzed the system for 3 years and found that for CIS modules the power loss was minimum. The drop in short circuit current, open circuit voltage and the increment in the cell resistance contribute to the performance degradation of the solar cell [25]. Liu et al. [26], investigated the operation of two solar modules that are in operation for 30 years. The power output of the modules was 5 W less than nameplate values. Sangwongwanich et al. [27], reported that the power output and the reliability of PV modules are impacted by the location. In hot climates, the inverter efficiency as well as module efficiency decreases at a faster rate over the life of the plant. Studies have also shown that accumulation of dust accelerates the degradation process of solar cells. Dust can reduce the power out of solar cell by 30% over the life cycle [28,29]. Effective and efficient methods to determine degradation is essential. Accurate and early detection of degradation is useful for proper planning, estimation and life cycle analysis of PV power plants. Sun et al. [30], proposed a simple and effective technique to measure degradation of PV modules using MPPT. They monitored the module current and voltage and used the data to calculate the degradation. Lyu et al. [31], proposed fluorescence imaging technique to accurately determine the failure rate of solar cells.

Solar PV modules need open land areas for efficient operation. With increasing population, open land spaces are becoming scarce. The increasing price of land is also detrimental in growth of large-scale PV power plants. The cost of land increases the overall cost of the plant, which in turn impacts the LCOE. A feasible alternative is to develop PV systems on water bodies. Developing FSPVs reduce the cost of land and hence help in reducing the capital cost of setting up PV power plant. FSPV provides added advantages like reduce algal growth in water bodies and help to maintain water quality. The evaporation of water is also reduced, thus helping in water conservation [32,33]. Due to cooling effect of water, the efficiency of FSPV modules is higher by 10%, which results in better output and performance than the land-based PV systems [34]. Owing to the advantages, FSPVs have witnessed tremendous growth in the last decade. Fig. 1, presents the energy generation potential of FSPV in the different continents.

It is seen from Fig. 1, that Africa has the highest potential for FSPV power generation. As of 2020, China has the highest FSPV generation capacity followed by Japan and Korea. Kim et al. [36], proposed the design of FSPV power plant using FRP members. FRP can effectively handle the water movements and protect the solar PV modules. They proposed that FRP can be used for large FSPV projects above 1 MWp. Temiz and Jayani [37], designed a FSPV system for hydrogen production and to generate electricity. The developed system can supply 99.34% of the demand independently. Kamuyu et al. [38], proposed a technique to predict the temperature of FSPV modules for large power plants. They considered environmental factors and found that FSPV has maximum yield when module temperature is below 40 °C. Silvério et al. [39], designed a hydro-FSPV hybrid power plant. They found that by optimally controlling the hybrid power plant, the energy output increased by 76% and the utilization factor increased by 17%. Song and Choi [40], proposed the use of FSPVs in pit lakes for powering mining industries. The designed system generated 972 MWh/year and it reduced the CO_2 emissions by twice. FSPVs can also be deployed on fish ponds. Studies suggest that FSPVs do not have significant impact on marine life. The water must be treated periodically to sustain the oxygen level of the pond [41,42].

FSPV systems are gaining importance in the recent times and policymakers are emphasizing on development of FSPV power plants. Prior to the development of large scale FSPV systems, it is essential to have proper knowledge on the long-term performance and the reliability of operation. Both these factors are impacted by the degradation rate, hence proper analysis of degradation of FSPV modules in real outdoor conditions is essential. During outdoor operation, the FSPV systems undergo physical and performance degradation due to various factors such as temperature, wind speed, humidity, UV rays and mechanical failure. Proper analysis of degradation will help in actual estimation of the energy output for large FSPV projects. Degradation rate also affects the running cost, operation and maintenance cost (O&M) and have a detrimental impact in LCOE calculation. Understanding the long-term performance of FSPV systems will be beneficial to everyone from researchers, investors to the people engaged in project planning, commissioning, operation and maintenance. This will also help investors to make sound decisions regarding risk-return profile in the development of FSPV systems. The

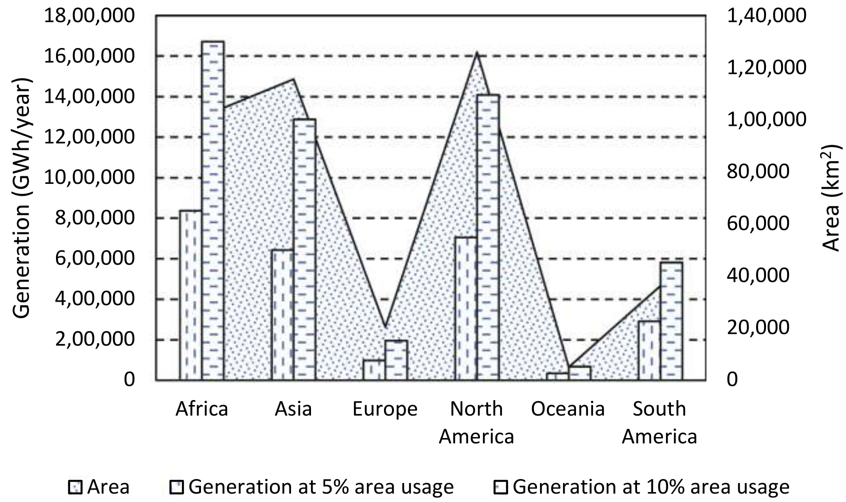

Fig. 1. FSPV generation potential by continents [35].

degradation analysis of FSPV modules is not widely reported. This paper presents the degradation analysis of FSPV module. To determine the actual degradation, an experiment was conducted at Indian Institute of Technology (ISM), Dhanbad, India, using PV modules on water. The experiment was conducted for 17 months and the performance was recorded. From the experiment the degradation rate was calculated and the effect of degradation on performance was also analyzed. Next, a feasibility study of setting up a 5 MW FSPV power plant in India is presented considering the degradation rates. The performance analysis of the plant is done for a period of twenty-five years. Economic analysis of the FSPV power plant is carried out and the LCOE is calculated. Comparison is presented between the FSPV power plant and a similar land-based PV power plant in terms of performance and financial benefits considering different degradation rates.

The rest of the paper is organized as: Section 2 describes the methodology adopted for performance analysis and determination of degradation. The procedure followed for feasibility study of the 5 MW FSPV power plant is given in Section 3. Section 4 presents the experimental results and the designing and economic assessment of the FSPV power plant. Finally, the conclusion is given in Section 5.

2. PV technology and performance assessment

The physical properties of PV cell/module can be expressed mathematically using electrical parameters through the single diode model (SDM). The model consists of one current source, a resistance and a diode in parallel and connected to the load via the series resistance as shown in Fig. 2.

The load current I_o for SDM is given as follows [43,44]:

$$I_o = I_{so} - I_{do} - I_{pr} \tag{1}$$

where, I_{so} is the photo-electric current, I_{pr} is the current flowing through the parallel resistor and I_{do} is the diode current. The current thorough the diode is given by Eq. (2).

$$I_{do} = I_{rs}\left(exp\left(\frac{V_o + I_o R_{sr}}{\gamma V_{jt}}\right)\right) \tag{2}$$

where, I_{rs} is the reverse saturation current, R_{sr} is the series resistance, V_{jt} is the voltage of the junction, V_o is the output voltage of the cell, and γ is the diode ideality factor. Again, V_{jt} can be represented as:

$$V_{jt} = \frac{N_{sr} KT}{q} \tag{3}$$

N_{sr} is the number of cells in series, T is the temperature of the module in Kelvin, K is the Boltzmann constant, and q is electron charge represented by 1.602×10^{-19} C.

Since FSPV modules are in floated over water, in tropical conditions the junction temperature remain less by 12 °C in an average. This increases the efficiency of FSPV by 10%–12% [45]. So, Eq. (3). is modified for FSPV cells and is given as:

$$V'_{jt} = \frac{N_{sr} K\,(T - 12)}{q} \tag{4}$$

The current though the shunt resistance is given by Eq. (5)

$$I_{pr} = \frac{V_o + I_o R_{sr}}{R_{pr}} \tag{5}$$

Thus, substituting Eqs. (2)–(5) in Eq. (1), the output current in SDM is given by Eq. (6).

$$I_o = I_{so} - I_{rs}\left[exp\left(\frac{V_o + R_{sr} I_o}{\gamma V'_{jt}}\right) - 1\right] - \frac{V_o + R_{sr} I_o}{R_{pr}} \tag{6}$$

For high voltage and high-power applications, the solar cells are connected in series and parallel combinations forming solar arrays. From Eq. (6) it is seen that the parameters like I_{rs}, I_o, R_{sr}, R_{pr} and γ are unknown. To evaluate these parameters, five set of non-linear equations are formed consideration the standard test conditions (STC), where the irradiance is 1000 W/m^2 and temperature is 25 °C.

Considering open circuit condition ($I_o = 0$ & $V_o = V_{ock,STC}$) at STC, Eq. (6) can be rearranged to:

$$I_{so,STC} = I_{rs,STC}\left[exp\left(\frac{V_{o,STC}}{\gamma_{STC} V'_{jt}}\right) - 1\right] + \frac{V_{ock.STC}}{R_{pr,STC}} \tag{7}$$

During short circuit condition ($V_o = 0$ & $I_o = I_{ssc,STC}$) at STC, Eq. (6) becomes:

$$I_{ssc,STC} = I_{rs,STC}\left[exp\left(\frac{V_{ock,STC}}{\gamma_{STC} V'_{jt}}\right) - exp\left(\frac{I_{ssc,STC} R_{sr,STC}}{\gamma_{STC} V'_{jt}}\right)\right] + \frac{V_{ock,STC} - R_{sr,STC} I_{ssc,STC}}{R_{pr,STC}} \tag{8}$$

where $I_{ssc,STC}$ is the short circuit current at STC.

The condition at which the current and voltage is maximum, thus yielding maximum power is called maximum power point (MPP) of the PV cell. At MPP, putting $I_o = I_{maxSTC}$ and $V_o = V_{max,STC}$

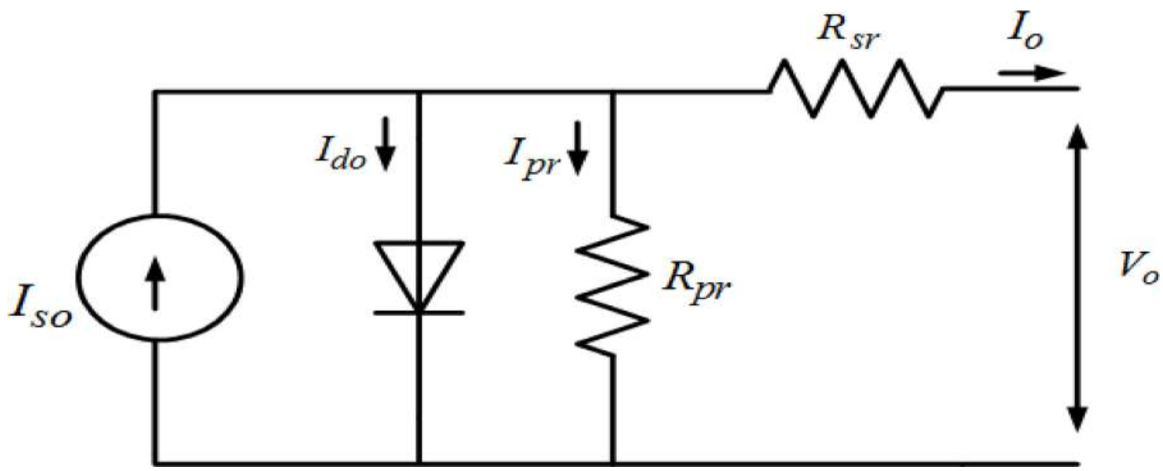

Fig. 2. Single diode representation of PV cell.

in Eq. (6):

$$I_{max,STC}\left(1+\frac{R_{sr,STC}}{R_{pr,STC}}\right)=I_{rs,STC}\left[exp\left(\frac{V_{ock,STC}}{\gamma_{STC}V'_{jt}}\right)-exp\left(\frac{I_{max,STC}R_{sr,STC}+V_{max,STC}}{\gamma_{STC}V'_{jt}}\right)\right]+\frac{V_{ock,STC}-V_{max,STC}}{R_{pr,STC}} \quad (9)$$

For STC condition the Eq. (9) is derived as:

$$\frac{I_{max,STC}}{V_{max,STC}}=\frac{I_{rs,STC}}{\gamma_{STC}V'_{jt}}\left(1-R_{sr,STC}\frac{I_{max,STC}}{V_{max,STC}}\right)\times exp\left(\frac{V_{max,STC}+R_{sr,STC}I_{max,STC}}{\gamma_{STC}V'_{jt}}\right)+\frac{1}{R_{pr,STC}}\left(1-R_{sr,STC}\frac{I_{max,STC}}{V_{max,STC}}\right) \quad (10)$$

Now, R_{prs} is unknown, considering $R_{prs} \gg R_{sr,STC}$ it is seen that $R_{prs} \approx R_{pr,STC}$, considering this the equation becomes:

$$\frac{1}{R_{pr,STC}-R_{sr,STC}}=\left[\frac{1}{R_{pr,STC}}+\frac{I_{rs,STC}}{\gamma_{STC}V'_{jt}}exp\left(\frac{R_{sr,STC}I_{SSC,STC}}{\gamma_{STC}V'_{jt}}\right)\right] \quad (11)$$

There are five variables and five non-linear equations represented by Eqs. (7)–(11). So, the five parameters are required to be determined accurately for plotting the I–V curve correctly.

2.1. PV performance analysis

Performance analysis of PV modules is very important for long term operation and for the growth in PV power plants. The performance analysis helps all the people in the supply chain to make an efficient estimation about the size of the project. Proper estimation further helps in component sizing and determining the operational cost of the plant. The PV output is impacted by climatic conditions like solar irradiance, wind speed, pollution and location. So, choosing the proper location is the first step while designing a PV power plant. Other factors like shadow, component reliability, system losses and inverter efficiency must be taken care of. There are three factors that determine the performance of PV systems [46].

- Final yield
- Reference yield
- Performance Ratio

Final yield (P_y) is defined as the ratio of energy produced by the PV system for a given amount of time by the rated power output of the system at STC.

$$P_y=\frac{E_{gen}}{E_{STC}} \quad (12)$$

where, E_{gen} is the energy generated by the PV system at any given period of time and E_{STC} is the power generated at STC.

Reference yield (P_r) is defined as the solar insolation received on the plane of the PV panel to the reference irradiance of 1 kW/m^2.

$$P_r=\frac{H_r}{G_0} \quad (13)$$

where, H_r insolation represented as sun hours and G_0 is the insolation at STC.

Performance ratio (PR) presents the actual efficiency of the PV system under real outdoor conditions. It represents the total energy available from the PV system considering all the system losses. It also represents the long-term effects on PV systems. It is defined as ratio of final yield to reference yield.

$$PR=P_y/P_r \quad (14)$$

The performance of the PV modules is largely dependent on the module temperature. The module temperature is influenced by weather conditions like temperature, wind speed and insolation. During outdoor operation of PV systems, the modules get heated up and the temperature deviates from the STC temperature. While analyzing the performance of the PV system using Eq. (14), the module temperature variation is not taken into account. To find out the actual performance of the PV system, the PR is corrected with respect to module temperature (PR_s) [47].

$$PR_s=\frac{PR}{1-\sigma(T-25)} \quad (15)$$

Using this method, the variation in PR due to very high or low temperature is minimized but this method may overestimate the PR. To determine the actual performance of the PV system the PR is corrected with respect to the annual average cell temperature (PR_c) as shown in Eq. (16) [48].

$$PR_c=\frac{PR}{1-\sigma(T_{ca}-T_c)} \quad (16)$$

where, σ is the power temperature coefficient of the panel (%/°C). T_{ca} is the annual average temperature of cell and T_c is the measured temperature of the cell.

Another important parameter to determine the PV system performance is capacity factor. It is defined as the energy produced at any given period of time (E_{tp}) to the energy it can produce it operated at rated power for 24 h a day (P_m).

$$CF = \frac{E_{tp}}{P_m} \tag{17}$$

Capacity factor does not take into account the effect of temperature on the PV system output.

2.2. Degradation analysis

To perform degradation analysis, the actual output of the PV system is considered. The weather conditions impact the voltage, current and power output of the PV system. Considering the effect of temperature, the PV output equation are modified with respect to STC [49].

$$I_{ssc,STC} = I_{ssc} \times \frac{\left(\frac{1000}{P}\right)}{[1+\lambda\,(T-25)]} \tag{18}$$

$$V_{o,STC} = \frac{V_o}{[1+\varphi\,(T-25)]} \tag{19}$$

$$P_{m,STC} = FF \times I_{ssc,STC} \times V_{o,STC} \tag{20}$$

$$FF = \frac{P_{max}}{I_{ssc} V_o} \tag{21}$$

$$E_{PV,STC} = \frac{E_{PV}}{1+\sigma\,(T-25)} \tag{22}$$

where, P denotes the total power input to the system (W) and λ is the current temperature coefficient (%/°C), φ is the voltage temperature coefficient (%/°C). FF is the fill factor, P_{max} is the power generated at MPP. $E_{PV,STC}$ is the power output of the PV system at STC and E_{PV} is the measured power output (W).

Degradation denotes the amount of performance reduction over the operation period of the system. Degradation is calculated using the temperature and irradiance corrected performance ratio. Linear regression model is used to find the degradation rate. The slope of time series trend line gives the performance loss [50]. The degradation rate (DR) can be calculated as:

$$DR = \frac{S \times 12}{I} \times 100 \tag{23}$$

where, S is the slope and I is the intercept of the trend line.

The determine the power output of the PV system over its life cycle Eq. (24) is used.

$$E_i = E_0\,(1+DR)^i \tag{24}$$

where, E_i represents the energy generated in the ith year (W) and E_0 is the energy produced in the first year (W).

3. Feasibility study and design of FSPV power plant

India being one of the fastest growing economy, has huge power demand. According to CERC reports, India has a demand of 1,274,595 MU energy as of 2019. The energy supplied is 1,267,526 MU, with a deficit of 0.6% [51]. To meet the massive energy demand, India is emphasizing on renewable power sources. Fig. 3, presents the total energy generation using conventional and non-conventional sources.

It is seen from Fig. 3 that the penetration of renewable energy sources (RES) in Indian electricity market is following an increasing trend. The share of RES as of 2019 is 9.21% and this is expected to grow exponentially in the next decade. India being a tropical country has huge solar energy potential. The total installed capacity of renewable energy in India is 77,641 MW, out of which 28,181 MW is supplied by solar PV systems which amounts to 36.30% of the total renewable energy generation. India being one of the most populous country face land crisis. Though India has huge solar power potential, solar energy cannot be harnessed properly due to lack of open space. The swelling land prices also provide major hindrance in setting up large PV power plants. The land prices increase the capital cost of the power plant and this in turn increases the LCOE. A practical alternative to this is to develop PV systems on water bodies. India has nearly 18,000 km^2 of reservoir water surface area which is suitable for developing FSPV systems. The estimated generation from the FSPV system is 280 GW [35]. Table 2, presents the FSPV systems installed in India.

Table 2
Installed FSPV system in India [35].

Place	Year	Capacity (MW)
Kolkata	2014	0.01
Chandigarh	2016	0.01
Kayamkulam	2016	0.1
Wayanad	2017	0.5
Panipat	2018	0.1
Vishakapatnam	2018	2

It is observed from Table 2, that though India has huge FSPV potential but FSPV systems installed in India are few. To bridge the gap between the energy demand and the energy supply, India need to install more FSPV systems.

For the accurate performance analysis of the FSPV power plant, various factors like energy generated, system efficiency, system losses and capacity factor must be taken into consideration [52, 53]. The total energy generated by the FSPV plant ($E_{FS,d}$) is given by Eq. (25).

$$E_{FS,d} = I_{pv} V_{pv} N \tag{25}$$

where, I_{pv} is the DC current produced by the FSPV system, V_{pv} is the DC voltage and N is the period of operation of the power plant. The DC power produced by PV system is converted into AC power by the inverter and fed in to the grid. The energy injected into the grid ($E_{FS,a}$) is given by

$$E_{FS,a} = I_a V_a N \tag{26}$$

where, I_a and V_a denotes the current and voltage output of the inverter respectively. The power output from the PV panel depends on the efficiency of the PV panel (η_{FS}).

$$\eta_{FS} = \frac{P_{FS,d}}{A_{FS} \times G_j} \tag{27}$$

where, $P_{FS,d}$ is the DC power generated by the FSPV system, A_{FS} is the area of the FSPV module and G_j is the solar irradiance. The AC power output of the inverter ($P_{FS,a}$) to the DC power output of FSPV module is known as inverter efficiency ($\eta_{FS,i}$).

$$\eta_{FS,i} = \frac{P_{FS,a}}{P_{FS,d}} \tag{28}$$

The overall efficiency of the system is given by:

$$\eta_o = \eta_{FS} \times \eta_{FS,i} \tag{29}$$

Due to scattering, dust deposition and shadow, the PV module cannot capture the total irradiance falling on it, this is known as array capture loss. Losses in the cables and balance of systems (BOS) causes the output of the PV system to reduce, this is called system losses. The annual energy output of the FSPV power is done considering all the losses.

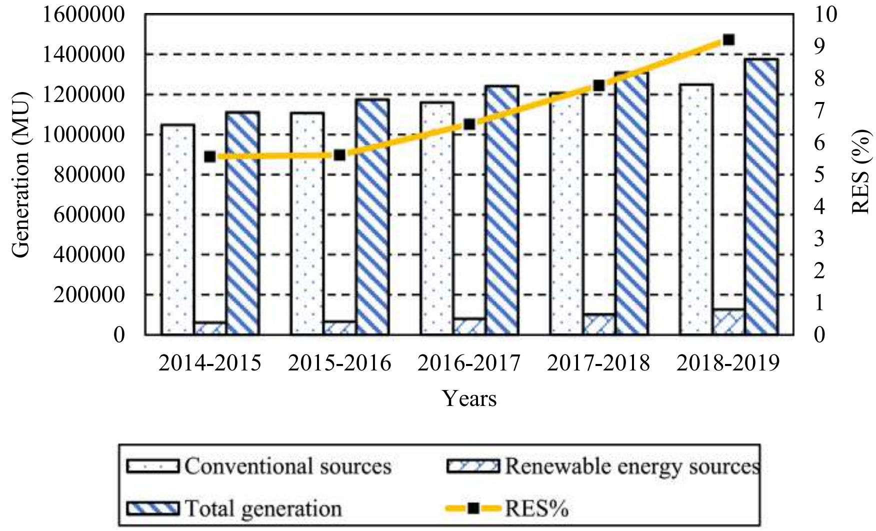

Fig. 3. Electricity generation by various sources [51].

3.1. Location and bathymetry

This section presents the feasibility study and design of FSPV power plant in West Bengal, in the Eastern part of India. West Bengal has seven number of reservoirs having total water surface area of 120 km^2 and the total generation potential is 2777 MW [35]. The FSPV power plant is proposed at one of the reservoirs situated in Sagardighi thermal power station (SgTP), India (24°21′42.7″N and 88°06′25.7″E).

The weather conditions are very important for determining the long-term performance of PV system. Selecting proper location with favorable weather conditions for PV power generation is very important in feasibility study of PV power plant. The weather analysis at Sagardighi is done for last 10 years to find out the average weather condition of the area. Fig. 4(a), (b), (c) and (d) presents the weather conditions at Sagardighi for the last one year.

Maximum temperature recorded in the last ten years is 46 °C and average temperature is 39 °C and lowest temperature is noted as 14 °C. Maximum wind speed for the period is 17.4 mph and maximum gust is 17 mph and average wind speed is 12.1 mph. The maximum cloud cover is 91%, the average cloud cover is 57% and maximum sun hours in a month is 154 h. As seen from Fig. 4, Sagardighi receives maximum insolation from January to April, the cloud cover is also less in that period. Thus, the FSPV system is expected to generate the maximum output in that period.

The selected water body is a raw water reservoir of Sagardighi power plant. The water from river Ganga is conveyed by pipeline and stored at the reservoir. The depth of the reservoir is 7.4 m and the has a free boat of 780 mm. As the reservoir is fixed to a power plant, the water level of the reservoir is maintained for whole year. Total surface area of raw water reservoir is approximately 125,000 m^2. For 1 MW floating Solar PV plant approximate 12,000 m^2 island surface is required. So, for 5 MW plant 60,000 m^2 island surface is required. The coverage ratio of the reservoir will be 48%. Maximum depth of the pond is 8.0 m and level variation could be 7.2 m. The proposed structure of the FSPV power plant over the reservoir is given in Fig. 5.

The raw water pond is filled by the water from the river Ganga through pipe line, so at the time of filling the pond only little water turbulence occurs otherwise only some wind generated waves are there in the pond. The average wind speed of the area is 12.1 mph, this can generate waves with average height of 0.28 m and average wavelength of 8.5 m. The wave can have a period of 3 s and travel at 10.2 km/h. Though the wind speed and wave height are low, the anchoring system is designed with wind load speed of 175 km/h, to counter environmental hazards like storms. The bottom and earth anchors are designed for a depth of 8 m and to withstand level variation of 7 m.

3.2. Electrical design and analysis

The FSPV power plant is designed to operate with the grid. For grid-connected system, power-conditioning unit (PCU) is very important. PCU supplies the power from FSPV system to the grid while maintaining grid synchronization and power quality parameters. It also ensures that power is not supplied from the FSPV system during low power generation period. A load demand management system controls the power flow to and from the grid. When the FSPV generation is higher than the on-site demand, the power is supplied to the grid and during night or cloudy conditions, power is taken from the grid. During grid outage or failure, the FSPV system operates in islanding mode to ensure safety. Fig. 6 presents the FSPV solar panel layout design.

The 5 MW FSPV power plant is designed on five islands, each having a DC capacity of 1.088 MW and AC capacity of 1 MW. The PV modules used for the design is poly crystalline (c-Si) type and rated at 320 Wp. As seen from Fig. 6, the 1 MW FSPV is further divided into two blocks of 500 kW each. There are 19 modules in each string and 10 arrays. Each array contains 9 strings and one array is kept as spare. So, the total number of modules used is 3382. The DC capacity of each block is 542 kWp. Each block is connected to 3 phase inverters (Sunny Central 500 cp) which operates at a maximum efficiency of 98.1% at 480 V. The inverter operates at a maximum MPP voltage of 850 V. The inverter output is connected to the 11 000 kVA, 0.4 kV/.04 kV/11 kV transformer that supply power to the existing 11 kV bus of the water pump house. The inverters used as a part of the floating power plant is envisaged to produce current at 400 V, which would be further stepped up to 11 kV for integration with the 11 kV bus of raw water pump house. A 11 kV switchgear is installed in the FSPV control room. It has three number of outgoing feeders. Two numbers feeder to be connected with the incomer of 11 kV bus raw water pump house which is 500 m from the bank of the pond and another feeder to be connected with the 11 kV feeder of the township supply.

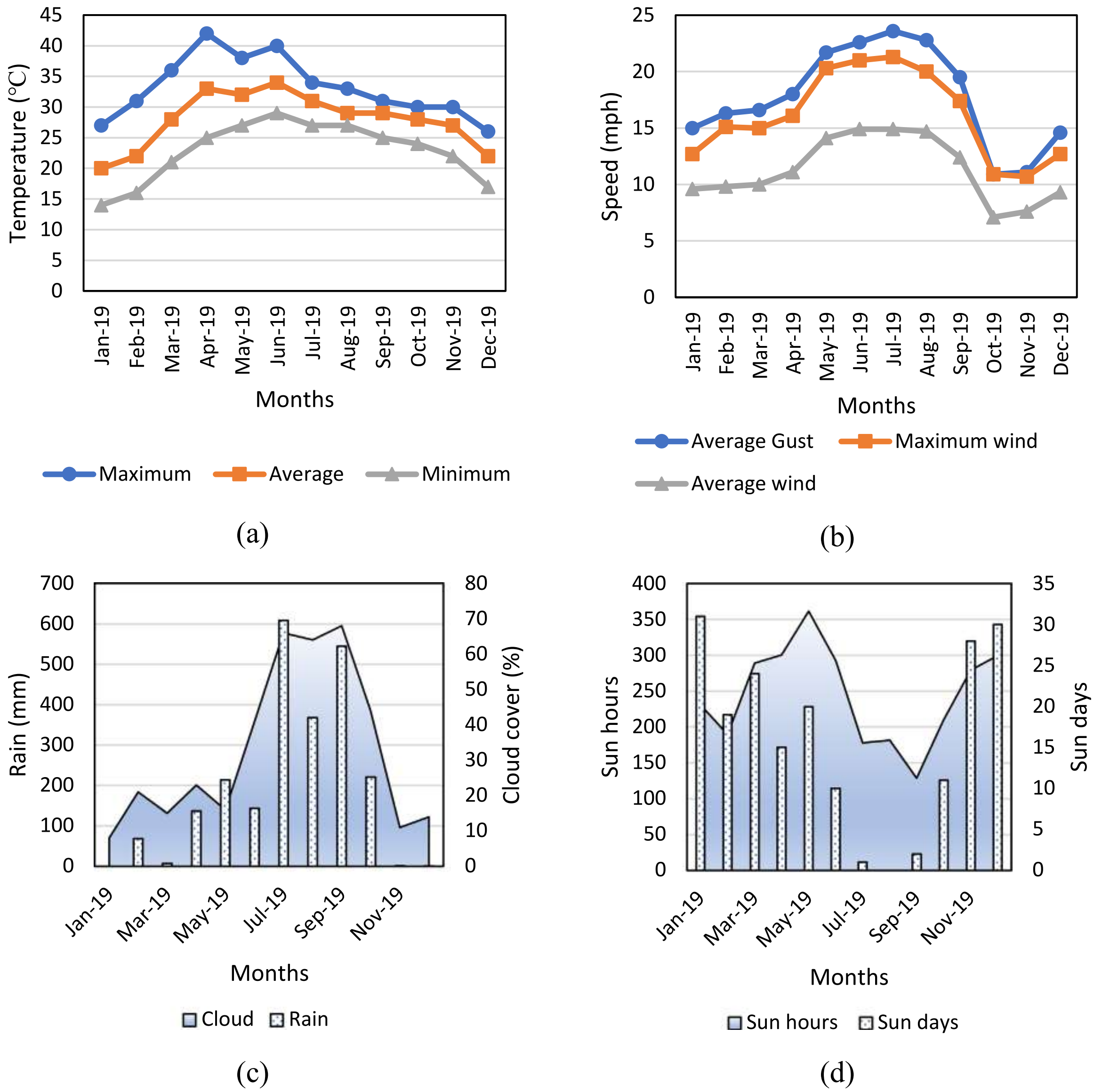

Fig. 4. Weather conditions at Sagardighi, (a) maximum, minimum and average temperature (b) maximum wind speed, average wind speed and average gust speed (c) rainfall and cloud cover (d) sun days and sun hours.

3.3. Financial estimate and LCOE calculation

Financial evaluation is very important before commission of any project. It helps to estimate the total supply cost, the cost of installation, the running cost and the cost of maintenance over the life of the project. A clear idea of the total cost of the FSPV power plant will help in calculating the LCOE and revenue generation. This will help the FSPV power plant to be economically sustainable. LCOE and net present value (NPV) are major parameters in determining the economic viability of the power plant [54,55]. Precisely, levelized cost can be calculated by using lifecycle cost analysis method. For a time period of t years, the levelized cost is calculated as given in Eq. (30).

$$LCOE_{FS} = \left[\frac{\mathrm{IC} + \mathrm{F} + \sum_{i=1}^{t} \frac{M + I_{FS}}{(1+d_{FS})^i}}{\sum_{i=1}^{t} \left(\frac{E_S (1-DR)^i}{(1-d_{FS})^i} \right)} \right] \tag{30}$$

where, IC is the investment cost ($), F is the cost of floating structures ($), M is the operation and maintenance cost ($), I_{FS} is the insurance cost ($), d_{FS} is the discounting factor, E_s total energy produced by the system in its lifetime (kWh). NPV is another financial parameter to judge economic feasibility. It is defined as the present value of the net cash inflows.

$$NPV_{FS} = \sum_{i=1}^{t} \frac{S_{in}}{(1+d_{FS})^i} \tag{31}$$

where, S_{in} is the cash inflow. The payback period (P_{FS}) denotes the time required to recover the initial investment cost and is given as:

$$P_{FS} = r + \frac{\sum_{i=1}^{r} S_{in}}{Cash\ Flow\ in\ year\ r+1} \tag{32}$$

where, r is final year with negative cash flow.

4. Results and discussion

4.1. Performance assessment of 100 W FSPV module

To determine the performance and degradation of FSPV solar module, an experiment was conducted at Indian Institute of Technology (ISM), Dhanbad (23.8144°N, 86.4412°E) using 100 W

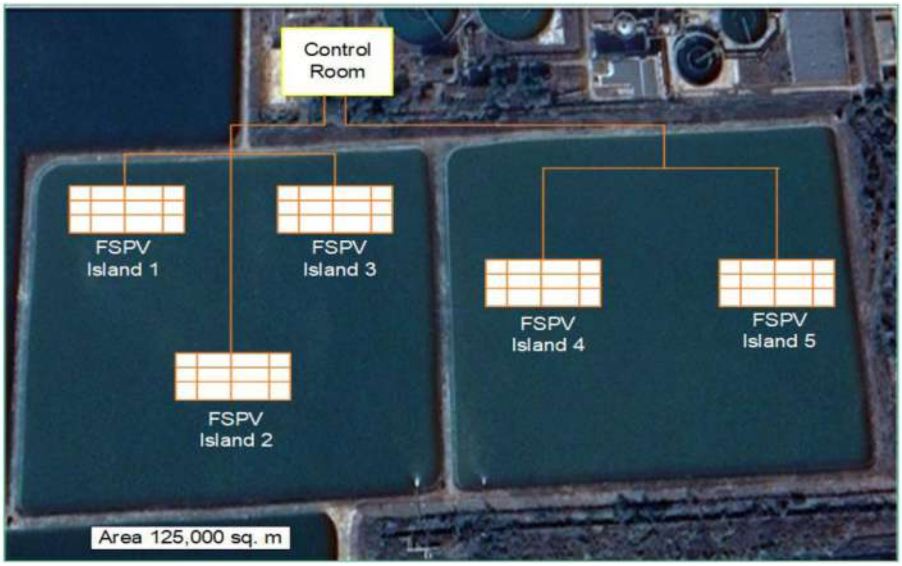

Fig. 5. Proposed 5 MW FSPV power plant.

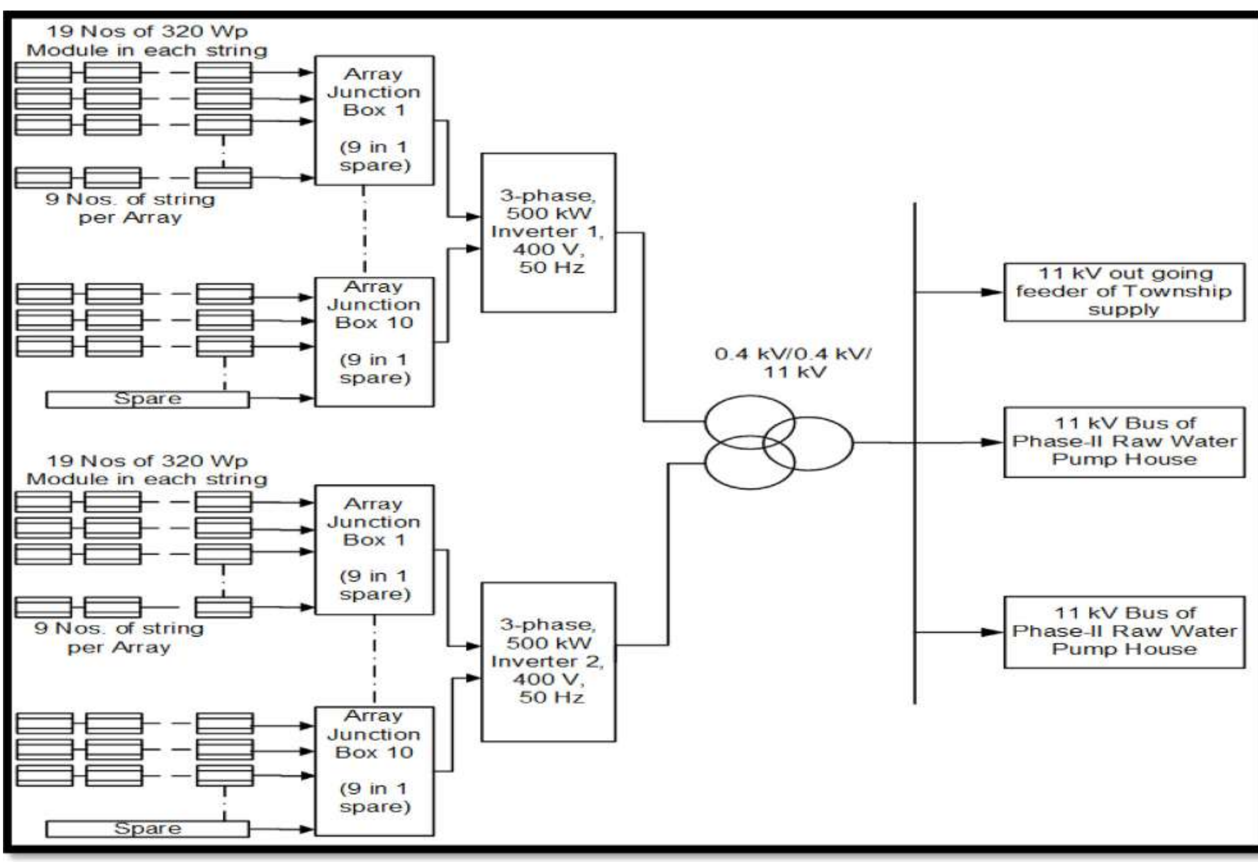

Fig. 6. FSPV solar panel layout.

module. The module was floated on water and the performance was noted for a period of 17 months, from September 2018 to January 2020. A similar experiment was conducted to determine the performance of land-based PV system for the same time period. For simplicity the FSPV module is called FPV and the land-based module is called LPV. The manufacturer details of the solar module are given in Table 3.

Environmental parameters such as ambient temperature and module temperature were collected using infrared thermometer (TM-207). Temperature was recorded at four corners of the module and at the center, the average temperature of the five readings were taken as module temperature. The wind speed was measured using digital anemometer (AVM-06). To measure solar irradiance solar power meter was used (T-206) and solar power analyzer (9018BT) was used for I–V curve measurement. The parameters of the solar module were measured using I–V

Table 3
Datasheet parameters of the solar panel.

Particulars	Value
Brand	Luminous
V_o	12 V
Type	Poly crystalline
V_{max}	17.4 V
I_{max}	5.7 A
I_{ssc}	5.92 A
Cells	36
R_{pr}	114.62 Ω
R_{sr}	0.244 Ω
γ	0.9755

measuring device (Meco 9018BT). The device measures current and voltage in the range 0.1–12 A and 1–1000 V with accuracy of ±1%. It measures irradiance in the range of 0–2000 W/m^2 with ±3% accuracy and temperature in the range of −22–85 °C with ±1% accuracy. The device was connected to a computer and the module parameters were analyzed using the dedicated software. The I–V curves of the PV module at STC were converted to real operating condition to find the performance parameters. Various parameters of the PV module such as I_{so}, I_{rs}, R_{sr}, R_{pr} and γ were calculated using Eqs. (7)–(11), utilizing the monitored electrical quantities of the PV module under real outdoor conditions. The equations are non-linear in nature therefore numerical techniques are employed to solve them. The output current and voltage of the module, the module temperature and the irradiance serve as the input and the PV parameters are extracted by solving the non-linear equations using 'fsolve' in Matlab. The experimental setup is given in Fig. 7.

Fig. 8, presents the temperature variation of the FPV module and the LPV module. It is observed that during summer time the temperature difference between the FPV module and the LPV module is higher. The FPV module is cooler by 22 °C than the LPV module in the month of May. The temperature difference follows an increasing curve between the period of March to May, from July to September, Dhanbad experiences rainfall, as the panels are cooled due to rain, the temperature difference decreases. During winter the temperature difference lowers to 6 °C (January 2019), as the ambient temperature is lower. On an average the FPV module was cooler by 6 °C during the time period of the experiment. The LPV module has higher temperature as the heat gets trapped in the earth and in the panel. The FPV module is cooler because it is in contact with water, as water has higher specific heat thus it takes longer to get heated.

From Fig. 9, it is seen that the daily average output and monthly average output of the FPV module is higher than the LPV module. Both the modules generate maximum power during winter period (December–March). The maximum output of the FPV module is 84 W, while the for the LPV module it is 72.4 W. During the summer months the output of both panels decrease. The maximum difference in power output of 11.6 W is observed in the month of December, 2018 and the minimum difference in power output of 2.8 W is observed in the month of July, 2019. The winter months have low cloud cover, high solar irradiance and lower temperature, this results in better PV output. The higher generation results from the lower temperature of FPV module.

The performance ratio and the efficiency of both FPV module and LPV module is given in Fig. 10. The efficiency and *PR* of both the panels follow the same pattern, they are higher in the winter period (December–February) and then gradually decrease. The *PR* difference of 16.1% is observed in the month of December, 2018 and the minimum *PR* difference of 3.7% is observed in the month of July, 2019. The average efficiency of the LPV system is 9.84% and for the FPV system it is 10.83%.

The temperature corrected *PR* of both the modules is presented in Fig. 11. The PR_s and the PR_c for the FPV module varies in the range 57.64–87.34% and 56.22–84.24% respectively. While, for the LPV system the variation observed in PR_s and PR_c is 55.20–75.84% and 54.48–73.79% respectively. For the FPV module the *PR* is 71.04%, the PR_s is 74.23% and the PR_c is 71.37% while for the LPV module the *PR* is 64.02%, PR_s is 69.61% and PR_c is 64.92%. Due to the cooling effect of water, huge variation in *PR* is not observed, the average PR_s is only 4.49% higher than the average *PR*. However, for the LPV module the average PR_s is higher than the average *PR* by 9.1%. The average variation of *PR*, PR_s and PR_c between the summer and winter months for the FPV system is 51.03%, 47.36% and 43.86% respectively, while for the LPV system the variation is 35.16%, 27.27% and 22.34% respectively. Though the values of *PR* and PR_c for both the modules are nearly same, PR_c displays the least seasonal variation.

It can be observed from Figs. 9–11, that the performance of the FPV module is better than the LPV module. The average power output of the FPV module is 10.96% more than the FPV module. FSPV systems has better output as the water keeps the temperature of the module lower thus increasing the efficiency of power generation.

4.2. Degradation study

The performance output of the FPV and LPV system is monitored continuously for 17 months to determine the degradation of the modules. From Figs. 9–11, it can be seen that the *PR* of both the panels decreases with time. To get an accurate estimation of the performance decay, the daily average *PR* of both the panels in the first year and second year is compared during the winter period, that is from December to January in 2018 and 2019 respectively. As the winter period has clear sky and good irradiance, the PV panels operate with higher efficiency and the estimation of degradation will be better. The daily variation of *PR*, PR_s and PR_c of the LPV and FPV module during the winter months is presented in Fig. 12. The PV modules operate with maximum average *PR* between the days 91–122 (December, 2018). In the first year, for the FPV module, the average maximum *PR*, PR_s, PR_c obtained is 84%, 85.6%, 83.4% respectively, while for the LPV module the average maximum *PR*, PR_s, PR_c is 73%, 75.4%, 72.1% respectively. For both the systems the *PR* and PR_c is nearly same but PR_s is overestimated. In the winter months, for the FPV system, the average PR_s is higher by 1.90% while for the LPV system the average PR_s is higher by 3.3%. Substantial increase in PR_s is not observed for both the system in the winter months as the module temperature remain lower and nearer to the STC.

For the next year, a dip in the *PR*, PR_s, PR_c is observed for both the panels. The average *PR*, PR_s, PR_c of the FPV module in the period 456–487 days (December, 2019) is 83%, 83.73% and 82.4% respectively, similarly the average *PR*, PR_s, PR_c for the LPV module is 72.2%, 74.56% and 71.8%. For the FPV module the *PR* reduced by 1.190% while for the LPV module it reduced by 1.096%. It can be seen that the performance degradation of the FPV module is higher compared to the LPV module. The higher degradation in performance of the FPV module is contributed by high relative humidity and corrosive effect of water on the module.

The output of the modules in outdoor conditions depends on the weather conditions such as insolation, rainfall, temperature, wind speed and dust. All these weather conditions impact the yield of the modules, and the reduction in *PR* may not give a correct idea about the degradation of the modules. For a better idea about the degradation, the I–V curves for both the modules are plotted before and after the experiment. The curves are plotted maintain almost the same operating conditions (G = 1000 ± 15 W/m^2 and T = 30 ± 3 °C).

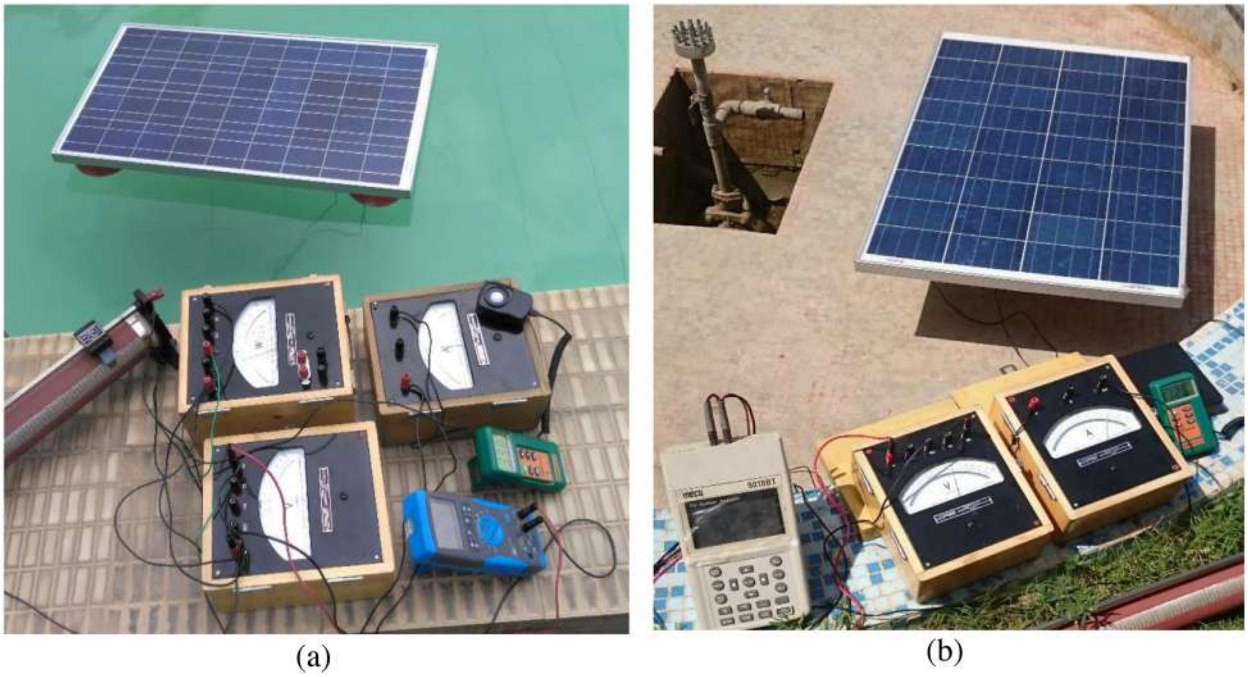

Fig. 7. Experimental setup (a) FSPV system (b) Land based system.

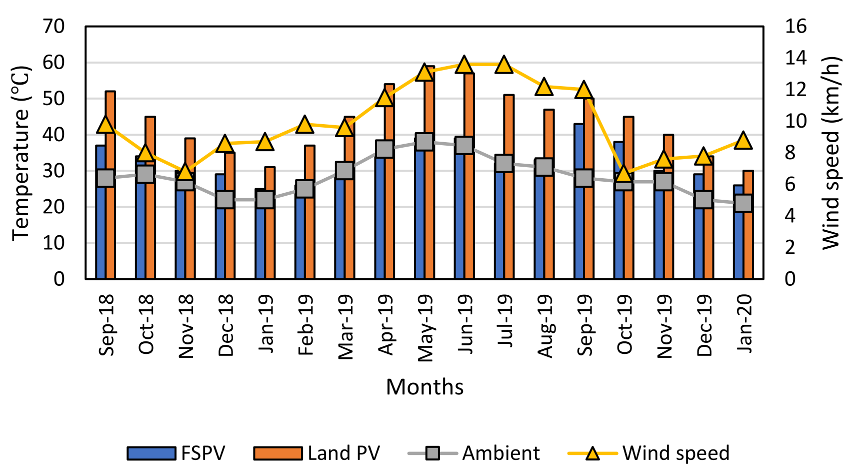

Fig. 8. Temperature profile of FSPV and land-based module.

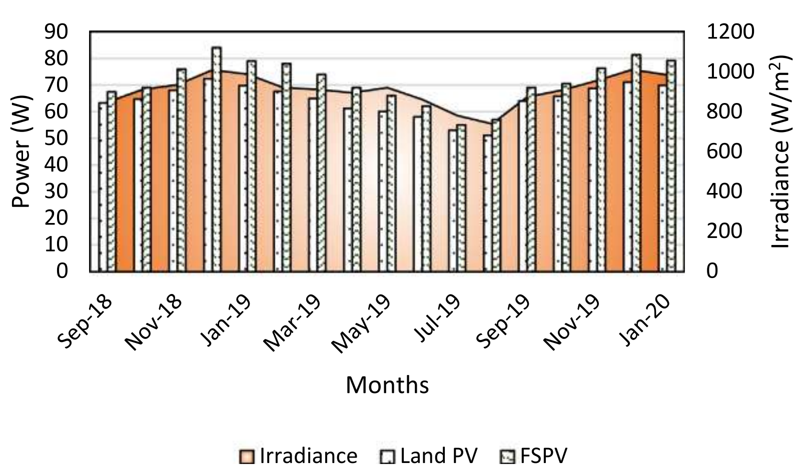

Fig. 9. Irradiance and power output.

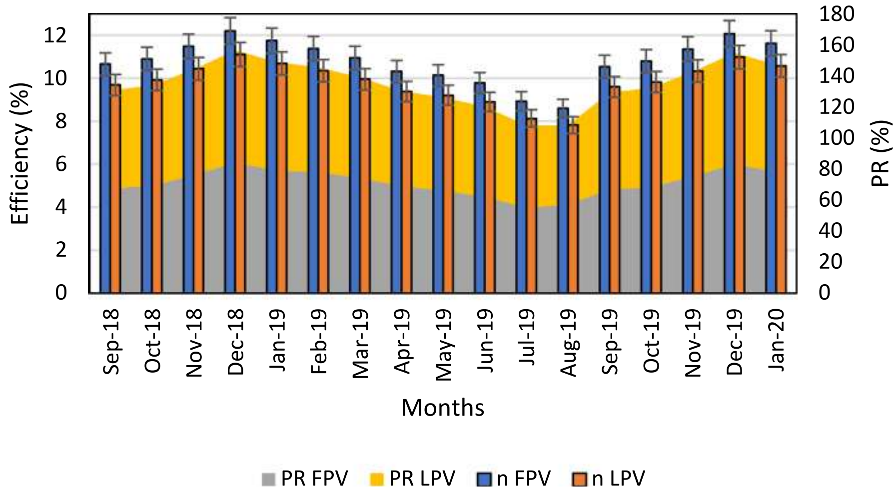

Fig. 10. *PR* and efficiency of FPV and LPV module.

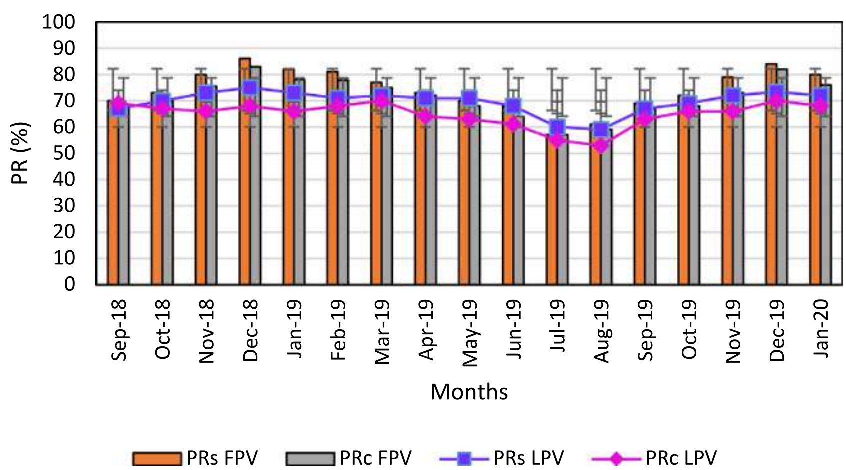

Fig. 11. Temperature corrected *PR* of FPV and LPV module.

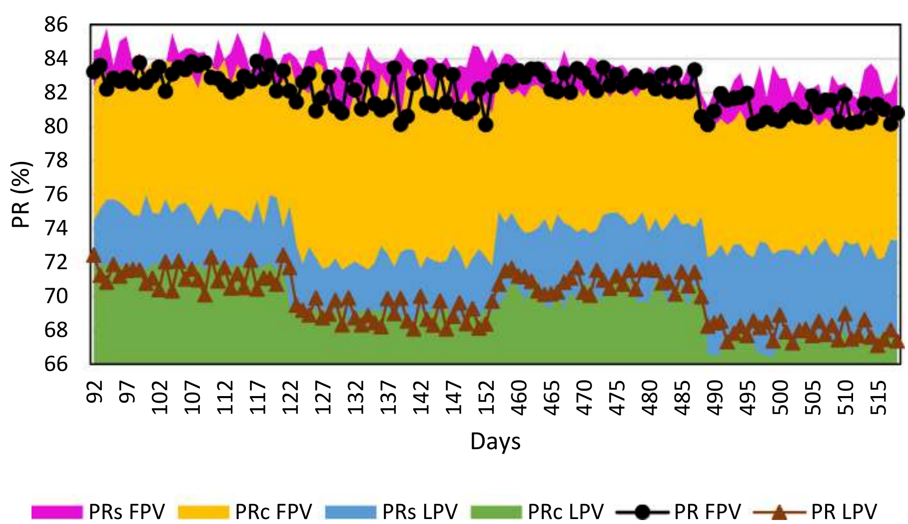

Fig. 12. Daily PR, PR_s, PR_c variation of LPV and FPV module in the winter months.

The maximum power obtained before the start of the experiment from FPV module was 98.62 W. After the experiment, the P–V curve of the module was again plotted, the maximum power obtained this time is 97.46 W. I1, I2 and P1, P2 denotes the current and power before and after the experiment respectively. During the 17 months the FPV module has undergone a degradation of 1.18%. The P–V and I–V curves for the LPV system is given in Fig. 14.

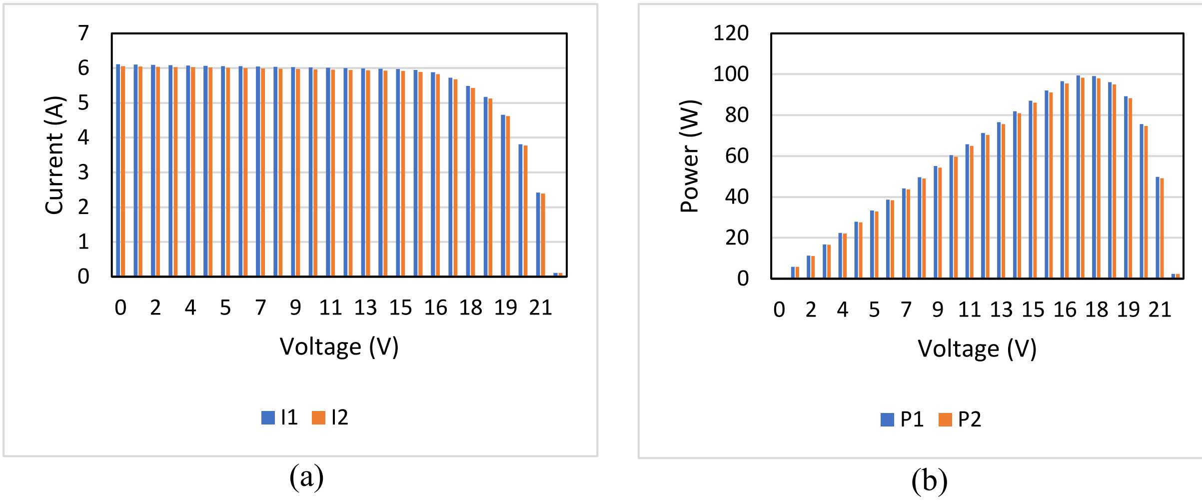

Fig. 13. I–V and P–V curves (a) I–V curves for FPV module (b) P–V curves for FPV (1- before experiment, 2-after 17 months operation).

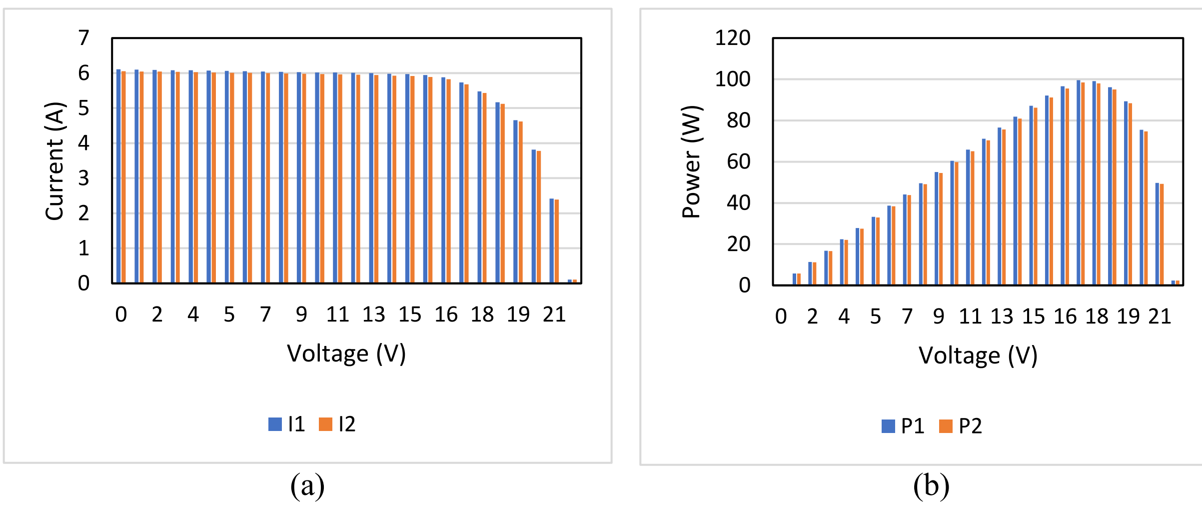

Fig. 14. I–V and P–V curves (a) I–V curves for LPV module (b) P–V curves for LPV module. (1- before experiment, 2-after 17 months operation).

Similarly, the maximum power generated by the LPV module at the start of the experiment was 98.8 W, while after the experiment the maximum power was 97.74 W. The LPV module degraded by 1.07%. From the P–V curves, it is seen that the FPV module has higher degradation than the LPV module. The FPV module degraded 4.4% more than the LPV module in the 17 months. To investigate the cause of the degradation, the change in series resistance (R_{sr}) and shunt resistance (R_{pr}) of the modules are monitored daily over the period of the experiment. At the start of the experiment the R_{sr} measured was 0.244 Ω.

The average value of R_{sr} for the LPV module at the end of the experiment is found to be 0.274 Ω, while for the FPV module the value of R_{sr} is 0.285 Ω. The increment in series resistance is 12.29% and 16.80% for the LPV and FPV module respectively. The variation in shunt resistance is given in Fig. 16.

The shunt resistance of the LPV module reduced to 111.4 Ω from the initial value of 115.32 Ω, while the shunt resistance of the FPV module reduced to 105.18 Ω from the initial value of 114.62 Ω. The LPV module exhibited a reduction in resistance of 3.39% while the FPV module's resistance reduced by 8.25%. The decrease in shunt resistance arise from the presence of parallel conductive paths. As the PV modules operated in outdoor conditions, with time they suffered from light induced degradation (LID) and crystal damages. These factors along with dust deposition on the modules created parallel paths, these paths gave rise to shunt currents thus decreasing the total shunt resistance of the module [56,57]. Since the LPV module was in contact with water, it suffered from moisture intrusion and water-based corrosion [58]. These factors increased the leakage currents hence further decreasing the shunt resistance. The FPV module displayed higher increment in series resistance and also higher reduction in shunt resistance. Due to excessive change in the resistance of the module, the FPV panel displayed greater degradation.

To further investigate the reason for performance loss of the PV modules, the variation of ideality factor (γ) is presented in Fig. 17. The γ for the FPV and LPV module varies in the range 1.22–1.29 and 1.32–1.38 respectively. The FPV module operates with better γ as the module temperature remains lower. It is seen that the γ increases in the winter period and decreases in the summer period. The increment of γ in the winter months is attributed to the escalation in recombination current [59], while the decrement in the summer months is due to band gap reduction and improvement in the lifetime of charge carrier [56]. The increment observed in γ for the FPV module after the experiment is 5.73% while the increment in LPV module is 4.45%. Due to water-based corrosion, the FPV module faced higher degradation and increased recombination and leakage currents, this led to the higher increment in γ.

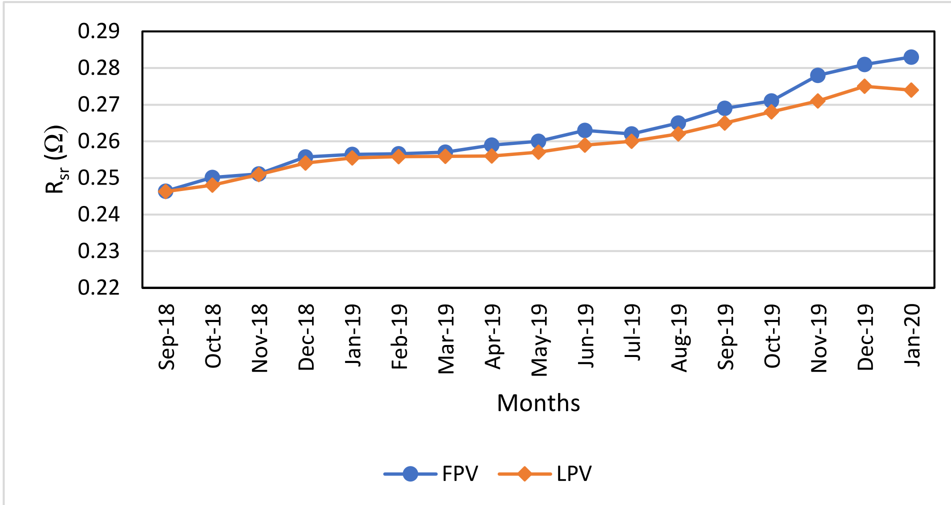

Fig. 15. Variation in R_{sr} for LPV and FPV module.

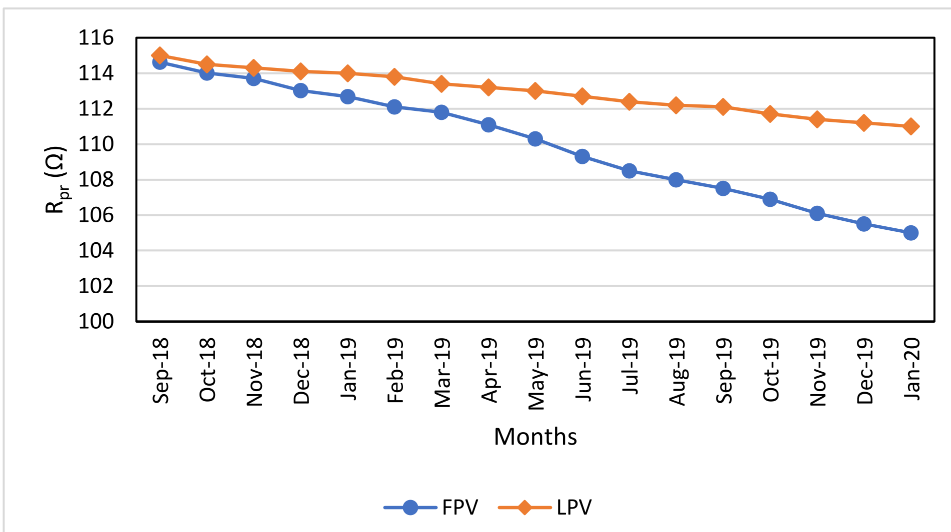

Fig. 16. Variation in R_{pr} for LPV and FPV module.

The variation of saturation current (I_{rs}) for both the modules during the 17 months of experiment is presented in Fig. 18. The I_{rs} increases in the summer months and decreases in the winter months. During summer the combined effect of high temperature and band gap reduction facilitates the increment of I_{rs} [56,58]. As the FPV module in contact with water, the temperature of the module is lower, hence the I_{rs} for the FPV module is lesser compared to the LPV module. For the same reason the increment of I_{rs} in the summer months is also lower than the LPV module.

Visual inspection was also performed to determine the defects on the PV modules due to long term exposure in outdoor conditions. After 17 months of operation, both the modules displayed slight discoloration. The discoloration occurred due to degradation of the anti-reflective coating of the modules. Long term exposure of the modules to UV rays causes this defect [60,61]. Higher delamination was observed in the FPV module. Delamination occurs due to reduced adhesive strength which is induced by UV rays and humidity [60]. The FPV module also displayed higher junction box degradation. Though the junction box was properly sealed before the experiment, due to moisture ingression and water corrosion, the junction box was slightly swollen and rusting of contacts were noticed. The frame damage in the FPV module was also higher, it was more rusted and discolored than the LPV module. Glass breakage and large cracks were not visible in any of the modules.

From Figs. 12–18, it is seen that the FPV module displayed higher degradation rate than the LPV module. The degradation of the FPV module is 1.18% while for LPV module it is 1.07%. Again from Figs. 8–10, it is seen that the power output of the FPV module is higher than LPV module. The FPV module operates at a higher efficiency than the LPV module and the average power output from the FPV module is 10.96% more than the LPV module. Considering degradation, the FPV module will generate 8.03% power more than the LPV module for 25 years operation.

4.3. Performance analysis of 5 MW FSPV power plant considering degradation

The 5 MW FSPV power plant is designed to be spread across 5 islands, each island has a generating capacity of 1 MW. The FSPV power plant is simulated using PVSyst software. To simulate each 1 MW FSPV system, 320 W solar modules are used having efficiency of 16.5%. The datasheet of the PV module used is given in Table 4.

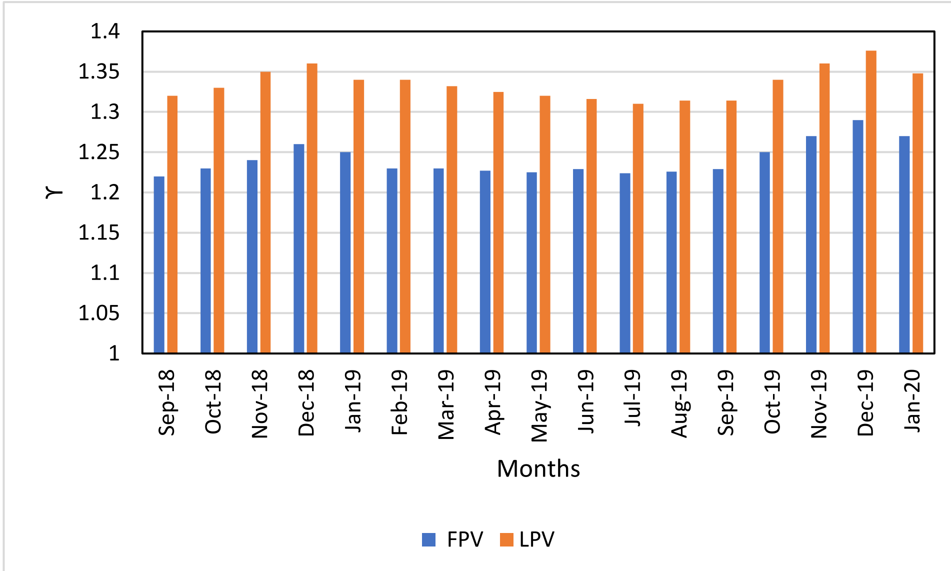

Fig. 17. Variation in γ for LPV and FPV module.

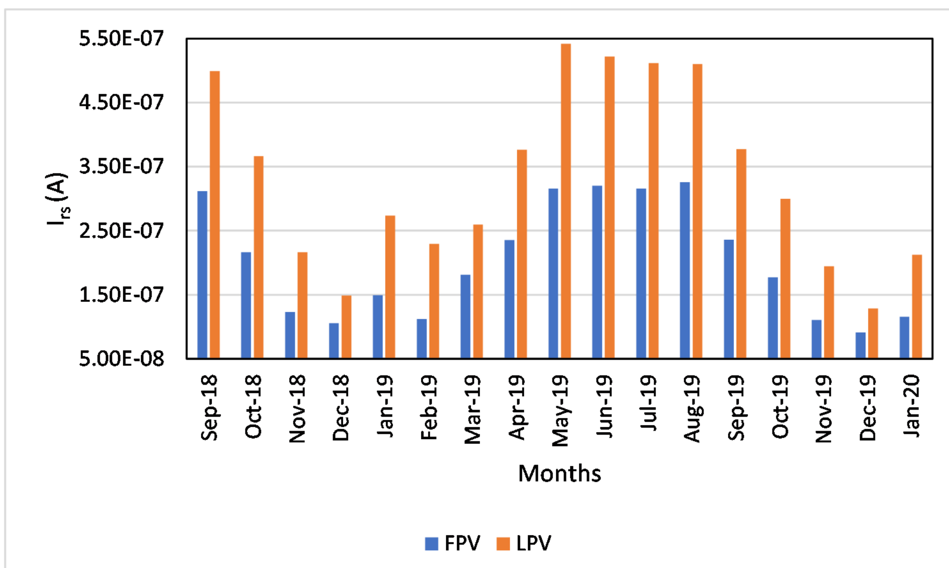

Fig. 18. Variation in I_{rs} for LPV and FPV module.

Table 4
Parameters of the 320 W FSPV solar module.

Particulars	Value
Brand	Topray
Type	Poly-crystalline
Size	0.992 × 1.946 m^2
V_o	45.5 V
V_{max}	36.9 V
I_{max}	8.67 A
I_{ssc}	9.02 A
Cells	72
R_{pr}	550 Ω
R_{sr}	0.31 Ω
FF	0.782

As the FSPV power plant is distributed into 5 islands each having capacity of 1 MW, performance analysis of the 1 MW system is analyzed. In order to determine the generation of the plant the global hourly irradiance and diffuse irradiance is analyzed for 1 year. Fig. 19, presents the monthly average irradiance on the 1 MW FSPV power plant.

From Fig. 19, it is seen that the maximum horizontal irradiance of 187.8 kWh/m^2 is obtained in the month of December and the minimum of 114.08 kWh/m^2 is obtained in the month of July. At Sagardighi, the yearly average of horizontal irradiance is 158.25 kWh/m^2, diffuse irradiance is 59.37 kWh/m^2, extraterrestrial irradiance is 280.44 kWh/m^2 and clearness index is 0.528. The monthly performance parameters of the 1 MW FSPV system is given in Table 5.

From Table 5, it is seen that the P_r, P_y and the performance ratio of the FSPV system is maximum in the winter period due to clear sky and cooler temperature. The annual average P_r, P_y and PR of the system is 5.23 kWh/kWp/day, 4.29 kWh/kWp/day and 0.821 respectively. The energy injected to the grid and system efficiency of the 1 MW FSPV power plant is given in Fig. 20. The system output is calculated after considering the normalized

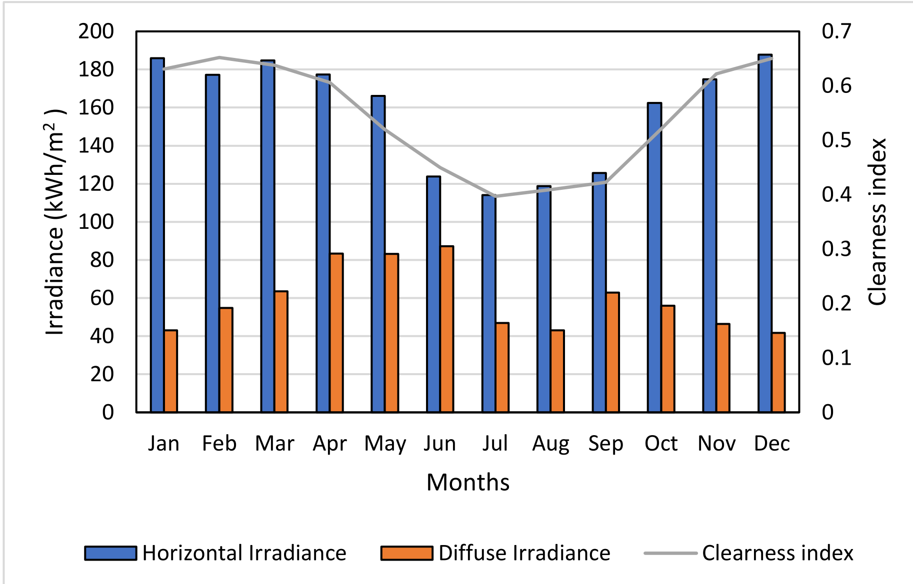

Fig. 19. Average monthly irradiance and clearness index at Sagardighi.

Table 5
Performance parameters of 1 MW FSPV power plant.

Month	P_r (kWh/kWp/day)	P_y (kWh/kWp/day)	PR
January	6.06	5.15	0.85
February	6.33	5.21	0.82
March	6.25	5.02	0.80
April	5.91	4.68	0.79
May	5.36	4.32	0.80
June	4.13	3.37	0.82
July	3.68	3.02	0.82
August	3.83	3.10	0.81
September	4.19	3.44	0.82
October	5.24	4.34	0.83
November	5.83	4.82	0.83
December	6.00	5.05	0.84

array losses and normalized system losses. The effective irradiance on the collector plate is calculated from the global effective irradiance by considering the incidence angle losses (IAM) and shading losses. Typically, IAM loss is taken as 2.9%. The PV loss due to irradiance and temperature is taken as 1% and 13.3% respectively. The module array mismatch loss is taken as 1% and the DC ohmic losses are taken as 1.1%. The inverter loss is 1.6% and the AC ohmic loss is 0.1%.

Each island of the FSPV system feeds 1720.9 MWh of energy to the grid annually. The average monthly generation of the system is 143.40 MWh. In total the 5 MW system will generate 8604.5 MWh of energy annually with monthly average generation of 717.04 MWh. To obtain the performance of the FSPV plant for the total life cycle of 25 years, the degradation rates are considered. As per Central Electricity Regulatory Commission (CERC), for Indian conditions the degradation rate for PV systems is generally taken as 1% [62]. Table 6, presents the degradation rates of some previously installed PV systems.

The total generation of the 5 MW FSPV plant in 25 years considering the obtained degradation rate is given in Fig. 21(a). Similarly, the total generation for a 5 MW land-based PV system is also given in Fig. 21(b) considering degradation.

The total generation of the 5 MW FSPV plant after 25 years considering 1.18% annual degradation is 187,238 MWh and generation of the same plant considering the standard degradation of 1% is 191,174 MWh. Considering the actual degradation rate, the FSPV power plant will generate 3936 MWh energy less, which amount to 2.06% reduction in lifetime generation. The power output of 5 MW land-based PV system is also simulated for comparison with the FSPV system. Land based PV system generate 10%–11% power less than the FSPV system. The total power output of the land-based PV plant considering 1.07% degradation rate is 168,815 MWh and considering the standard degradation of 1%, the power output is 170,189 MWh. The reduction in energy generation by the system is 1374 MWh if actual degradation is considered. Thus, actual degradation of PV module is important for accurate estimation of the energy generation by the PV system.

4.4. Effect of degradation on LCOE

Degradation affects the total lifetime generation of the PV system. Degradation also impacts the financial factors such as the total cost, running cost, LCOE and payback period. Considering the actual degradation rate of 1.18%, the generation of the FSPV plant reduces by 3936 MWh, this will impact the LCOE and the payback period. The estimated cost required to set up the 5 MW FSPV plant is given in Table 7.

All the cost and taxes have been calculated following the guidelines provided by CERC for tariff calculation of renewable systems in India. The electrical equipment like transformers, inverters are selected such that they follow the all safety standards. The normalized cost for the FSPV plant is 969,393 $/MWp. The operational details required to calculate the LCOE is given in Table 8.

Using the operational details, the LCOE of the system is calculated. Proper estimation of the maintenance cost is a vital factor in determining the LCOE. LBPV systems face the problem of excessive module heating, this causes reduction in the form factor hence reduction in power output. To overcome this problem, cooling system such as water-based cooling, heat exchangers and heat sinks must be designed as described by Hernández-Callejo et al. [69]. These extra cooling systems increase the capital and maintenance cost of LBPV system. Whereas, FSPV systems are designed to operate on water bodies hence the module temperature remains lower. Thus, the modules are naturally water cooled and external cooling systems are not required. Both the LBPV and FSPV systems suffers from soiling losses [69,70]. This effect the

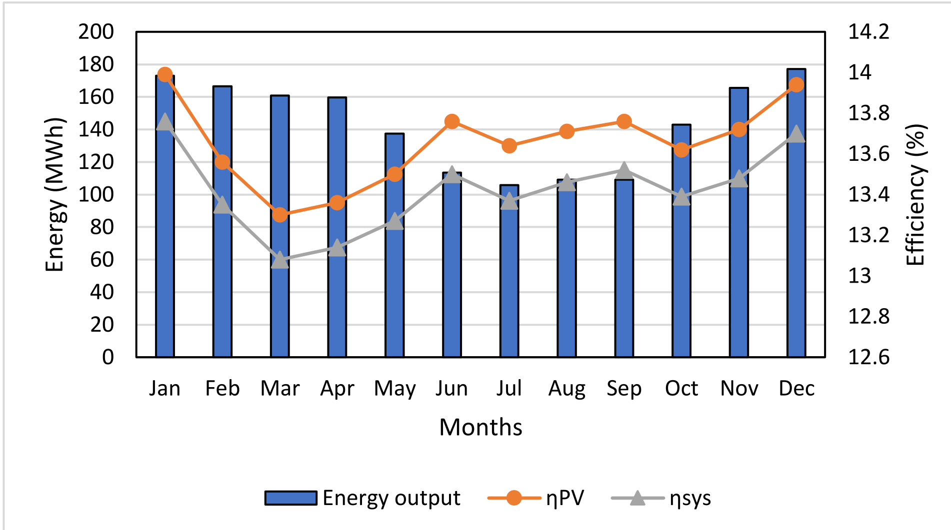

Fig. 20. Energy output and efficiency of the FSPV system.

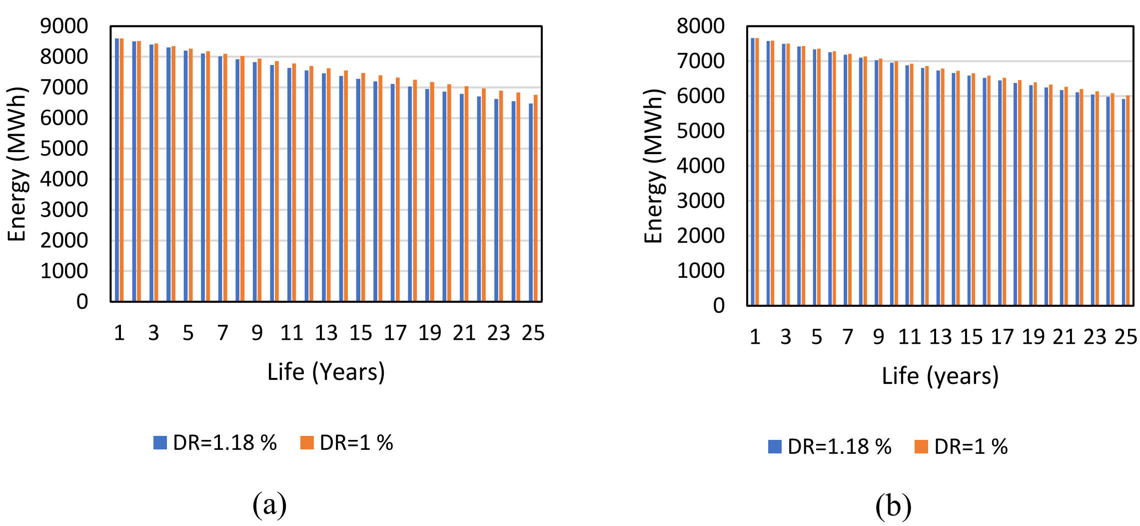

Fig. 21. Total annual generation considering degradation (a) FSPV system (b) land-based PV.

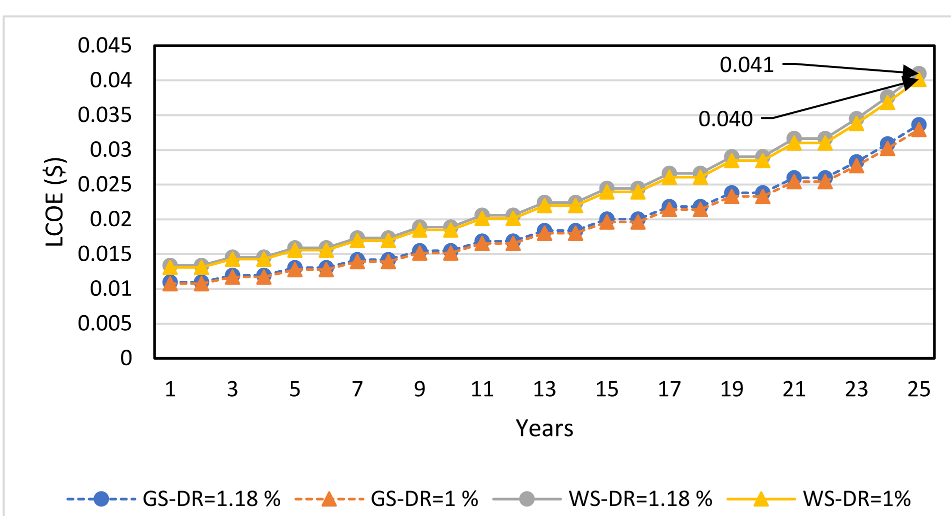

Fig. 22. Effect of degradation on LCOE.

Table 6
Comparison of degradation rates of previously installed PV systems and the current system.

Region	Operation period (years)	Capacity	Capacity	DR (per year)	Reference
Morocco	3	Poly-C-Si	5.9 kW	0.92%	[63]
UK and Australia	10	Poly-crystalline	3.9 kW	UK: 1.05-1.16% Australia: 1.32–1.46%	[64]
Brazil	15	Mono-C-Si	4.8 kW	0.7%	[65]
Gurgaon	22	Mono-C-Si	3.6 kW	1.9%	[66]
Himachal Pradesh	2.5	Mono-C-Si	1 kW	0.51%	[67]
Telangana	4	Multi-crystalline	1 MW	0.83%	[68]
Present system	17 months	Poly-C-Si	5 MW	FPV: 1.18% LPV: 1.07%	–

Table 7
Estimated cost of 5 MW FSPV system [62].

Sl. No.	Particulars	Cost ($)
1	**Cost of material**	
a	Module	1,625,000
b	Floater	2,210,000
c	Inverter	195,000
d	Balance of system	520,000
e	Total material cost	4,550,000
f	Contingency 1.5%	68,250
g	Total system cost	**4,618,250**
2	**Installation and commissioning cost**	
a	Installation	195,000
b	Service tax (15%)	29,250
c	Total	**224,250**
3	**Project management**	
a	Project management cost	3900
b	Tax (15%)	585
c	Total	**4485**
4	**Total project cost**	**4,846,985**

Table 8
Operational details of 5 MW FSPV system [62].

Sl. No.	Particulars	Value
1	**Project particulars**	
a	Capacity	5 MW
b	Project life	25 years
2	**Operational details**	
a	Performance ratio	81.2%
b	Utilization factor	16.68%
3	**Tax**	
a	Modules	5%
b	BOS	18%
4	**Running cost**	
a	O & M cost (2% of initial cost)	96,940 $/year
b	O & M escalation	5.75%/year
c	Spares maintenance (15% of O&M)	14 541 $/year
5	**LCOE calculation**	
a	Discounting factor	9.64%
b	Degradation rate	1.18%/year
C	Depreciation rate (first 12 years)	5.83%
d	Depreciation rate (rest of the years)	1.52%
e	Government subsidy	30% of initial cost

power efficiency of the modules by impacting the module output current. Thus, regular maintenance and water-based cleaning of the modules are required. Again, for the FSPV systems, water is available but for the LBPV systems the cost of water increases the maintenance cost. LBPV systems suffer from shading losses due to presence of trees, buildings [71]. Shading reduces the power output capacity of the PV systems and requires regular maintenance. As FSPV systems are designed over water bodies, they are less prone to partial shading. FSPV systems are also free from maintenance involving cleaning terrestrial vegetation. All these factors help in reducing the overall maintenance cost for FSPV systems. Again, from the experimental results it is seen that the degradation rate of FSPV system is higher compared to LBPV systems. FSPV systems also require extra components such as floaters, anchors and moors. The risk of component failure is higher in FSPV systems as they are prone to storms, waves and salt water corrosion. These factors increase the cost and maintenance of spares for FSPV systems. To minimize the income tax, accelerated depreciation method [72] is used to calculate the LCOE. In this method the depreciation is kept higher in the initial years and lower in the later years. In this method the overall profit of the project is not hampered while reducing the income tax. Fig. 22, presents the effect of degradation rate on LCOE calculation. The LCOE is calculated considering government subsidy (GS) and without subsidy (WS).

In Fig. 22, the dashed lines represent the LCOE considering subsidy and the solid lines represent LCOE without subsidy. The LCOE considering 1.18% degradation is 0.041 $/kWh without subsidy and 0.034 $/kWh with subsidy. Likewise, the LCOE considering the standard 1% degradation is 0.040 $/kWh without subsidy and 0.033 $/kWh with subsidy. The LCOE with 1.18% degradation rate is 2.5% higher than the LCOE with 1% degradation rate. Thus, it is seen that degradation rate impacts the LCOE calculation.

The power developed by the FSPV power plant is sold to the utility grid. According to the power purchase agreement (PPA), the tariff decided for 25 years is 0.0585 $/kWh, maintaining the state regulatory commission guidelines. The annual cash flow with and without subsidy and considering degradation is given in Fig. 23. Finally, the budgeting analysis performed considering the PPA rate is given in Table 9.

From Table 9, it is observed that the LCOE, payback period and NPV for the subsidized case is lower compared to the without subsidy case. In the subsidized case, the Government provides 30% subsidy on the initial capital invested, to promote renewable power generation. As a part of the capital is paid by the Government, all the financial parameters decrease. It is also seen that the payback period is higher by 1 month when the degradation rate is 1.18% for both with subsidy and without subsidy case. Similarly, the NPV is lower by 1.32% when actual degradation of 1.18% is considered. The internal rate of return (IRR) is also impacted by degradation, though the effect is not that high. Thus, it can be concluded that degradation of PV systems has detrimental effect on the performance and also on the financial parameters. Accurate estimation of degradation is very important to perform precise feasibility study of FSPV systems.

4.5. Environmental benefits of FSPV system

A major advantage of FSPV systems is that they help in water saving. FSPV systems cover the water surface over which they are installed thus reducing the evaporation of water. According to the Central Water Commission of India, the annual evaporation loss in the areas east of 85°E is 174 cm/m^2, which amounts to 1.75 kL/m^2. For the present 5 MW FSPV system, estimated area required is 60,000 m^2. The total water saving by reducing evaporation is 105,000 kL/year. Thus, the total water consumption of the plant and the auxiliary power consumption of the intake pump house is reduced.

FSPV systems are also instrumental in protecting the environment by reducing the carbon dioxide (CO_2) footprint. Conventional power plants are a major source of CO_2 production as they

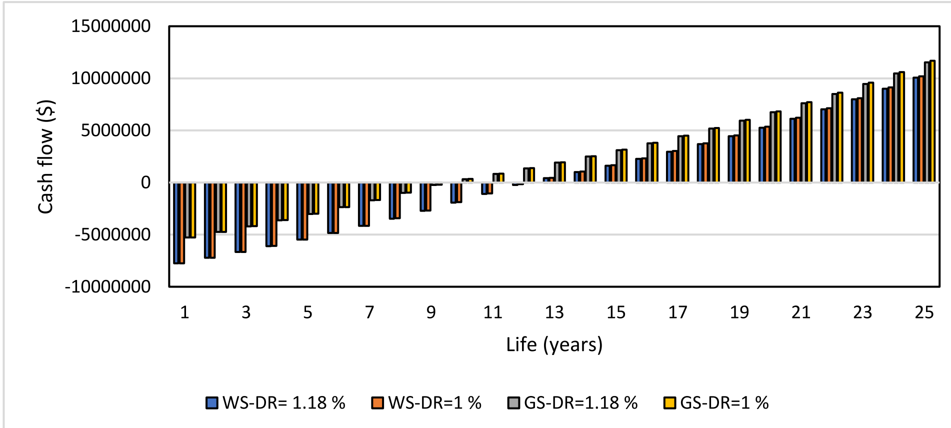

Fig. 23. Annual cash flows for the FSPV system.

Table 9
Budgeting analysis of the FSPV system.

Sl. No.	Parameters	Without subsidy		With subsidy	
		DR = 1.18%	DR = 1%	DR = 1.18%	DR = 1%
1	LCOE ($/kWh)	0.041	0.040	0.034	0.033
2	Payback period (months)	159	158	124	123
3	NPV ($)	10 071 079	10 205 940	11 534 424	11 692 612
4	IRR (%)	11.20	11.25	16.58	16.73

use coal for energy production. Generally, 0.98 kg CO_2 is produced to generate 1 kWh of energy from coal [73]. The total annual CO_2 saving by the 5 MW FSPV plant is 8432.41 tCO_2. In the life time of 25 years with 1.18% degradation the plant will save 183,493.24 tCO_2. Usually conventional power plants required 0.498 kg of coal to produce 1 kWh of energy [74]. The total savings in coal by the present system will be 4285.04 mt annually, and in 25 years it will save 93,244.52 mt of coal.

5. Conclusion

Scarcity of open lands combined with increasing land prices has led to the emergence of FSPV systems for electricity generation in recent times. This paper examines the degradation rate of FSPV module under real outdoor conditions. An experiment was performed to determine the performance and degradation rate of FSPV module and compare it to land-based PV system. Results show that the FSPV module remains cooler than the land-based PV system, the average temperature difference is 6 °C. The temperature difference increases to 22 °C in the summer months and deceases in the winter time. The performance of the FSPV system is also higher, it generates 10.96% power more than the land-based PV system. The efficiency of the FSPV system is 10.06% more than the land-based counterpart. The lower temperature of the FSPV modules attributes to the higher performance. From the 17 months of experiment it was found that the FSPV module had undergone 4.4% higher degradation than the land-based PV module. The reasons for degradation are explained by analyzing the parameters of the PV modules under real outdoor conditions. The results showed that the increment in series resistance for the FSPV module was 4.1% more than land-based PV system. On the contrary, the shunt resistance of the FSPV module also displayed 4.86% additional reduction. Similarly, the FSPV module displayed higher increment in ideality factor compared to the LBPV module while the saturation current displayed opposite trend. Visual inspection also revealed higher degradation in the FSPV module due to water-based corrosion and moisture ingression. On the basis of experimental results, it is seen that FSPV module has higher degradation than land-based modules. Considering the degradation rates obtained from the experiment, a feasibility study of 5 MW FSPV power plant is also done in the paper. The plant is designed with 5 units each having capacity of 1 MW and it is spread over a total water surface area of 60,000 m^2. The power generated by the plant in its lifetime of 25 years by considering 1.18% degradation rate is 187,238 MWh, which is 2.06% lower compared to the power output considering standard degradation of 1%. The LCOE calculated is also 2.5% higher considering the actual degradation rate. From the results it is concluded that proper estimation of degradation is very important before performing feasibility study of FSPV projects as degradation rate impacts the performance and financial parameters of the project. FSPV systems also have environmental benefits, the proposed 5 MW system will save 105,000 kL of water from evaporation annually. The FSPV plant will also save 183,493.24 mt of CO_2 in its lifetime.

CRediT authorship contribution statement

Anik Goswami: Conceptualization, Methodology, Software, Validation, Writing - original draft, Visualization. **Pradip Kumar Sadhu:** Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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