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Article

Long-Term Reliability Analysis of ESS - Multicrystalline Silicon and Conventional Polysilicon Modules in a Grid-Connected Photovoltaic System

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Abstract: This work provides a long term reliability evaluation according to the field degradation and early-life failure behaviour of a 6.72 kWp rooftop photovoltaic (PV) system deployed at B V Raju Institute of Technology (BVRIT), at Telangana, India (17.37° N, 78 489 m asl). The plants consist of 28 modules and are separated into 4 arrays (7 modules × 4) two arrays filled with Elkem Solar multicrystalline silicon (ESS®) and the other two with conventional polysilicon. Real time 1 min inputs of plane-of-array irradiance, module/ambient temperature and AC/DC electrical quantities were collected for 12 months. Rate of degradation was determined from standard condition peak powers (Pmax) and classical two-parameter Weibull model with maximum likelihood estimation (MLE) was applied to estimating B10, B50 and B80 lifetimes. The average first-year power degradation of ESS® modules stood at 0.42 % compared with 0.61 % for polysilicon and their B10 estimated life is 19 years in comparison to 16 years for polysilicon. This supports the make of ESS technology as being more long-term reliable under hot-humid Indian conditions.
Keywords: Elkem Solar, Photovoltaic module, Reliability, Power degradation rate, Weibull lifetime analysis.

1. Introduction

All around the world, there is an acceleration of the scaling up of the deployment of the photovoltaic (PV) technology on an unprecedented manner. During 2024, it was the world that installed somewhere well over 350 GW of new solar capacity, pushing cumulative installations well past 1 TW and putting PV among the lowest-cost sources of absolute bulk electrification in many markets [1], [2]. Annual installed capacity of top countries is given in Fig. 1, Cumulative capacity of top countries is given in Fig. 2. India, driven by exciting governmental target and decreasing of levelized costs of electricity (LCOE), has become one of top-three growth markets; rooftop systems have become an increasingly significant part of national additions, especially on educational campuses and commercial buildings that provide favourable load profiles and parcel level control over investment in infrastructure. However, the viability of these assets from an economic perspective depends relatively on how effectively their PV modules withstand performance degradation and outright failures caused by environmental stressors with which they are exposed over their nominal 25–30-year service life [3], [4]. Performance losses rates (PLRs) from 0.6–0.8 % yr^{-1} are often called nominal in the case of crystalline-silicon (c-Si) modules, however, wide spread according to field surveys of different climate zones and bill-of- materials-variations and factory quality-control-levels [5], [6]. In hot–humid climate, moisture ingress, electrochemical corrosion and high operating temperature share synergistic influence in accelerating degradation pathways like potential-induced degradation (PID), solder-joint fatigue, and encapsulant discoloration.

For that reason, robust design architectures of modules are crucial both for optimising lifetime energy yield as well as for providing confidence for investors of PV finance models which assume single digit internal rates of return [7], [8].

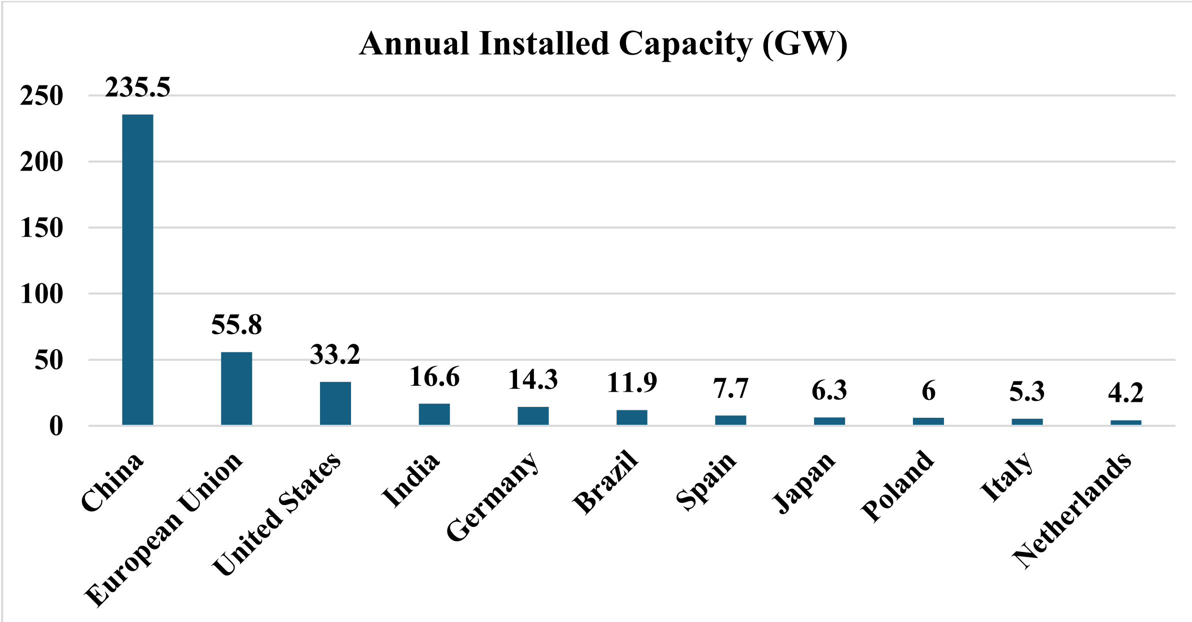

Fig. 1 Annual Installed Capacity of Top Countries

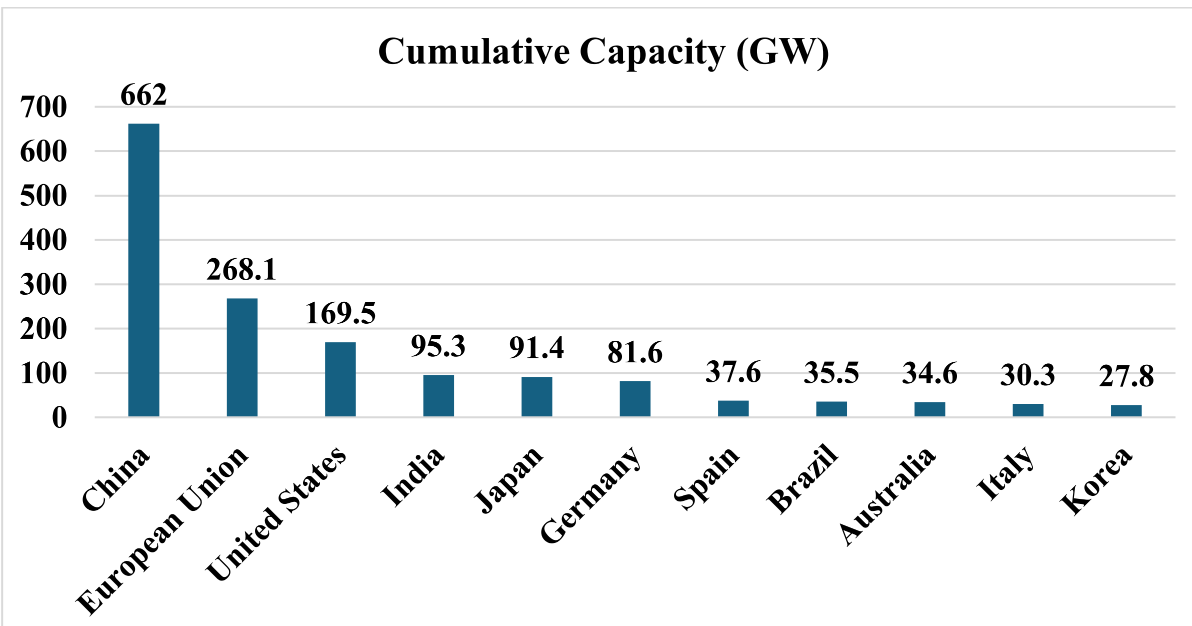

Fig. 2 Cumulative Capacity of Top Countries

In the crystalline-silicon family, the conventional "polysilicon" modules are grown from Siemens-process feedstockally purified to 9N–11N levels through energy-consuming Chemical Vapor Deposition (CVD) of trichlorosilane. On the contrary, Elkem Solar's upgraded metallurgical-grade silicon (ESS) route utilizes sequential slag refining and vacuum metallurgical procedures in order to attain solar grade purity (6N–7N) at presumably a third of the energy footprint of the Siemens process [9], [10]. Previous pilot-line investigation would indicate the residual metallic contaminants namely Fe, Ti and Al can be reduced to values where bulk carrier lifetimes are greater than 100 μs, to enable cell efficiencies that are comparable to standard multicrystalline wafers. The interest for the ESS technology was reawakened by recent studies, where breakthroughs in impurity gettering and ingot casting that compensates for the trade-offs of performance penalties historically associated with the technology Frontiers [11]. Due to a lack of long-term field data in relation to a variety of climatic exposures, the adoption of ESS has been slow, among other reasons. The most available Reliability Tests (RT) remain largely in the control of panel assembly by conventional polysilicon forming panels (i.e. manufactured panels), for which – except for PV manufacturers – practitioners are left with little insight on the overall lifetime risk profile of ESS within actual arrays [12]. Comprehensive meta-analyses provide the average first-year degradation rates of about 1 % yr^{-1} with a fat-tailed distribution extending to >3 % yr^{-1} for some module batches – the spread that emphasises the particularity of technology-specific characterisation [13]. Insurance-sector briefings in the last two years are mindful that just a 0.2 percentage-point annual shift in degradation can move LCOE by >3 % over 25 years, in turn re-sizing Power Purchase Agreement (PPA) pricing and warranty reserves [14], [15].

The composite tropical–semi-arid climate of the Indian sub-continent worsens the thermal-mechanical cycling, wind-driven dust abrasion and exposure to ultraviolet (UV) – all of these are notorious aging agents of solar photovoltaics. Therefore, field comparisons side-by-side in such climates are crucial for distinguishing incremental from substantial improvements in robustness of modules [16], [17]. By contrast, prior degradation studies in India often had to work with heterogeneous system vintages in combination with disparate mounting geometries or short monitoring windows, all of which compound direct fingerprinting of technology levels. In this setting, the present work provides a controlled experiment, whereby two strings filled with Elkem Solar multicrystalline modules were compared to a set of two identical strings that contain standard polysilicon modules, both simultaneously installed on a single rooftop at B V Raju Institute of Technology (BVRIT) in Telangana [18], [19]. It is possible to mention several benefits of the BVRIT rooftop installation for reliability research. First of all, its 17° south-facing tilt reflects local best practice for maximising annual irradiance capture at 17.37° N latitude. Second, given a relative simplicity of the system, its rather limited 6.72 kWp rating split into four separate 7-modules stands, it's possible to implement DC side monitoring on granular level, dispensing with the hassle of complexity of utility-scale plants. Third the campus setting enables secure, perpetual access for answering the flashed question-getting and Figure herry pictures ball pool magnet series-questions-X-ray detection of electrical crutches-X-ray, one of the vital diagnostics to connect observed loss of power to underlying failure modes. Lastly, the tailored DAQ infrastructure (sampling electrical and meteorological parameters at 1 min resolution) goes beyond "Class A" ratings given by the IEC 61724-1 and thus facilitates the determination of high-confidence degradation rate.

Weibull analysis has therefore emerged as the de facto statistical framework for quantifying the lifetime of PV modules as it can account for an early (infant mortality) as well as wear-out failure regime with a shape parameter β that can take on many values. $\beta < 1$ implies shrinking rate of failure that is typical of manufacturing defects; $\beta \approx 1$ represents random failures; and $\beta > 1$ stands for a growing rate of hazard controlled by ageing processes [20], [21]. As a notable fact, large fleet studies provide β values between 3 and 6 for crystalline-silicon modules within several years of their operation [22]. In this research, classically MLE is used to fit Weibull functions with two parameters to observed and projected failures, and, thus, providing the abilities to estimate not only the B50 (the median life) but also the more practically useful B10 and B80 percentiles that are being used for performing warranty burn-rate estimates and invasion planning for modules [23], Life Cycle Assessment (LCA) literature continues to push the need for serious field assessment of ESS as they have comparatively less embodied energy and greenhouse-gas footprint than polysilicon [24]. A cradle-to-gate assessment of an ESS™-based rooftop system estimated a 25 % decrease in energy-payback time when being used for at least 25 years under the insolation of Europe [25], [26]. However, the environmental benefit may be neutralised or even turned around if premature degradation or catastrophic failures shorten service life. Therefore, for their claims of sustainability to be verified, empirical lifetime data are necessary for emergent silicon purification routes.

2. Reliability Oriented Performance Evaluation Methodology

A reliability-oriented performance evaluation of photovoltaic (PV) modules is to forecast the useful lifetime and reliability of PV modules as a function of the power output and failure modes, mainly in adverse environmental conditions of hot-humid climates. The methodology starts off by obtaining high-resolution field data acquisition which usually includes measurements of solar irradiance, ambient and module temperature and electrical output parameters (AC / DC current, voltage, and power) measured at minute or hourly intervals. Such measurements are cumulated to calculate the rates of degradation.

In this work degradation is calculated as follows

$$\% P_{DR} = \frac{(P_{Installaion} - P_{After})}{P_{Installation}} * 100 \quad \% \quad \text{--(1)}$$

Where

P_{DR} = PV Power Degradation Rate

$P_{Installation}$ = P_{max} at Installation

P_{After}= P_{max} after one year

Periodic power degradation assessment forms a critical part of the evaluation of the reliability. To measure the performance loss, the Standard test condition (STC) peak power measurements are used. Statistical modeling with particular focus on Weibull distributions is used to describe the early-life failure behavior and estimate the lifetime parameters like B_{10} (time when 10% of the modules are expected to fail), B_{50} median life (50% failure) and B_{80} service life (80% failure). The maximum likelihood estimation (MLE) is a preferred approach that can be used in the fitting of two-parameter Weibull models with strong estimates even with small sizes of samples.

The Weibull lifetime modelling is given as follows

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \text{--} (2)$$

Where

- $\beta < 1$ → decreasing hazard (manufacturing defects)
- $\beta = 1$ → random (Poisson) failures
- $\beta > 1$ → wear-out (ageing)

MLE with a form of right censoring (Kaplan–Meier) gives the estimates of the scale η and shape β parameters

Likelihood Function with Right-Censoring is given as follows

Let:

- t_i: observed lifetime of the i-th module
- δ_i: failure indicator (1 if failed, 0 if censored)
- n: total number of observations

The log-likelihood function is:

$$\ln L(\beta,\eta) = \sum_{i=1}^{n} \delta_i \ln f(t_i;\beta,\eta) + (1-\delta_i)\ln S(t_i;\beta,\eta) \text{ --} (3)$$

Where:

- $f(t_i)$ is the PDF (for failed modules),
- $S(t_i) = \exp\left[-\left(\frac{t_i}{\eta}\right)^{\beta}\right]$ is the survival function (for censored modules).

Substitute into the log-likelihood:

$$\ln L(\beta,\eta) = \sum_{i=1}^{n} \delta_i \left[\ln\beta - \ln\eta + (\beta-1)\ln t_i - \left(\frac{t_i}{\eta}\right)^{\beta}\right] + \sum_{i=1}^{n} (1-\delta_i)\left[-\left(\frac{t_i}{\eta}\right)^{\beta}\right] \text{ ------------} (4)$$

Or simplified:

$$\ln L(\beta, \eta) = n_1 \ln\beta - n_1 \ln\eta + (\beta - 1)\sum_{i=1}^{n} \delta_i \ln t_i - \sum_{i=1}^{n}\left(\frac{t_i}{\eta}\right)^{\beta} \quad (5)$$

Where $n_1 = \sum_{i=1}^{n} \delta_i$ is the number of failures.

The Maximum Likelihood Estimation is given as

To estimate $\hat{\beta}, \hat{\eta}$, solve the system:

$$\frac{\partial \ln L}{\partial \beta} = 0, \quad \frac{\partial \ln L}{\partial \eta} = 0 \quad (6)$$

Form the obtained scale η and shape β parameters the following lifetime percentiles are calculated.

- B_{10} – time when 10 % have failed (bankability focus)
- Median life (B_{50}) – half the fleet failed
- Service life (B_{80}) – 80 % failed, end-of-life for large arrays

3. Experimental Setup:

This research work provides a long term reliability projection on the basis of field degradation and early life failure behaviour of a 6.72 kWp rooftop photovoltaic system installed in B V Raju Institute of Technology (BVRIT), Telangana, India (17.37° N, 78.47° E) 489 m asl). The plant consists of 28 modules, which fall into 4 arrays (7 modules per array): two arrays filled with Elkem Solar multicrystalline silicon (ESS®) and two that of conventional multicrystalline polysilicon as presented in Fig. 3. One-minute data of the real-time plane of array irradiance, module/ambient temperature, and AC/DC electrical quantities were then gathered for 12 months. Rates of degradation were calculated from standard condition peak power measurements (Pmax) with the help of a classical two-parameter Weibull model, fitted by maximum likelihood estimation (MLE), that was used to determine B10, Median life (B50) and Service life (B80) lifetimes. The Experimental Setup and module specifications are tabulated in Table 1 and Table 2 respectively.

Fig. 3 Experimental Setup of 6.72kWp rooftop photovoltaic (PV) system

Table 1 Experimental Setup

S.No	Item	Specification
1	System Capacity	6.72 kWp
2	Installation Site	B V Raju Institute of Technology (BVRIT), Telangana, India
3	Coordinates	17.37° N, 78.47° E
4	Altitude	489 meters above sea level (asl)
5	Total Modules	28
6	Arrays	4 arrays (7 modules per array)
7	Module Types	2 arrays with Elkem Solar multicrystalline silicon (ESS®) 2 arrays with conventional multicrystalline polysilicon
8	IV Curve Tracer	Day Star

Table 2 Module Specifications

S.No	Item	Specification
1.	PV Module Make	TITAN
2.	Maximum Power (Pmp)	240 W
3.	Maximum Voltage (Vmp)	30.23 V
4.	Maximum Current (Imp)	7.94 A
5.	Open Circuit Voltage (Voc)	37.56 V
6.	Short Circuit Current (Isc)	8.44 A

4. Results and Discussion

This work provides a long term reliability evaluation according to the field degradation and early-life failure behaviour of a 6.72 kWp rooftop photovoltaic (PV) system deployed at B V Raju Institute of Technology (BVRIT), at Telangana, India. The proposed long term reliability evaluation is implemented under the following cases

- Reliability Oriented Performance Evaluation with Poly Modules
- Reliability Oriented Performance Evaluation with ESS Modules

Reliability Oriented Performance Evaluation with Poly Modules

In this case, reliability oriented performance evaluation is implemented on conventional polysilicon modules. The array 1 and array 2 consists of conventional polysilicon modules, each array consists of 7 module with a total of 14 Modules. The Pmax at the time of installation and Pmax after one year for array 1 and array 2 are presented in Fig. 4 and Fig. 5 respectively.

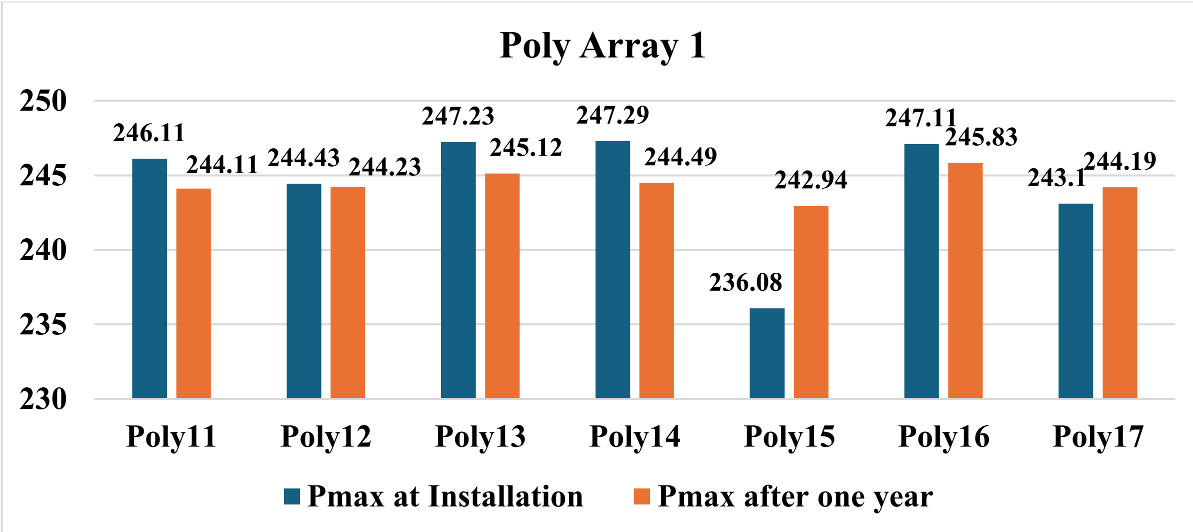

Fig. 4 Pmax at Installation and After One Year for Array 1

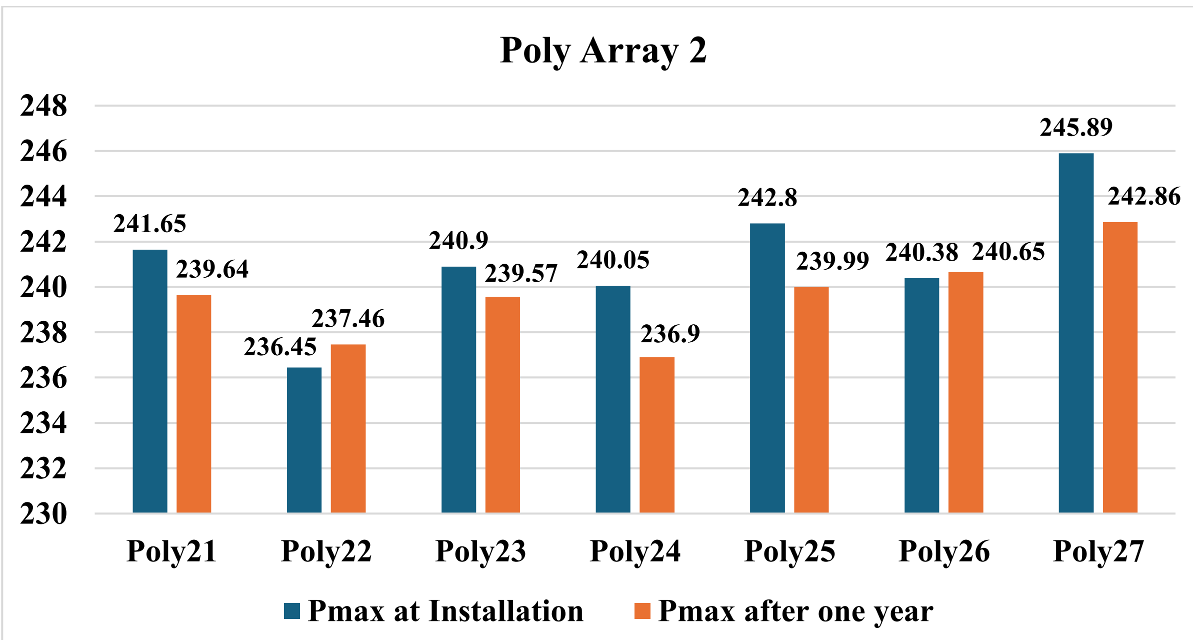

Fig. 5 Pmax at Installation and After One Year for Array 2

From the above evaluation the degradation for all the modules are evaluated using Eq. (1) and tabulated in Table 3

Table 3 Degradation Assessment for Poly Modules

Array	Module	Degradation (%)
Poly Array 1	Poly11	0.82
	Poly12	0.08
	Poly13	0.86

	Poly14	1.14
	Poly15	No Degradation
	Poly16	0.52
	Poly17	No Degradation
Poly Array 2	Poly21	0.84
	Poly22	No Degradation
	Poly23	0.56
	Poly24	1.33
	Poly25	1.17
	Poly26	No Degradation
	Poly27	1.25

From the above it is observed that the average degradation is 0.61 %. Using this degradation estimation, Weibull lifetime modelling is implemented. The estimates of the scale η and shape β parameters are obtained using MLE with a form of right censoring. Here right censoring is taken as 20 years. For 20 years of operation four panels fails at 15.04 years, 16.00 years, 17.09 years, 17.54 years respectively. The obtained scale η parameter is 24.07 and shape β parameter is 5.64. With these parameters the reliability curves are extracted as shown in Fig. 6 and lifetime percentiles are tabulated in Table 4.

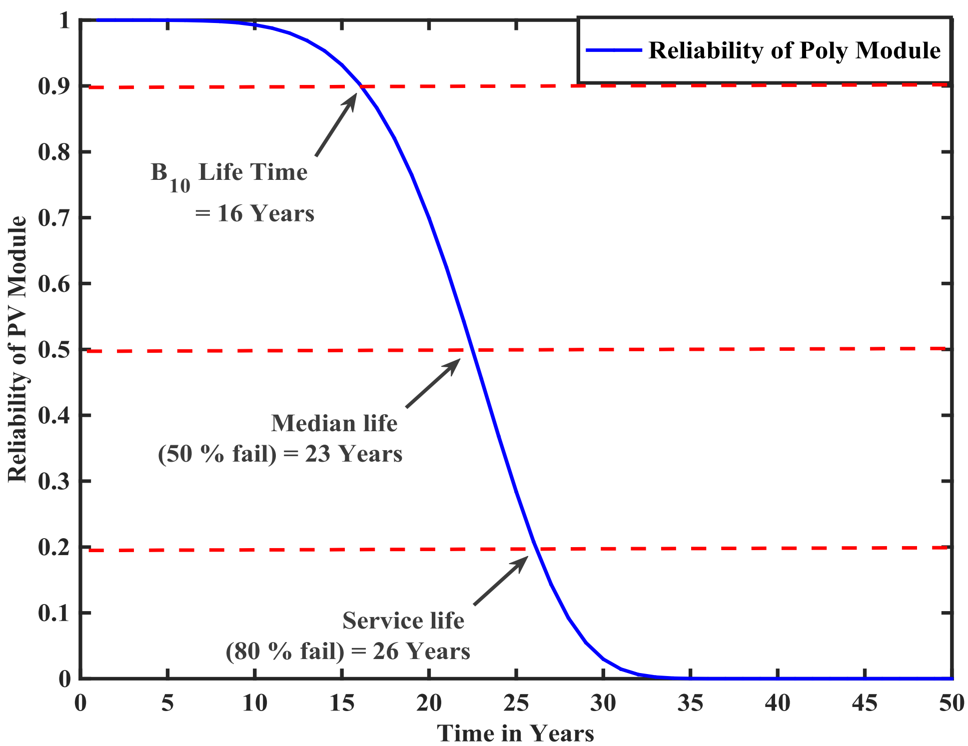

Fig. 6 Reliability Curve for Poly Module

Table 4 Lifetime percentiles for Poly Modules

Parameter	Value
Scale	24.07
Shape	5.64
B10 life (10 % fail) Years	16 Years
B50 Median life (50 % fail) Years	23 Years
B80 Service life (80 % fail) Years	26 Years

Reliability Oriented Performance Evaluation with ESS Modules

In this case, reliability oriented performance evaluation is implemented on Elkem Solar multicrystalline silicon (ESS®) modules. The array 3 and array 4 consists of Elkem Solar multicrystalline silicon (ESS®) modules, each array consists of 7 module with a total of 14 Modules. The Pmax at the time of installation and Pmax after one year for array 1 and array 2 are presented in Fig. 7 and Fig. 8 respectively.

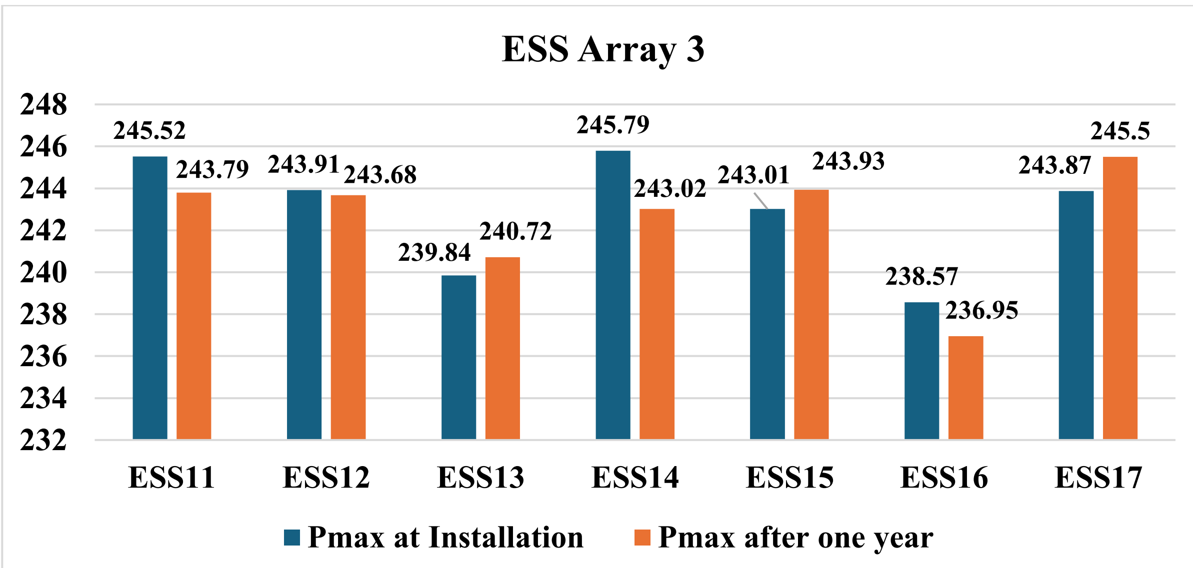

Fig. 7 Pmax at Installation and After One Year for Array 1

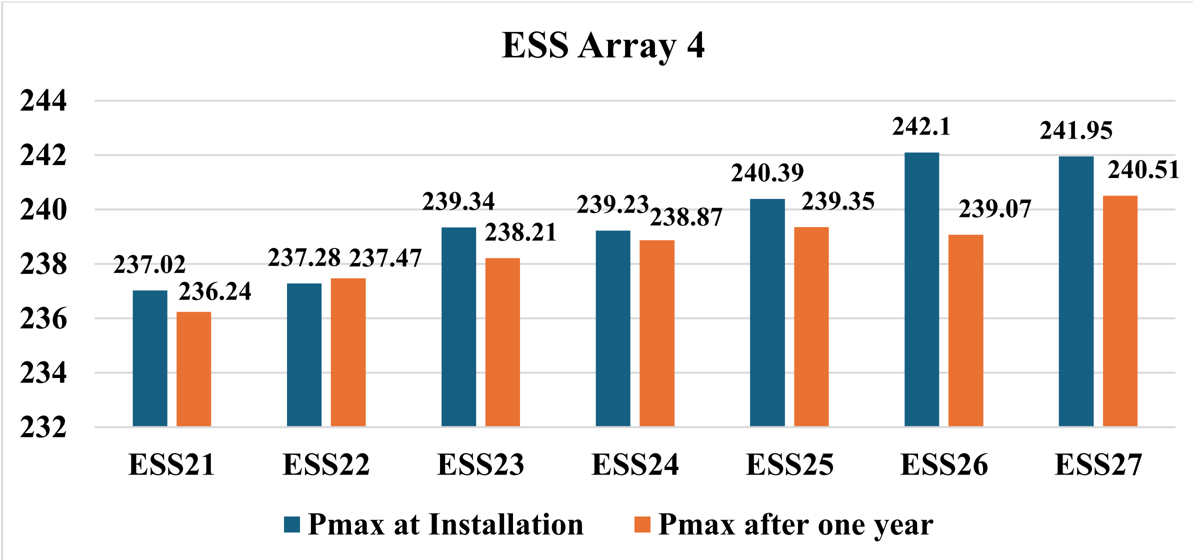

Fig. 8 Pmax at Installation and After One Year for Array 2

From the above evaluation the degradation for all the modules are evaluated using Eq. 1 and tabulated in Table 5

Table 5 Degradation Assessment for ESS Modules

Array	**Module**	**Degradation (%)**
ESS® Array 3	ESS11	0.71
	ESS12	0.09
	ESS13	No Degradation
	ESS14	1.14
	ESS15	No Degradation
	ESS16	0.68
	ESS17	No Degradation
ESS® Array 4	ESS21	0.33
	ESS22	No Degradation
	ESS23	0.48
	ESS24	0.15
	ESS25	0.44
	ESS26	1.27
	ESS27	0.6

From the above it is observed that the average degradation is 0.42 %. Using this degradation estimation, Weibull lifetime modelling is implemented. The estimates of the scale η and shape β parameters are obtained using MLE with a form of right censoring. Here right censoring is taken as 20 years. For 20 years of operation two panels fails at 15.75 years and 17.54 years respectively. The obtained scale η parameter is 27.67 and shape β parameter is 5.7. With these parameters the reliability curves are extracted as shown in Fig. 9 and lifetime percentiles are tabulated in Table 6.

Table 6 Lifetime percentiles for ESS Modules

Parameter	Value
Scale	27.67
Shape	5.7
B10 life (10 % fail) Years	19 Years
B50 Median life (50 % fail) Years	26 Years
B80 Service life (80 % fail) Years	30 Years

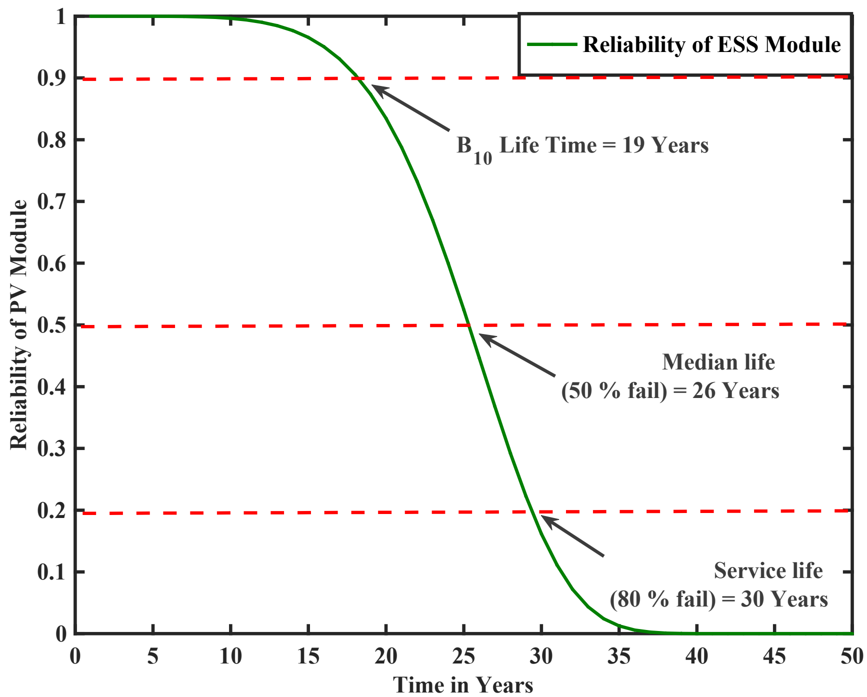

Fig. 9 Reliability Curve for ESS Module

Comparison Analysis

The comparison between Elkem Solar multicrystalline silicon (ESS®) modules and convention polysilicon modules shows very significant differences over long-term performance and reliability, particularly in hot-humid ambients such as in southern India. According to the year-long field study of 6.72 kWp rooftop PV system at B V Raju Institute of Technology (BVRIT), durability and rate of degradation at ESS® modules were better than poly modules. In particular, the average first-year power degradation rate for ESS® modules was found to be 0.42% and 0.61% in case of poly modules. This reduced degradation has the effect of a longer projected operational lifespan for ESS modules. Weibull reliability analysis estimated the difference further ESS modules demonstrated B10 lifetime of 19 years. PV modules using polysilicon showed shorter B10 life, as it was 16 years. The Weibull reliability comparison is presented in Fig. 10.

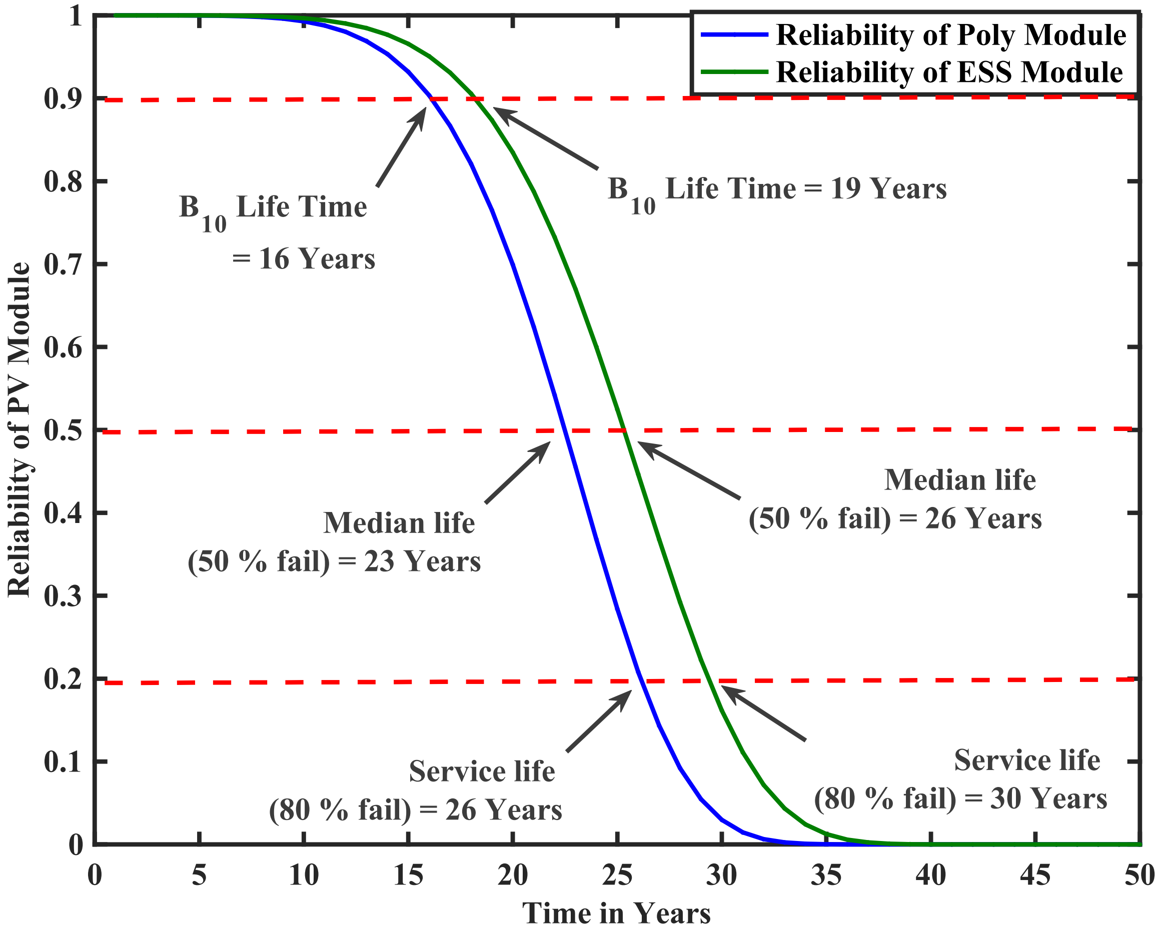

Fig. 10 Weibull Reliability Comparison

5. Conclusion

In this paper, the long term reliability assessment of the 6.72 kWp rooftop photovoltaic system at BVRIT is presented. The reliability of Elkem Solar multicrystalline silicon modules exhibited the superior performance, when compared with the conventional polysilicon modules. Rate of degradation was determined from standard condition peak powers (Pmax) and classical two-parameter Weibull model with maximum likelihood estimation (MLE) was applied to estimating B10, B50 and B80 lifetimes. The average first-year power degradation of ESS modules stood at 0.42 % compared with 0.61 % for polysilicon. This reduced degradation has the effect of a longer projected operational lifespan for ESS modules. Weibull reliability analysis estimated the difference further ESS modules demonstrated B10 lifetime of 19 years. PV modules using polysilicon showed shorter B10 life, as it was 16 years. This supports the make of ESS technology as being more long-term reliable under hot-humid Indian conditions. The imparted knowledge of this study not only confirms increased resilience of ESS modules but also provides an excellent reference for system designers, investors, and policymakers who want to optimize the solar PV deployment in tropical weather.

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