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Analysis of various degradations of five years aged mono c-Si, poly c-Si, and thin-film photovoltaic modules from rooftop solar installations in Dhaka's tropical wet and dry climate conditions

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This study evaluates the degradation of mono, poly, and thin-film silicon solar photovoltaic (PV) modules through visual and electrical measurements in Dhaka's tropical wet and dry climate conditions. For this, several sites of rooftop solar PV installations in Dhaka, aged at least 5 years, were selected for field investigation. A visible inspection for visual degradation followed by experimental testing on various electrical characteristics of the PV modules installed on the rooftop using a portable Seaward I–V Tracer for measuring the electrical degradation was done. The electrical data were used to evaluate the degradation of short circuit current, open circuit voltage, fill factor, and maximum power in the field as compared to the nameplate values. Experimental results showed the varying types of visual degradation types such as visible cracks, snail trails, moisture intrusion, front glass, and discoloration for the investigated PV modules. The degradation of PV modules in terms of short circuit current was 0.7%/year for 85Wp mono c-Si, 7.6%/year for 150Wp poly c-Si, and 9.7%/year for 105Wp silicon thin-film, respectively. We believe this study would guide the maintenance of the solar PV systems installed on Dhaka city's rooftop buildings.

KEYWORDS

silicon solar cells, photovoltaics modules, degradation, short circuit current, fill factor, rooftop solar in dhaka

1 Introduction

The National Energy Policy of Bangladesh-2010 (NEP-2010) had set targets to generate 5% of the total electricity from renewable energy resources by 2015, 10% by 2020, and 17% by 2041 to reduce greenhouse gas emissions (National Energy Policy of Bangladesh-2010, 2010). At present, the renewable energy share of the national electricity production capacity is 3% (Uddin et al., 2019). In total share of 3%, hydro, solar, and wind energy shares are 60%, 39.5%, and 0.5%, respectively (Uddin et al., 2019). This suggests that after hydropower, solar energy is the fastest-growing renewable energy in Bangladesh's energy sector. Also, the government's set targets for solar energy dominate the other renewable energy sources (Sustainable and Renewable Energy Development Authority SREDA, 2019), see Figure 1.

Since then, solar PV has emerged as a popular source of electricity and is even become popular in remote areas with the government initiative under the motto of 'access to electricity for all' (Sustainable and Renewable Energy Development Authority SREDA, 2019). The PV systems that have been deployed in Bangladesh are i) solar home systems, ii) solar systems on the roof of an industrial and commercial building, iii) solar irrigation, iv) solar street lighting, v) large scale solar power plants, and vi). Solar-based electric vehicle charging stations (Sustainable and Renewable Energy Development Authority SREDA, 2019). These PV systems showed a great scope in favoring the SDG7 criteria (Kumar et al., 2020). Though it favors the SDG7 criteria, concerns related to stable long-term performance in terms of energy generation were raised (Kumar et al., 2020). This is mainly due to the degradation that is often observed in solar PV modules and is PV cell (monocrystalline silicon (mono c-Si), polycrystalline silicon (poly c-Si), and thin-film) technology dependent, sensitive to climatic conditions and surrounding influences (Kumar et al., 2019a). During the PV module's lifetime, its energy generation levels degrade yearly at an average rate of 0.5% to higher, depending on the cell technology and the installation location (Kumar and Malvoni, 2019). From a maintenance point of view, degradation plays a crucial role; also, some evidence shows the decline in revenues due to PV degradation in solar power plants (Kumar et al., 2019b). So it is imperative to measure the degradation, which can be done mainly by conducting visual (Chekired et al., 2021) and electrical performance experiments (Rajput et al., 2019) and, in some cases prediction algorithms (Kumar and Subathra, 2019). However, experimental studies are more notable and mostly confined to specific geographical locations. For instance, for degradation in mono c-Si, studies on 7 years aged modules in Singapore (Luo et al., 2019), 5 years aged modules in India (Dubey et al., 2017), 5 and 10 years aged modules in Algeria (Charrouf et al., 2017), 3 years aged modules in Senegal (Ndiaye et al., 2015), 12 years aged modules in Ghana (Aboagye et al., 2021), and 22 years aged modules in Spain (Lillo-Sánchez et al., 2021) are notable. For degradation in poly c-Si, studies on 3 years aged modules in Indonesia (Sinaga et al., 2019), 9 years aged modules in Malaysia (Islam et al., 2018), and 3 years aged modules in India (Dubey et al., 2017) are notable. Similarly, few studies exist on solar PV module types such as CIGS, CdTe, and HIT (Dubey et al., 2017). However, in our brief literature study, we observed that studies confining to Bangladesh on solar PV degradation do not exist, and we believe it is important to investigate as Bangladesh is trying to enhance solar share in the national energy mix.

Hence, this research aims to estimate the degradation in various PV modules (mono c-Si, poly c-Si, and thin-film silicon) operating in a real-time environment for at least 5 years through visual and electrical inspection methods in Bangladesh's geographical and environmental context, especially for Dhaka city.

2 Methods

2.1 Detail of test sites

This study considered 4 rooftop solar PV installation sites (1 mono c-Si, 2 poly c-Si, and 1 thin-film silicon); see Table 1

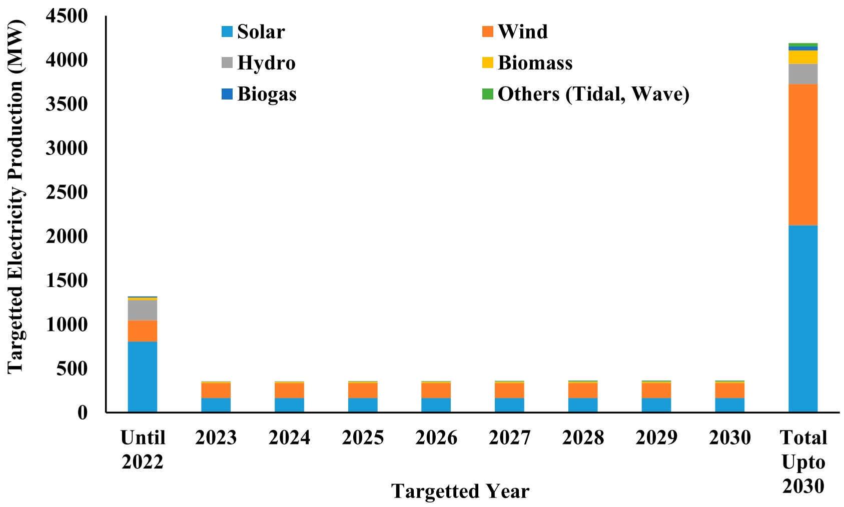

FIGURE 1
Year-wise set targets for increasing renewable share in Bangladesh's energy mix. Drawn based on data source (Sustainable and Renewable Energy Development Authority SREDA, 2019).

TABLE 1 Investigated installation sites and rooftop solar PV power plant data.

Parameters	Site-1	Site-2	Site-3	Site-4
Locations in Dhaka City, Bangladesh	Mirpur-12	Mirpur-DOHS	Mirpur-12	Tejgaon Industrial Zone
Installed Capacity	5000 W	2,550 W	3000 W	5,000 W
Module capacity and no. of such modules	50 W and 100 Modules	150 W and 17 Modules	100 W and 30 Modules	100 W and 50 Modules
Size of the PV modules and number of PV cells in each module	2.5 × 6 inches rectangular 36 cell	6 × 6 inches square and 36 cell	6 × 6 inches pseudo square and 36 cell	3 × 3 feet and single cell
PV module technology type	Poly c-Si	Poly c-Si	Mono c-Si	Thin-film silicon
Installation year	2014	2013	2014	2015
Type of installation as for electrical power system	On-Grid	Off-Grid	On-Grid	Off-Grid

TABLE 2 PV modules characteristics data as provided by the manufacturer.

PV modules parameters	PVM-1 20PolySi 50 W	PVM-2 40PolySi 150 W	Reference 22Poly Si 100 W	PVM-3 36MonoSi 85 W	Reference 16Mono Si 100 W	PVM-4 25ThinSi 105 W	Reference thin Si 110 W (Aboagye et al., 2021)
Maximum Power (P_{max}) (Wp)	50	150	100	85	100	105	110
Open Circuit Voltage (V_{oc}) (V)	21.6	21.6	22.5	21.5	22	71.0	71.0
Short Circuit Current (I_{sc}) (A)	3.29	8.85	5.76	5.42	5.88	2.40	2.5
Voltage at Maximum Power (V_{mpp}) (V)	17.3	17.2	18.35	17.2	18	53.5	54
Current at Maximum Power (I_{mpp}) (A)	2.94	8.72	5.45	4.94	5.54	1.96	2.04
Fill Factor (FF) (%)	71.6	78.5	77.17	72.9	77.09	61.54	62.06
Efficiency (E_{ff}) (%)	14.53	21.12	15.87	15.17	19.18	11.65	10.01
Nominal Operational Cell Temperature (°C)	(−)40 to +85	45 ± 3	47 ± 3	45 ± 3	45 ± 3	N/A	N/A
Cell Area (cm^2)	6.4 × 15.4	14 × 14	15.5 × 6	12.5 × 12.5	15.5 × 9.3	96.3 × 93	118 × 94
No. of Cells	36	36	36	36	36	N/A	N/A
Module Area (cm^2)	66 × 67	134 × 62	115 × 67.5	119 × 54	92 × 67	99 × 96	124 × 100

for more details on the test sites. These test sites fall under the Tropical savanna climate (Aw) as per the Köppen-Geiger climate classifications (Köppen, 1884). In these test sites as per the local weather station, the average temperature in summer is 40°C; in monsoon, it is 35°C; and in winter, it is 25°C. The average wind speed in summer is 10 km/h; in monsoon, it is 6 km/h; and in winter, it is 4 km/h. The average solar irradiation in summer is 900 Wm-2; in monsoon, it is 1,000 Wm-2; and in winter, it is 800 Wm-2. The average humidity in summer is 60%; in monsoon, it is 80%, and in winter, it is 55%. The average rainfall in summer is 90 mm; in monsoon, it is 90 mm; and in winter, it is 10 mm. The average sunshine hours in summer are 10 h/day; in monsoon and winter, they vary from 7–8 h/day.

The manufacturer-provided data for each type of PV module is given in Table 2. Mono and poly c-Si reference PV modules were bought from the market for comparison. For the thin film module, 110Wp PV modules data from the reference by (Ustun et al., 2019) was used.

2.2 Experimental instrumentation setup

The electrical data under sunlight were measured using the PV-200 Seaward I–V tracer from Seaward Electronic Limited, UK (PV-200 Seaward, 2023) (see Table 3 for technical features). The solar irradiation, PV module temperature, and ambient temperature

TABLE 3 Features of PV module survey and solar irradiation metesr.

Solar PV 200 I-V tracer	Solar survey 200 irradiance meter
PV voltage range 0–1000 V DC	PV Sensor 100–1,250 W m^{-2} ±1
PV current range 0–15A DC	Ambient temperature sensor (floating type) (−)30 to +125°C (±1)
Measurement sweep time <250 m	Module temperature sensor (suction type)
Voltage accuracy ±0.5% @ 55°C	Tilt angle sensor (0°–90°)
Current accuracy ±1% @ 55°C	Wireless data transfer
Wireless sensor range 100 ft	PV Module mounting bracket

were measured using wireless Solar Survey 200 from Seaward Electronic Limited, UK (PV-200 Seaward, 2023). The current-voltage (I–V) data was measured by connecting the I–V tracer standard probes with the connectors in the back terminal of the PV module of interest. The data acquisition from the PV modules under sunlight was carried out following the standard operating procedure of the I–V tracer. The PV modules were isolated from the array at the beginning of the process to ensure safety. The radiation flux meter was kept at the same plane with the PV module using a clamp; thus, the PV module and the solar irradiation meter received an identical amount of sunlight. The suction-type temperature sensor was connected to the rare side of the PV module, and the ambient temperature sensor kept hanging around the PV module.

2.3 Translation of experimental data to standard testing condition (STC) values

The I-V data processing was performed using the Seaward Solar Chart tool from Seaward Electronic Limited, UK (PV-200 Seaward, 2023). The transfer of I–V data from the survey meter to a computer was completed by using the SolarCert data logger software tool (SolarCert, 2023). The software allows us to plot the I–V graph and power-voltage (P-V) graph under STC following Procedure 1a of IEC 60891 (Photovoltaic devices, 2009; Li et al., 2021).

3 Results and discussions

3.1 Visual inspections results

The degradation of PV modules can be categorized into four major categories, i) degradation of packaging material, ii) loss of adhesion, iii) degradation of module interconnects, and iv) degradation of the solar cell material (Sinha et al., 2020). Some of these degradations lead to visible changes in the module and can be detected by visual inspection of the module without doing any electrical characterization of the module (Meena et al., 2022). The images of the various visual degradations observed in our investigation are given in Figure 2, which are inline with other visual degradation studies in literature (Menoufi et al., 2017; Ingenhoven et al., 2019; Tanesab et al., 2020; Meena et al., 2022). For instance, large visible cracks (Figure 2A), discoloration (Figure 2B), glass degradation and front-side delamination (Figure 2C), moisture and dust accumulation (Figure 2D), snail tracks (Figure 2E), and a minor cracks (Figure 2F). Based on our observation, the visual degradation observed in studied PV modules is classified as per the variations shown in literature and presented in Table 4. Overall, it was observed that all three types of PV modules (mono c-Si, poly c-Si, and thin-film silicon) are subject to degradation, though poly c-Si modules suffer more.

3.2 Electrical inspections results

The comparisons of various electrical parameters monitored for degradation analysis are shown in Figure 3. Figure 3 shows the results for temperature, open circuit voltage, short circuit current, voltage at maximum power, current at maximum power, fill factor, maximum power, and efficiency for the investigated mono c-Si, poly c-Si, and thin-film silicon solar PV module types. Each bar chart in Figure 3 shows 3 bars corresponding to the measured data (blue), STC data (green), and nameplate data (brown).

3.2.1 Module temperature

Figure 3A shows the average PV module temperature compared to the ambient temperature. The maximum and minimum temperature of the poly c-Si PV module was 67°C and 53°C for the times between 12:00 H −14:00 H under the irradiation of 961.8 W m^{-2}. The average mono c-Si PV modules temperature was 51°C under the irradiation of 959.2 W m^{-2}. The average thin-film module temperature was similar to the ambient temperature of 40°C under the irradiation of 911.8 W m^{-2}. At the temperature range of 67°C–50°C, PV modules are subject to high thermal stress (Kurtz et al., 2009; Vaillon et al., 2020). The variations in the PV module's temperature are due to cooling under natural wind flow (Dwivedi et al., 2020; Amber et al., 2021).

3.2.2 Electrical characteristics

As shown in Figure 3B, the open circuit voltage (V_{oc}) at STC of each module compared to the nameplate data is higher; this is due to the fact that the operating temperatures of these modules are higher than 25°C and inline with literature evidence as suggested by (Chattopadhyay et al., 2014). As a consequence of this higher open circuit voltage, the short circuit current (I_{sc}) at STC of each module is lower than the nameplate data; see Figure 3C. This reduction in the short circuit current (I_{sc}) causes a decrease in the fill factor, as shown in Figure 3G. The above argument is consistent with the voltage at the maximum

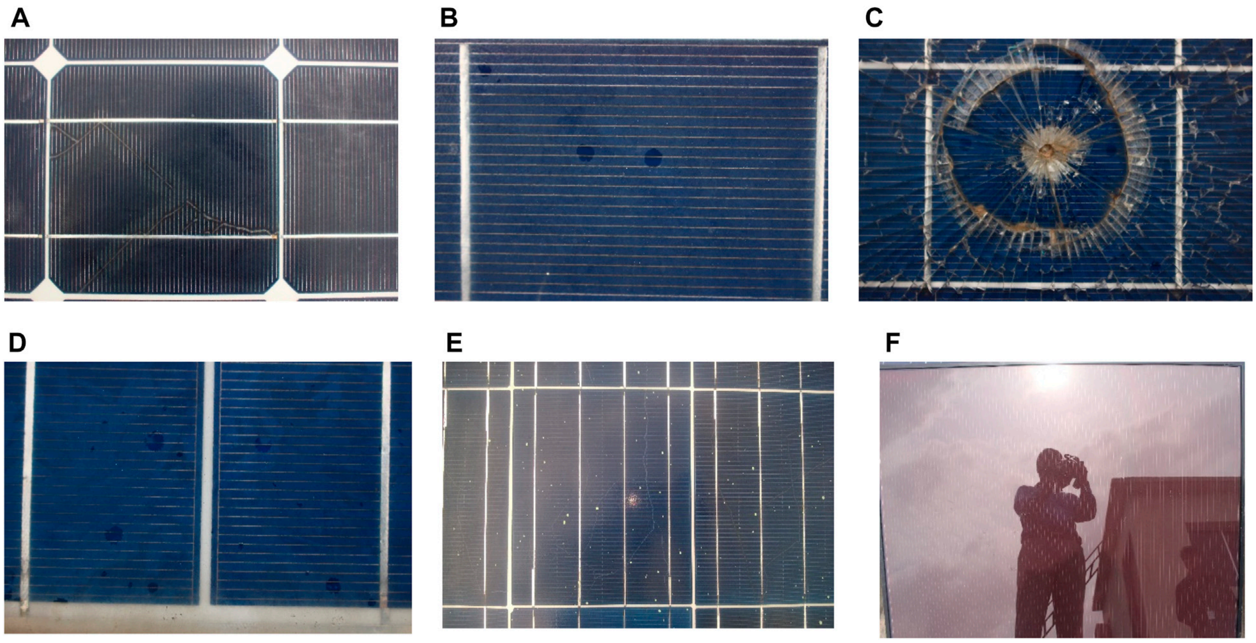

FIGURE 2
Various visual degradations observed in PV modules in rooftop solar power plants in building of Dhaka City. **(A)** PVM-3 36MonoSi100W; **(B)** PVM-1 20PolySi50W; **(C)** PVM-1 20PolySi50W; **(D)** PVM-2 40PolySi150W; **(E)** PVM-2 40PolySi150W; **(F)** PVM-4 25ThinSi105 W.

TABLE 4 Various degradations of PV modules during visual inspection.

Visual PV Cell/Module degradation	PVM-1 20PolySi50 W	PVM-2 40PolySi150 W	PVM-3 36MonoSi100 W	PVM-4 25ThinSi105 W
Visible cracks	√	×	×	×
Snail trails	√	√	×	×
Moisture intrusion	√	√	√	×
Front glass	√	×	×	×
Discoloration	√	√	√	√

power point and current at the maximum power point, as shown in Figure 3D and **(E)**. The maximum power of PV modules is significantly less than the nameplate data of PVM-2-40 PolySi-150 W as shown in Figure 3F. This may be due to the presence of inactive cells in the module, which can explain the lower short circuit current for the same module, as shown in Figure 3C. The efficiency *versus* PV technology plot shown in Figure 3H represents the performance of the PV modules in terms of efficiency.

3.2.3 Analysis of degradation

The short circuit current, shown in Figure 3C, and the fill factor, shown in Figure 3F of PV modules, are considered for estimating the degradation in this study following the procedure proposed mentioned by (Dhoke et al., 2018). The degradation of short circuit current and Fill Factor is evaluated for the PV modules with 5 years of field exposure. Table 5 shows the degradations of 5 years aged PV modules in Dhaka, Bangladesh. The data in Table 5 shows that the short circuit current of high power poly c-Si PV module suffers more degradation than lower powered PV module. This is due to the fact that the high-powered module generates more current, which introduces high current and induces degradations, which is in accordenace with literature as suggested by (Dhimish and Tyrrell, 2022). The thin-film silicon solar PV module shows 9.66% degradation in the short circuit current. Thin-film PV modules are expected to be more affected by photo-induced degradation.

Table 6 shows the rate of silicon PV module performance degradation in terms of short circuit current, published in the literature, along with the data from this study. The mono c-Si PV modules are more resilient to the environment of Bangladesh than poly c-Si and thin film silicon modules; thus, the degradation rate is around 1%/year.

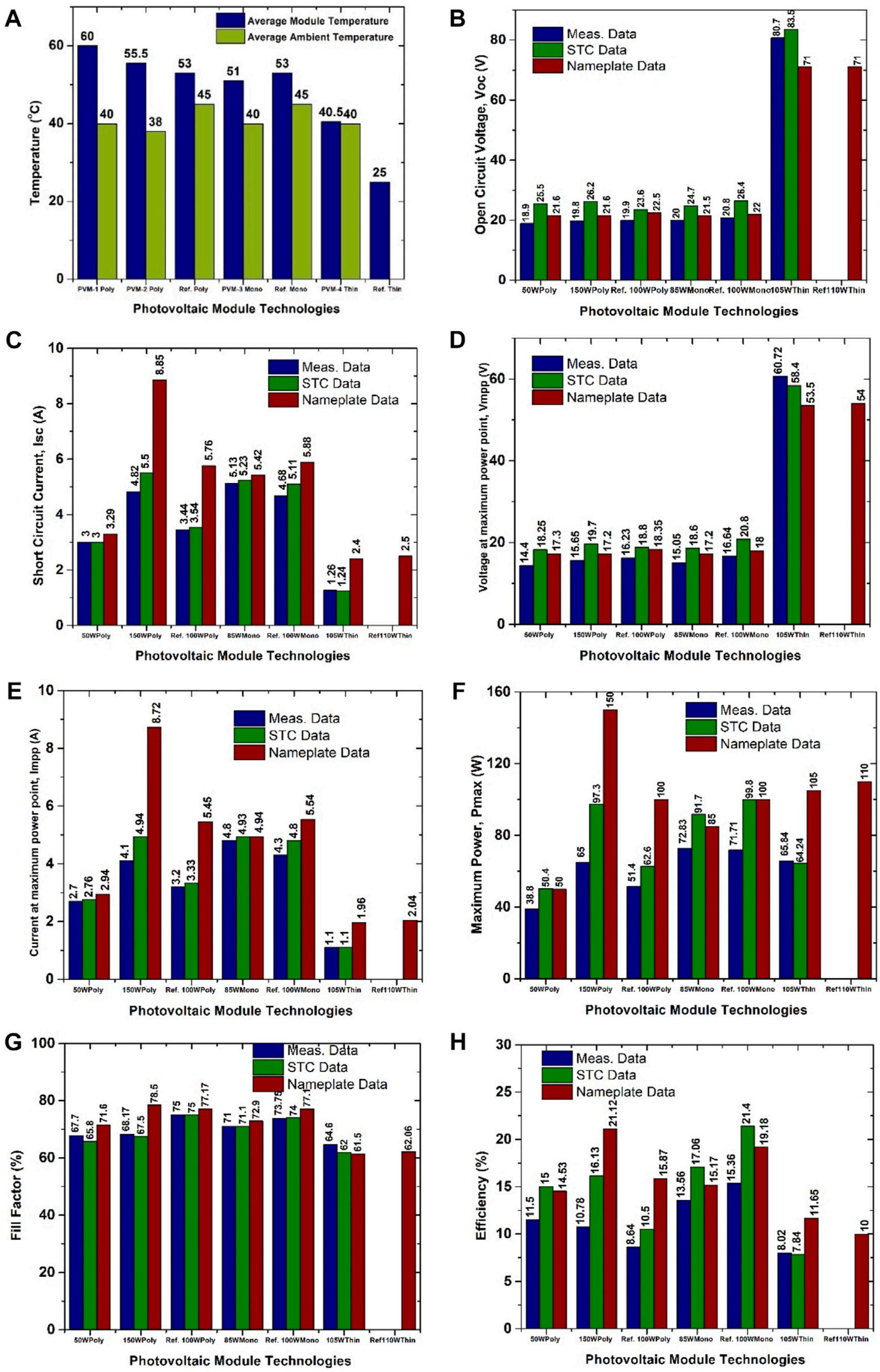

FIGURE 3
Observed degradation characteristics of mono c-Si, poly c-Si, and thin film silicon solar PV modules. **(A)** Ambient and module temperature; **(B)** Open circuit voltage; **(C)** Short circuit current; **(D)** Voltage at maximum power; **(E)** Current at maximum power; **(F)** Maximum power; **(G)** Fill factor; **(H)**. Efficiency.

10.3389/fenrg.2023.996176

TABLE 5 The degradations of 5 years aged PV modules in Dhaka, Bangladesh.

PV modules parameters	Degradation rate (%/year)			
	PVM-1 20PolySi 50 W	PVM-2 40PolySi 150 W	PVM-3 36MonoSi 85 W	PVM-4 25ThinSi 105 W
Short circuit current, I_{sc}	1.76	7.57	0.7	9.66
Fill Factor	1.62	2.78	0.5	−0.16

TABLE 6 Rate of silicon solar PV module performance degradation in terms of short circuit current in literature.

Location	Age of PV module (Years)	PV cell technology	Degradation rate (%/year)	Reference
Indonesia	3	Poly c-Si	4	Sinaga et al. (2019)
Singapore	7	Mono c-Si	0.5	Luo et al. (2019)
Malaysia	9	Poly c-Si	4.6	Islam et al. (2018)
India	5	Mono c-Si	1.33	Dubey et al. (2017)
Algeria	5	Mono c-Si	3.6	Charrouf et al. (2017)
	10		1.7	
Senegal	3	Mono c-Si	4.33	Ndiaye et al. (2015)
Ghana	12	Mono c-Si	3.19	Aboagye et al. (2021)
Spain	22	Mono c-Si	1.4	Lillo-Sánchez et al. (2021)
Dhaka, Bangladesh	5	150 Wp poly c-Si	7.6	Present Study
		85 Wp mono c-Si	0.7	
		105 Wp thin-film	9.7	

4 Conclusion

The degradation of three different types of PV module technologies widely used in Dhaka city's rooftop solar plants was evaluated under visual and electrical inspection methods. This study considered 5 years old rooftop solar installations because of the availability of data. The PV modules showed clear signs of visual degradation, such as visible cracks, snail trails, moisture intrusion, front glass damage, and discoloration of contacts; however, it was not the same for all the three types of PV technologies investigated, and at the same, it was observed visual degradations intensity was higher for poly c-Si followed by mono c-Si and thin-film silicon. The electrical inspection showed a degradation of 0.7%/year for 85Wp mono c-Si, 7.6%/year for 150Wp poly c-Si, and 9.7%/year for 105Wp silicon thin-film. During our investigation, we also identified that the PV modules were not regularly cleaned or monitored, so the accounted degradation may vary if inspected for the frequently maintained modules, which are hard to find in Dhaka city. Also, frequent monitoring options were not clear on these sites, as there were no promised options by the installers during installation to identify and replace faulty modules and for regular maintenance. So, we believe this study's results reveal the importance of maintenance, especially from a degradation point of view, and will encourage appropriate measures such as bringing awareness on promoting consumer-involved maintenance after proper training; installers' responsibility to maintain the solar power plants by charging some premium from the consumers. At the same time, these results could trigger and lead to initiations on degradation discounted feed-in tariffs in the electricity policy.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

AH and NM formulated the concept and work schedule for the experiments. AH performed the ground level experiments followed by data analysis by NM. Validation and visualization done by AH and NM. Original manuscript writing followed by revisions during the peer review process done by AH and NM.

MB, MA, ME, and SK supported the experimental process, funding for experiments followed by further improvements in manuscript revisions.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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