

Automation of Risk Priority Number Calculation of Photovoltaic Modules and
Evaluation of Module Level Power Electronics

by

Mathan Kumar Moorthy

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Graduate Supervisory Committee:

Govindasamy Tamizhmani, Chair
Devarajan Srinivasan
Bradley Rogers

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ABSTRACT

This is a two part thesis:

Part – I

This part of the thesis involves automation of statistical risk analysis of photovoltaic (PV) power plants. Statistical risk analysis on the field observed defects/failures in the PV power plants is usually carried out using a combination of several manual methods which are often laborious, time consuming and prone to human errors. In order to mitigate these issues, an automated statistical risk analysis (FMECA) is necessary. The automation developed and presented in this project generates about 20 different reliability risk plots in about 3-4 minutes without the need of several manual labor hours traditionally spent for these analyses. The primary focus of this project is to automatically generate Risk Priority Number (RPN) for each defect/failure based on two Excel spreadsheets: Defect spreadsheet; Degradation rate spreadsheet. Automation involves two major programs – one to calculate Global RPN (Sum of Performance RPN and Safety RPN) and the other to find the correlation of defects with I-V parameters' degradations. Based on the generated RPN and other reliability plots, warranty claims for material defect and degradation rate may be made by the system owners.

Part – II

This part of the thesis involves the evaluation of Module Level Power Electronics (MLPE) which are commercially available and used by the industry. Reliability evaluations of any product typically involve pre-characterizations, many different accelerated stress tests and post-characterizations. Due to time constraints, this part of the

project was limited to only pre-characterizations of about 100 MLPE units commercially available from 5 different manufacturers. Pre-characterizations involve testing MLPE units for rated efficiency, CEC efficiency, power factor and Harmonics (V_{thd} (%) and I_{thd} (%)). The pre-characterization test results can be used to validate manufacturer claims and to evaluate the product for compliance certification test standards. Pre-characterization results were compared for all MLPE units individually for all tested parameters listed above. The accelerated stress tests are ongoing and are not presented in this thesis. Based on the pre-characterizations presented in this report and post-characterizations performed after the stress tests, the pass/fail and time-to-failure analyses can be carried out by future researchers.

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TABLE OF CONTENTS

	Page
LIST OF TABLES	xiii
LIST OF FIGURES	xv
CHAPTER	
PART 1: AUTOMATION OF RISK PRIORITY NUMBER CALCULATION OF PHOTOVOLTAIC MODULES	1
1.1 INTRODUCTION	1
1.1.1 Background	1
1.1.2 Statement of the Problem	2
1.1.3 Objective	3
1.2 LITERATURE REVIEW	4
1.2.1 Defects/Failures in PV Modules	4
1.2.2 Financial Risk Calculations	4
1.2.3 FMECA Method for PV Power Plant	4
1.2.4 Correlation of Defects with IV Parameters	5
1.3 METHODOLOGY	6
1.3.1 Change in Severity Table	6
1.3.2 Defects Segregation – Safety vs Performance	8
1.3.2.1 Safety Failures	8

CHAPTER	Page
1.3.2.2 Performance Defects.....	9
1.3.3 MATLAB Program Input Data.....	10
1.3.4 MATLAB Program – RPN Program and Correlation Program.....	11
1.3.5 Program Flowchart.....	12
1.3.5.1 Performance RPN Program Flowchart	12
1.3.5.2 Safety RPN Program Flowchart.....	14
1.3.5.3 Global RPN Program Flowchart.....	16
1.3.5.4 Correlation Program Flowchart	17
1.3.6 RPN Program	18
1.3.6.1 Determination of Performance RPN Using Pmax Degradation Rates.....	19
1.3.6.2 Determination of Performance RPN Using Voc, Isc and FF Degradation Rates.....	20
1.3.6.3 Determination of Safety RPN Using Pmax Degradation Rate	21
1.3.6.4 Determination of Global RPN – Performance RPN + Safety RPN	23
1.3.6.5 Global RPN Using Severity and Occurrence.....	24
1.3.6.6 Reliability Vs Durability Vs Safety Failures - Pie Chart.....	26
1.3.6.7 Severity Vs Occurrence Vs Detection Plot for Global RPN.....	27
1.3.7 Correlation Plots	28
1.3.7.1 Box Plot for Comparing IV Parameter Degradation Rates.....	28

CHAPTER	Page
1.3.7.2 Linear Relation between Pmax Rd (%/year) Vs Isc Rd (%/year), Voc Rd (%/year) and FF Rd (%/year).....	29
1.3.7.3 Linear Relation between Pmax Drop Vs Voc Drop, Isc Drop and FF Drop	30
1.3.7.4 Histogram for Pmax Rd	31
1.3.7.5 Pmax Degradation Rate (%/year) Vs Frequency (%).....	32
1.3.7.6 Combined Histogram of Degradation Rates Vs Frequency	33
1.3.7.7 Comparison of Average Degradation Rates (%/year) of IV Parameters for Performance Defects	35
1.3.7.8 Comparison of Median Degradation Rates (%/year) of IV Parameters for Performance Defects	37
1.4 RESULTS AND DISCUSSION	38
1.4.1 Manual Vs Program Result Comparison – Model J	38
1.4.1.1 Correlation Results.....	39
1.4.1.1.1 Box Plot	39
1.4.1.1.2 Correlation of Defects with Dominant IV Parameter Affected	41
1.4.1.2 RPN Results	43
1.4.1.2.1 Global RPN.....	43
1.4.1.2.2 Difference in Severity Calculation.....	45
1.4.1.2.3 Difference in Occurrence Calculation	46

CHAPTER	Page
1.4.1.2.4 Difference in Detection Calculation	47
1.4.1.2.5 Pie Chart.....	48
1.4.2 Manual Vs Program result comparison – Model JVA.....	48
1.4.2.1 Correlation Results.....	49
1.4.2.1.1 Box Plot	49
1.4.2.1.2 Correlation of Defects with Dominant IV Parameter Affected	51
1.4.2.2 RPN Results	54
1.4.2.2.1 Global RPN.....	54
1.4.2.2.2 Difference in Severity Calculation.....	56
1.4.2.2.3 Difference in Occurrence Calculation	57
1.4.2.2.4 Difference in Detection Calculation	58
1.4.2.2.5 Pie Chart.....	59
1.4.3 Manual Vs Program Result Comparison – Model HP.....	60
1.4.3.1 Correlation Results.....	60
1.4.3.1.1 Box Plot	60
1.4.3.1.2 Correlation of Defects with Dominant IV Parameter Affected	62
1.4.3.2 RPN Results	64
1.4.3.2.1 Global RPN.....	64

CHAPTER	Page
1.4.3.2.2 Difference in Severity Calculation.....	66
1.4.3.2.3 Difference in Occurrence Calculation	67
1.4.3.2.4 Difference in Detection Calculation	67
1.4.3.2.5 Pie Chart.....	68
1.5 CONCLUSION.....	69
PART 2: EVALUATION OF MODULE LEVEL POWER ELECTRONICS (MLPE) ..	71
2.1 INTRODUCTION	71
2.1.1 Background.....	71
2.1.2 Statement of the Problem.....	72
2.1.3 Objective	72
2.2 LITERATURE REVIEW	73
2.3 METHODOLOGY	74
2.3.1 UUT A Pre-Characterization Procedure	74
2.3.1.1 Steps.....	74
2.3.1.2 Problems Encountered	75
2.3.2 UUT B Pre-Characterization Procedure	76
2.3.2.1 Steps.....	76
2.3.2.2 Problems Encountered	77

CHAPTER	Page
2.3.3 UUT C Pre-Characterization Procedure	77
2.3.3.1 Steps	78
2.3.3.2 Problems Encountered	78
2.3.4 UUT D Pre-Characterization Procedure	79
2.3.4.1 Steps	79
2.3.4.2 Problems Encountered	80
2.3.5 UUT E Pre-Characterization Procedure.....	81
2.3.5.1 Steps	81
2.3.5.2 Problems Encountered	82
2.4 RESULTS AND DISCUSSION	83
2.4.1 Efficiency Comparison	83
2.4.2 Harmonics – V _{thd} (%) Comparison	84
2.4.3 Harmonics – I _{thd} (%) Comparison	86
2.4.4 CEC Efficiency Comparison.....	88
2.4.5 Power Factor Comparison.....	90
2.5 CONCLUSION	93
REFERENCES	95

APPENDIX	Page
A STANDARD OPERATING PROCEDURE FOR MATLAB PROGRAM.....	97
B PLOTS FROM MODEL J.....	106
RPN RESULTS	107
CORRELATION RESULTS.....	109
C PLOTS FROM MODEL JVA.....	113
RPN RESULTS	114
CORRELATION PLOTS	117
D PLOTS FROM MODEL HP.....	122
RPN PLOTS.....	123
CORRELATION PLOTS	126

LIST OF TABLES

Table	Page
1. Modifications in Severity Ranking	6
2. Occurrence Table	7
3. Detection Table	7
4. Safety Failures	9
5. Performance Defects	10
6. Model J - Comparison of Matlab and Manual Median Degradtion Rates (%/year) for IV Parameters	40
7. Model J - Comparison of Matlab and Manual Isc Degradation Rates (%/year)	42
8. Model J - Comparison of Matlab and Manual Voc Degradation Rates (%/year)	42
9. Model J - Comparison of Matlab and Manual FF Degradation Rates (%/year)	43
10. Model J - Global RPN Comparison	43
11. Model J - Severity Comparison	46
12. Model J - Occurrence Comparison	47
13. Model J - Detection Comparison	47
14. Model J - Pie Chart Comparison	48
15. Model JVA - Comparison of Median Degradation Rate (%/year) for IV Parameters	51
16. Model JVA - Comparison of Isc Median Degradation Rate (%/year)	52
17. Model JVA - Comparison of Voc Median Degradation Rate (%/year)	53
18. Model JVA - Comparison of FF Median Degradation Rate (%/year)	53
19. Model JVA - Comparison of Global RPN	54
20. Model JVA - Comparison of Severity	57

Table	Page
21. Model JVA - Comparison of Occurrence	58
22. Model JVA - Comparison of Detection	59
23. Model JVA - Pie Chart Comparison.....	59
24. Model HP - Comparison of Median Degradation Rates (%/year) for IV Parameters	62
25. Model HP - Comparison of Median Isc Degradation Rate (%/year).....	63
26. Model HP - Comparison of Median Voc Degradation Rate (%/year).....	63
27. Model HP - Comparison of Median FF Degradation Rate (%/year)	64
28. Model HP - Comparison of Global RPN Results	65
29. Model HP - Comparison of Severity	67
30. Model HP - Comparison of Occurrence	67
31. Model HP - Comparison of Detection	68
32. Model HP - Comparison of Pie Chart Results	68
33. MLPE Efficiency Comparison.....	84
34. MLPE Vthd(%) Comparison	86
35. MLPE Ithd(%) Comparison.....	88
36. CEC Weightage Table	89
37. MLPE CEC Efficiency Comparison.....	90
38. MLPE Power Factor Comparison.....	92

LIST OF FIGURES

Figure	Page
1. IV Data Format	10
2. Visual Inspection Data Format	11
3. Performance RPN Flowchart	12
4. Safety RPN Flowchart	14
5. Global RPN Flowchart.....	16
6. Correlation Program Flowchart	17
7. Performance RPN Plot.....	19
8. Comparison of Performance RPN	20
9. Safety RPN Plot	21
10. Global RPN Plot	23
11. Global RPN Plot Using Severity and Occurrence	24
12. Pie Chart.....	26
13. Defects Vs Ranking Plot.....	27
14. Box Plot of Degradation Rates (%/year) for IV Parameters.....	28
15. Linear Relation between Degradation Rates (%/year) of Pmax and Isc, Voc and FF	29
16. Linear Relation between Pmax Drop and Isc, Voc and FF Drop	30
17. Histogram of Pmax Degradation Rate (%/year)	31
18. Histogram of Pmax Degradation Rate (%/year) with Frequency in Percentage	32
19. Combined Histogram of Isc and Pmax Degradation Rate (%/year).....	33
20. Combined Histogram of Voc and Pmax Degradation Rate (%/year).....	34
21. Combined Histogram of FF and Pmax Degradation Rate (%/year)	34

Figure	Page
22. Comparison of Average Degradation Rate (%/year) of IV Parameters for Performance Defects	35
23. Comparison of Median Degradation Rates (%/year) of IV Parameters for Performance Defects	37
24. Matlab - Model J - Box Plot of IV Parameter Degradation Rates (%/year)	39
25. Manual - Model J - Box Plot of IV Parameter Degradation Rates (%/year)	40
26. Model J - Comparison of Median Degradation Rates (%/year) of IV Parameters for Performance Defects	41
27. Model J - Global RPN Plot Using Matlab	44
28. Model J - Global RPN Results Comparison	45
29. Model JVA - Box Plot of IV Parameter Degradation Rates (%/year) - Matlab	49
30. Model JVA - Box Plot of IV Parameter Degradation Rates (%/year) - Manual	50
31. Model JVA - Comparison of Median Degradation Rate (%/year) of IV Parameters for Performance Defects Using Matlab	51
32. Model JVA - Global RPN Plot	55
33. Model JVA - Comparison of Matlab and Manual RPN Results.....	56
34. Model HP - Box plot of IV Parameter Degradation Rates (%/year) Using Matlab ...	60
35. Model HP - Box Plot of IV Parameter Degradation Rates (%/year) - Manual.....	61
36. Model HP - Comparison of Median Degradation Rate (%/year) of IV Parameters for Performance Defects using Matlab.....	62
37. Model HP - Global RPN plot Using Matlab.....	65
38. Model HP - Comparison of Global RPN Results	66

Figure	Page
39. UUT A Pre-Characterization Setup	74
40. UUT B - Pre-Characterization Setup	76
41. UUT C - Pre-Characterization Setup	77
42. UUT D - Pre-Characterization Setup	79
43. UUT E - Pre-Characterization Setup	81
44. MLPE Efficiency Comparison.....	83
45. MLPE Vthd (%) Comparison	85
46. MLPE Ithd(%) Comparison	87
47. MLPE CEC Efficiency Comparison.....	89
48. MLPE Power Factor Comparison.....	91

PART 1: AUTOMATION OF RISK PRIORITY NUMBER CALCULATION OF PHOTOVOLTAIC MODULES

1.1 INTRODUCTION

1.1.1 Background

Photovoltaic (PV) industry requires various accelerated tests for new modules in order to emulate different types of field failure modes. Different types of generic accelerated tests have been used by the industry, but the industry still needs climate-specific accelerated test programs [1]. For effective climate-specific accelerated test programs, the industry needs to identify all the potential field defects/failures in diverse climatic conditions. Once the climate-specific field defects are identified, the industry needs to quantify the associated safety risks and performance risks for each of these defects so appropriate accelerated tests can be developed. In this project, an automated data processing has been developed to quantify the safety and performance risks through Risk Priority Number (RPN) based on two databases: defect rate database and degradation rate database. Advantages of RPN values include the quantitative risk assessment of the plant for off-take transactions, the material defect warranty claims by the plant owners, the performance warranty claims by the plant owners and the safety warranty claims by the plant owners.

Janakeeraman et.al [2] performed statistical analysis on data obtained from many PV power plants in hot-dry Climate, Arizona to identify I-V parameters responsible for power degradation of PV modules. Metric definitions for safety failures, reliability failures and durability failures were provided by Mallineni et.al [3] to facilitate financial

risk calculations. Shrestha et.al [4] identified the RPN values for failure and degradation modes in diverse climatic conditions and Rajasekar and Boppana et al [5, 6] further classified the RPN values in three categories: Safety RPN (S-RPN), Performance RPN (P-RPN) and Global (G-RPN). However, there was still a need for continuous improvement to quickly and accurately determine the RPN values through the automation of entire process including: standardization defect rate databased based on Excel file format for about 86 different module defects; standardization degradation rate database based on Excel file format for annual degradation rates for each defect; and development of a MATLAB program to generate about 20 different statistical plots (including various RPN plots) in about 3-4 minutes . In order to aid this continuous improvement, this project was initiated at ASU Photovoltaic Reliability Laboratory (ASU-PRL).

1.1.2 Statement of the Problem

Failure mechanism and degradation rate of photovoltaic modules are influenced by environmental condition, design, installation and electrical configuration [4]. Industry is in a need to come up with appropriate accelerated tests for the existing and new modules. In order to achieve this, statistical analysis of field defect and performance data are necessary to determine degradation/defect modes responsible for the degradation of those performance parameters. Performance parameters are the parameters responsible for the degradation of power. Those parameters are: current, voltage and fill factor along with series resistance and shunt resistance. Previous researchers at ASU-PRL [4] developed an RPN technique for the PV industry to objectively and quantitatively to determine the risk [safety or performance) for each of the field observed defect. All the previous works [4] [5] [6] were performed manually and they are often laborious, time consuming and prone

to human errors. In order to mitigate these issues, an automated statistical risk analysis (FMECA, failure mode effect criticality analysis) is necessary. This data processing automation also helps researchers to analyze the PV power plant data in a consistent and visually attractive manner.

1.1.3 Objective

Evaluation of a PV power plant and performing FMECA analysis on the defects in PV power plant is carried out manually as there is no software available to perform automatically. Manual evaluation is time consuming and laborious. In order to overcome this, it is better to automate the process. .

By automating the process, researchers working on power plant data would be able to save time and also carry out their research more effectively with the analysis provided. It also helps PV power plant owners to identify the modules with failures and understand the failure modes causing it. This provides an opportunity for the PV power plant owners to either replace the modules by using the warranty provided by the module manufacturer or even opt for a module which is resilient to those failure modes specific to their climatic condition [4]. From manufacturer's point of view, finding dominant failure mode will facilitate the designers to understand or find the flaws in their designs and enable them to rectify it and provide a better reliable product with low warranty return [4]. Primary focus of this project is to automatically generate Risk Priority Number (RPN) for each defect based on two Excel spreadsheets: Defect spreadsheet; Degradation rate spreadsheet.

1.2 LITERATURE REVIEW

1.2.1 Defects/Failures in PV Modules

Photovoltaic defects/failures list were populated based on defect/failures discussed in the Review of Failures of Photovoltaic Modules [7], Fielded PV Module Condition [8] and Accelerated Lifetime Testing of Photovoltaic Modules [1]. Later, based on the discussion about each defect/failures from [1], [7] and [8], they were segregated into Safety failures and performance defects.

1.2.2 Financial Risk Calculations

J. Mallineni et.al [3] provided a metric definition for safety failures, reliability failures and degradation loss for the PV modules to evaluate PV power plant performance in terms of financial risks involved with defects/failures in PV power plants.

1.2.3 FMECA Method for PV Power Plant

According to IEC 60812 2006-01 Standard, FMEA (Failure mode effect analysis) can be employed to identify failure modes that can potentially affect a system performance. FMEA was further extended into FMECA (Failure mode effect and criticality analysis) in order to perform a detailed quantitative analysis of the criticality of failure modes. It is usually employed in the process development stage or Quality function deployment. RPN (Risk Priority Number) is the major indicator obtained through FMECA as a product of severity, occurrence and detection, where severity denotes the criticality of a defect/failure in affecting the product/user, occurrence denotes the probability of occurrence of a failure mode in a particular system and detection denotes the feasibility with which a defect/failure can be identified within a system.

Shrestha et.al [4] provided a method for employing FMECA for PV power plants to identify the dominant failure modes affecting that particular PV power plant and also identified the dominant failure mode in three different PV power plants.

1.2.4 Correlation of Defects with IV Parameters

Janakeeraman et.al [2] statistically analyzed the IV data collected from 8 different PV power plants in Arizona to identify the IV parameters which are responsible for degradation of power and correlated it with defects/failures on a power plant level.

Umachandran et.al [9] correlated the visual defect data obtained from 5 different PV power plants in Arizona and New York with IV parameters to identify particular defect/failure which is responsible for affecting the dominant IV parameter causing Pmax degradation.

1.3 METHODOLOGY

1.3.1 Change in Severity Table

Severity table proposed by Shrestha et.al [4] has to be changed as it covers only till 1.5% degradation rate/ year, whereas PV modules have degraded more than 1.5%/year based on various PV power plant studies done by ASU-PRL. Modified severity table is shown below with changes in Rank 8, 9 and 10.

Table 1: Modifications in Severity Ranking

Severity Ranking	Severity Criteria	Changes to the severity table
1	No Effect, Rd < 0.3%	No change
2	Insignificant, Rd approx to 0.3%	No change
3	Minor Cosmetic Defect, Rd < 0.5%	No change
4	Cosmetic defect with Rd < 0.6%	No change
5	Reduced performance, Rd < 0.8%	No change
6	Performance Loss approx to typical warranty, Rd approx to 1%	No change
7	Significant degradation, Rd approx to 1.5%	No change
8	Remote safety concerns, Rd < 1%	Rd > 1.5 & Rd <= 2 for performance defects Bypass diode OC failure
9	Remote safety concerns, Rd < 2%	Rd > 2 for performance defects Rd <= 2%
10	Safety Hazard, Catastrophic	Rd > 2% 18 safety failures

It is to be noted that there are no changes in the Occurrence and Detection table.

Occurrence and Detection table provided by Shrestha et.al [4] is provided below:

Table 2: Occurrence table

Failure Mode Occurrence	Frequency CNF/1000	Ranking O
Remote: Failure is unlikely	≤ 0.01 module per thousand per year	1
Low: Relatively few failures	0.1 module per thousand per year	2
	0.5 module per thousand per year	3
Moderate: Occasional failures	1 module per thousand per year	4
	2 module per thousand per year	5
	5 module per thousand per year	6
High: Repeated failures	10 module per thousand per year	7
	20 module per thousand per year	8
Very high: Failure is almost inevitable	50 module per thousand per year	9
	≥ 100 module per thousand per year	10

Table 3: Detection table

Ranking	Criteria: Likelihood	Detection
1	Monitoring System itself will detect the failure mode with warning 100%	Almost certain
2	Very high probability (most likely) of detection through visual inspection	Very high
3	50/50 probability (less likely) of detection through visual inspection	High
4	Very high probability (most likely) of detection using conventional handheld tool e.g. IR, Megger	Moderately high
5	50/50 probability (less likely) of detection using conventional handheld tool e.g. IR, Megger	Moderate
6	Very high probability (most likely) of detection using non-conventional handheld tool e.g. diode/line checker	Low
7	50/50 probability (less likely) of detection using non-conventional handheld tool e.g. diode/line checker	Very low
8	Very high probability (most likely) of detection using	Extremely

	performance measurement equipment e.g. IV tracer	Low
9	50/50 probability (less likely) of detection using performance measurement equipment e.g. IV tracer	Remote
10	Detection impossible in the field	Absolutely uncertain

1.3.2 Defects Segregation – Safety vs Performance

In order to be clear with defects/failure in PV modules, various literature from NREL [7] [8] and SolarABC [1] were referred. From the literature, it was identified that there were almost 86 defects/failures affecting the performance of the PV modules and also causing safety problems to personnel operating them.

1.3.2.1 Safety Failures

Of the 86 defects/failures identified from the literature, it was necessary to separate the failures which can affect the safety of the personnel operating the PV modules. Based on previous experiences of ASU-PRL [3] [4] [5] [6] and NREL [7] [8], 25 failures were identified as safety failures depending on the component of the PV module affected. Of the 25 failures, 4 failures affected the glass (front/ rear), 5 failures affected the frame, 5 failures affected the junction box, 3 failures affected the wires/connectors, 5 failures affected the backsheet, 2 failure affecting the cell and 1 failure affecting the bypass diode. Safety failures separated based on component affected is given below in table 4.

Table 4: Safety failures

Glass	Frame	Bypass diode	Junction box
Front glass crack Front glass shattered Rear glass crack Rear glass shattered	Frame grounding severe corrosion Frame grounding minor corrosion Frame major corrosion Frame joint separation Frame cracking	Bypass diode open circuit	Junction box crack Junction box burn Junction box loose Junction box lid fell off Junction box lid crack
Wires	Backsheet	Cell	
Wires insulation cracked / disintegrated Wires burnt Wires animal bites / marks	Backsheet peeling Backsheet delamination Backsheet burn mark Backsheet crack /cut under cell Backsheet crack /cut between cells	String Interconnect arc tracks Hotspot over 20°C	

1.3.2.2 Performance Defects

Of the 86 defects/failures identified from the literature, 61 defects were identified as performance defects affecting the PV module power output based upon reports from NREL and power plant experience from ASU-PRL. Of the 61 defects, 7 defects were affecting glass (front/rear), 22 defects affecting cell, 5 defects affecting frame, 4 defects affecting edge seal, 5 defects affecting encapsulant, 8 defects affecting junction box, 3 defects affecting backsheet, 3 defects specific to Thin Film PV modules and 1 defect each affecting bypass diode and wires. Also 2 more defects – Module mismatch and Solder bond fatigue/failure were identified to be responsible for performance loss totaling the list of performance defects to 61. Performance defects are listed below as shown in table 5.

Table 5: Performance defects

Glass	Frame	Junction box	Cell
Front glass lightly soiled Front glass heavily soiled Front glass crazing Front glass chip Front glass milky discoloration Rear glass crazing Rear glass chipped	Frame bent Frame discoloration Frame adhesive degraded Frame adhesive oozed out Frame adhesive missing in areas	Junction box lid loose Junction box warped Junction box weathered Junction box adhesive loose Junction box adhesive fell off Junction box wire attachments loose Junction box wire attachments fell off Junction box wire attachments arced	Cell discoloration Cell burn Mark Cell crack Cell moisture penetration Cell worm mark Cell foreign particle embedded Cell Interconnect discoloration Gridline discoloration Gridline blossoming Busbar discoloration Busbar corrosion Busbar burn marks Busbar misaligned Cell Interconnect ribbon discoloration
Edge Seal	Encapsulant	Backsheet	
Edge seal delamination Edge seal moisture penetration Edge seal discoloration Edge seal squeezed / pinched out	Encapsulant delamination over the cell Encapsulant delamination under the cell Encapsulant delamination over the junction box Encapsulant delamination near interconnect or fingers Encapsulant discoloration (yellowing/browning)	Backsheet wavy Backsheet discoloration Backsheet bubble	Cell Interconnect ribbon corrosion Cell Interconnect ribbon burn mark Cell Interconnect ribbon break String Interconnect discoloration String Interconnect corrosion String Interconnect burn mark String Interconnect break Hotspot less than 20°C
Wires	Thin Film	Bypass diode	Others
Wires corroded	Thin Film Module Discoloration Thin Film Module Delamination - Absorber coating Thin Film Module Delamination - AR coating	Bypass diode short circuit	Module mismatch Solder bond Fatigue / Failure

1.3.3 MATLAB Program Input Data

Input data required for the program are as follows: IV data and Visual Inspection data. IV data should follow the same format as shown below in fig 1. No changes should be made as it will affect the results from the program and may cause errors. IV data should be an excel spreadsheet with name IV data.xlsx. Name should not be changed from IV data.xlsx to any other names.

Module	Rated Isc	Rated Voc	Rated Imax	Rated Vmax	Rated FF	Rated Pmax	Measured Isc	Measured Voc	Measured Imax	Measured Vmax	Measured FF	Measured Pmax	Age
C2-S1-T1	3.87	42.10	3.56	33.70	73.63	120.00	3.65	41.26	3.13	33.84	70.30	105.77	17.79
C2-S1-T2	3.87	42.10	3.56	33.70	73.63	120.00	3.87	41.38	3.22	35.28	70.79	113.44	17.79
C2-S1-T3	3.87	42.10	3.56	33.70	73.63	120.00	3.71	41.33	3.31	33.51	72.48	111.04	17.79
C2-S1-T4	3.87	42.10	3.56	33.70	73.63	120.00	3.71	40.54	3.35	32.46	72.30	108.67	17.79
C2-S1-T5	3.87	42.10	3.56	33.70	73.63	120.00	3.70	41.07	3.33	33.31	73.08	111.00	17.79
C2-S1-T6	3.87	42.10	3.56	33.70	73.63	120.00	3.68	41.05	3.31	32.91	72.07	108.89	17.79
C2-S2-T1	3.87	42.10	3.56	33.70	73.63	120.00	3.75	41.05	3.36	33.07	72.12	111.16	17.79

Figure 1: IV data format

Visual Inspection data format should follow the format as shown below in fig 2. Total number of columns excluding module are 86 defects/failures. It is not advised to change the name of the defect/failure in the spreadsheet. 0 denotes the absence of defect/failure in the module and 1 denotes the presence of defect/failure in the module

Module	Front glass lightly soiled	Front glass heavily soiled	Front glass crack	Front glass crazing	Front glass shattered	Front glass chip	Front glass milky discoloration	Rear glass crazing	Rear glass crack
C2-S1-T1	0	0	0	0	0	0	0	0	0
C2-S1-B1	0	0	0	0	0	0	0	0	0
C2-S1-T2	0	0	0	0	0	0	0	0	0
C2-S1-B2	0	0	0	0	0	0	0	0	0

Figure 2: Visual Inspection data format

1.3.4 MATLAB Program – RPN Program and Correlation Program

MATLAB was used to code program to automatically calculate RPN using FMECA technique and also correlate Pmax degradation rate with other IV parameters to identify which IV parameter affects Pmax based on defects. The RPN program had three codes separately for calculating performance RPN, safety RPN and global RPN. Several references for coding in both the programs were referred from MATHWORKS [17].

1.3.5 Program Flowchart

1.3.5.1 Performance RPN Program Flowchart

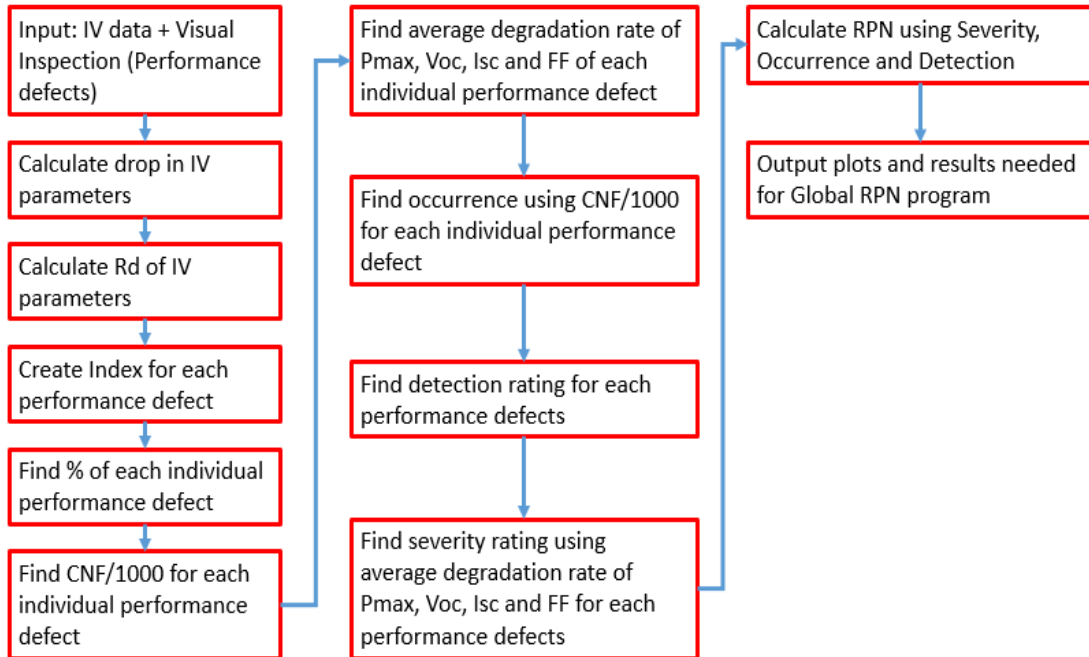


Figure 3: Performance RPN flowchart

Steps involved with calculating Performance RPN using MATLAB is outlined below.

1. Input required for Performance RPN program are IV data and Visual Inspection data of a Photovoltaic power plant.
2. From the Visual Inspection data, only performance defects are to be imported leaving out safety failures.
3. Combine both the inputs together (i.e.) IV data and performance defects from step 2.
4. Calculate drop in IV parameters from the combined data from step 3 using the formula: **Drop = ((Rated – Measured)/ Rated) *100**

5. Calculate degradation rate in IV parameters using the formula: **Degradation rate = Drop/ Age of the PV powerplant.**
6. Create index for each performance defect (61 defects) for all modules Visual Inspection data including for modules for which IV was not taken.
7. Find total number for each individual performance defect for all modules for which Visual Inspection was performed in a particular PV power plant.
8. Find % of each individual performance defect from total calculated using step 7.
9. Find CNF/1000 for each individual performance defect for all modules including non-IV modules. **CNF/1000 = Σ system(% defects)*(10/ Σ system(operating time))**
10. Create index for each performance defect for combined IV and performance defects visual inspection data from step 3.
11. Find average degradation rate of Pmax, Voc, Isc and FF separately for each defects
12. Find Occurrence using CNF/1000 value for each performance defects
13. Use detection values for each performance defects based on PV power plant experience.
14. Find severity using average degradation rate of Pmax, Voc, Isc and FF for each performance defects.
15. Calculate RPN for each performance defect using severity from average degradation of Pmax, Voc, Isc and FF, occurrence and detection.
16. Calculate RPN for each performance defect using severity from average degradation of Pmax and occurrence.

17. Populate all results into two tables – one for Performance RPN using various IV parameters and other one for Global RPN calculation
18. Plot concerned with performance RPN using various IV parameters is generated at the end of performance RPN program.

1.3.5.2 Safety RPN Program Flowchart

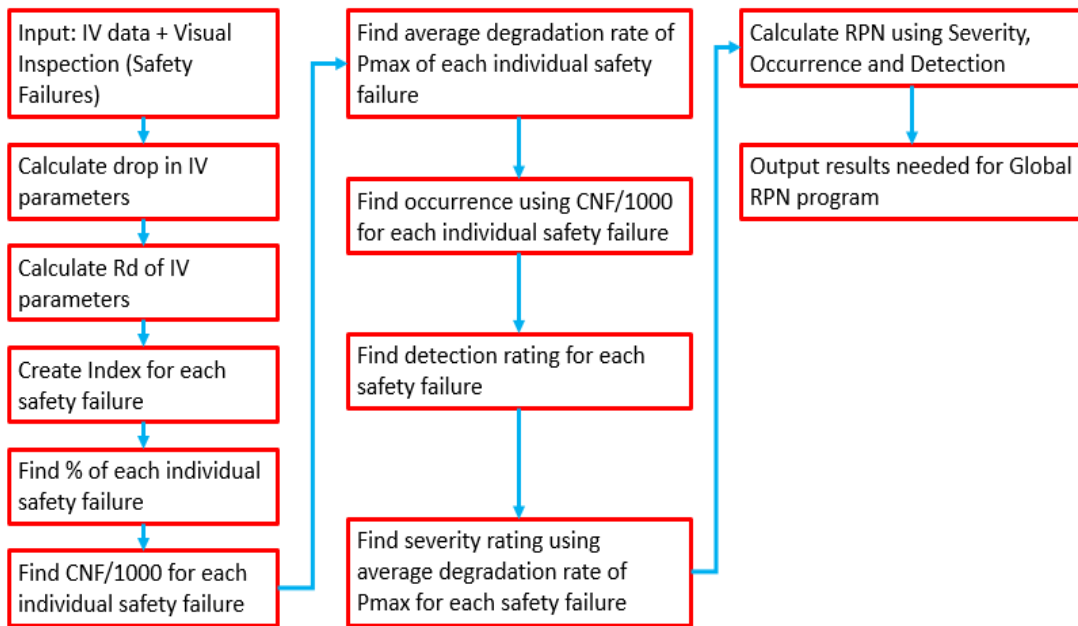


Figure 4: Safety RPN Flowchart

1. Input required for Safety RPN program are IV data and Visual Inspection data of a Photovoltaic power plant.
2. From the Visual Inspection data, only safety failures are to be imported leaving out performance defects.
3. Combine both the inputs together (i.e.) IV data and safety failures from step 2.

4. Calculate drop in IV parameters from the combined data from step 3 using the formula: **Drop = ((Rated – Measured)/ Rated) * 100**
5. Calculate degradation rate in IV parameters using the formula: **Degradation rate = Drop/ Age of the PV powerplant.**
6. Create index for each safety failure (25 failures) for all modules Visual Inspection data including for modules for which IV was not taken.
7. Find total number for each individual safety failure for all modules for which Visual Inspection was performed in a particular PV power plant.
8. Find % of each individual safety failure from total calculated using step 7.
9. Find CNF/1000 for each individual safety failure for all modules including non-IV modules. **CNF/1000 = Σ system(% defects)*(10/ Σ system(operating time))**
10. Create index for each safety failure for combined IV and safety failure visual inspection data from step 3.
11. Find average degradation rate of Pmax for each safety failure
12. Find Occurrence using CNF/1000 value for each safety failure
13. Use detection values for each safety failure based on PV power plant experience.
14. Find severity using average degradation rate of Pmax for each safety failure and also severity ratings available for hazardous safety failures based on previous PV power plant experience – Eg: Front glass crack, Bypass diode open circuit, etc.
15. Calculate RPN for each safety failure using severity, occurrence and detection.
16. Populate all results into one table – safety RPN for Global RPN purpose.

1.3.5.3 Global RPN Program Flowchart

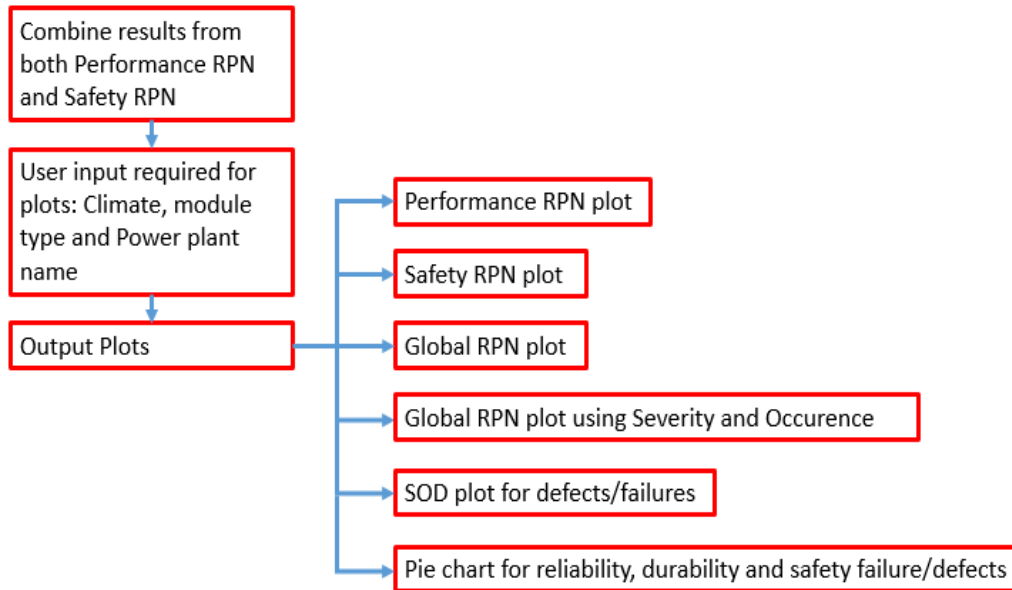


Figure 5: Global RPN flowchart

1. Combine results of both Performance RPN and Safety RPN for calculating Global RPN.
2. User are required to input the type of climate, power plant name and module type to be added as description in the plots.
3. Output RPN Plots are color coded based on climatic conditions – Hot dry (red), cold dry (dark blue), hot humid (orange) and Temperate (green).
4. Plots are generated as follows: Performance RPN plot, Safety RPN plot, Global RPN plot, Global RPN plot using severity and occurrence and SOD plot for defects/failures in global RPN plot.
5. Pie chart is also generated for reliability, durability and safety failures/defects.

1.3.5.4 Correlation Program Flowchart

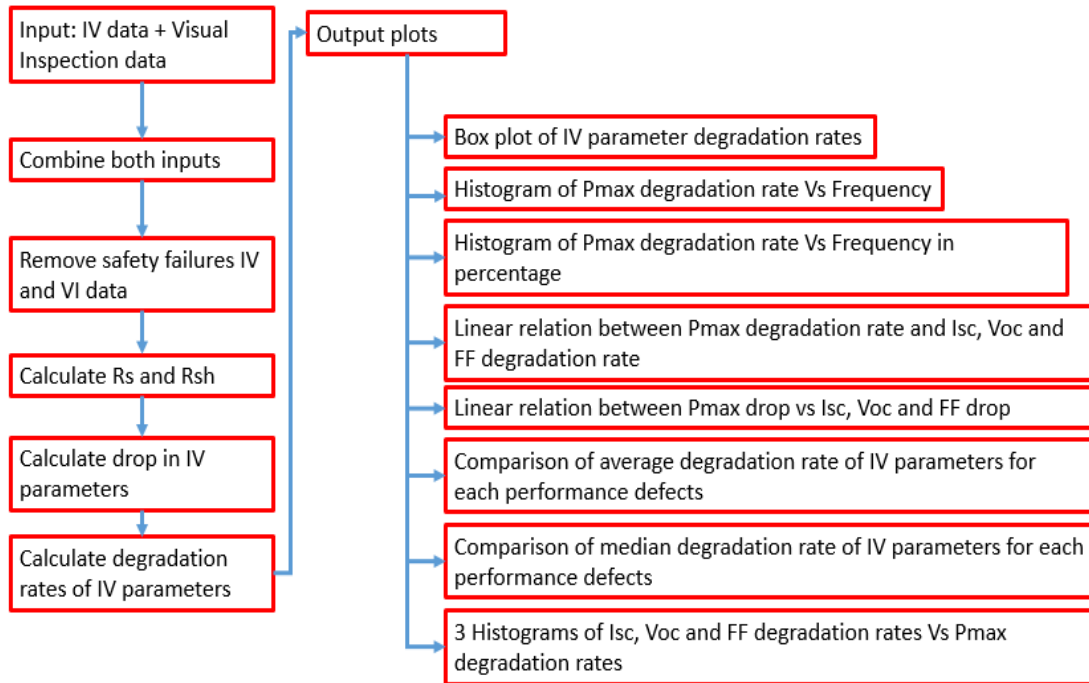


Figure 6: Correlation program flowchart

Steps for generating correlation plots are outlined below:

1. Input required for generating correlation plots are IV data and Visual Inspection data for a particular PV power plant.
2. Combine both inputs from step 1 together.
3. Remove safety failures IV and Visual Inspection data as safety failures are not good for correlation as they may generate outliers in the plots thereby skewing the data.
4. Calculate Series resistance (R_s) and Shunt resistance (R_{sh}) using method explained by Dobos et.al [16]. This step requires user input of type of PV module for finding out the coefficients needed for calculating R_s and R_{sh} .

5. Calculate drop in IV parameters.
6. Calculate degradation rates of IV parameter.
7. Output plots are generated from correlation plots as follows: Box plot of IV parameter degradation rates, Histogram of Pmax degradation rates vs frequency, Histogram of Pmax degradation rates vs frequency in percentage, Linear relation between Pmax degradation rate per year with Isc, Voc and FF, Linear relation between Pmax drop vs Isc, Voc and FF drop, Comparison of average degradation of IV parameters, Comparison of median degradation of IV parameters and combined histogram of Pmax degradation rates with degradation rates of Isc, Voc and FF separately.

1.3.6 RPN Program

RPN Program involves program for Performance RPN, Safety RPN and Pie Chart.

Coding for labels for plot were developed based on concept provided in [19].

3. Dominant performance defect that is present in a particular PV power plant – defect having the maximum Performance RPN.
4. As they are color coded based on 4 different climatic conditions, it is also possible to group performance defects for a particular climate, thus assisting the reliability improvement for PV modules based on climatic conditions.
5. Total Performance RPN is provided in the plot which can be used for rating PV power plants based on performance as suggested in [5] and [6].

1.3.6.2 Determination of Performance RPN Using Voc, Isc and FF Degradation Rates

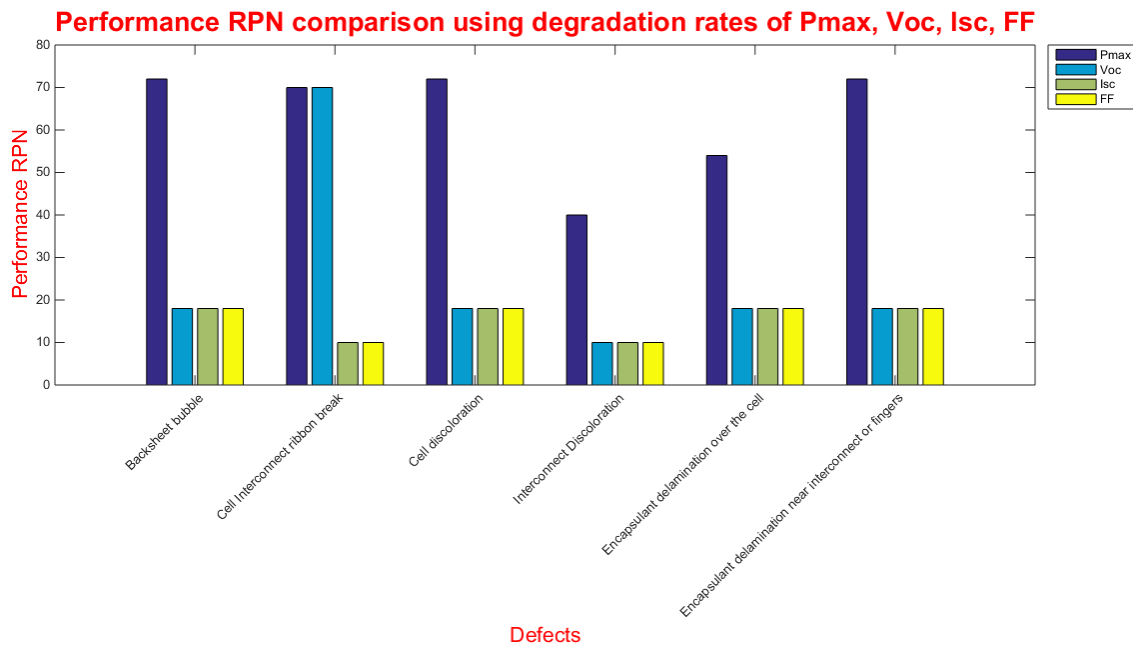


Figure 8: Comparison of Performance RPN

Apart from Performance RPN calculated using Pmax degradation rate (%/year), it can also be calculated using degradation rates (%/year) of other IV parameters such as Voc, Isc and FF. Based on the results, bar plot is generated to identify the performance RPN

for the defects that are present in the concerned PV power plant. From fig 8, we can identify the following:

1. IV parameter (Voc, Isc or FF) which is affecting the Pmax degradation based on RPN value for different defects.
2. It can be used as a quantitative information along with correlation results to identify the IV parameter affecting the Pmax degradation rate for a particular defect.

1.3.6.3 Determination of Safety RPN Using Pmax Degradation Rate

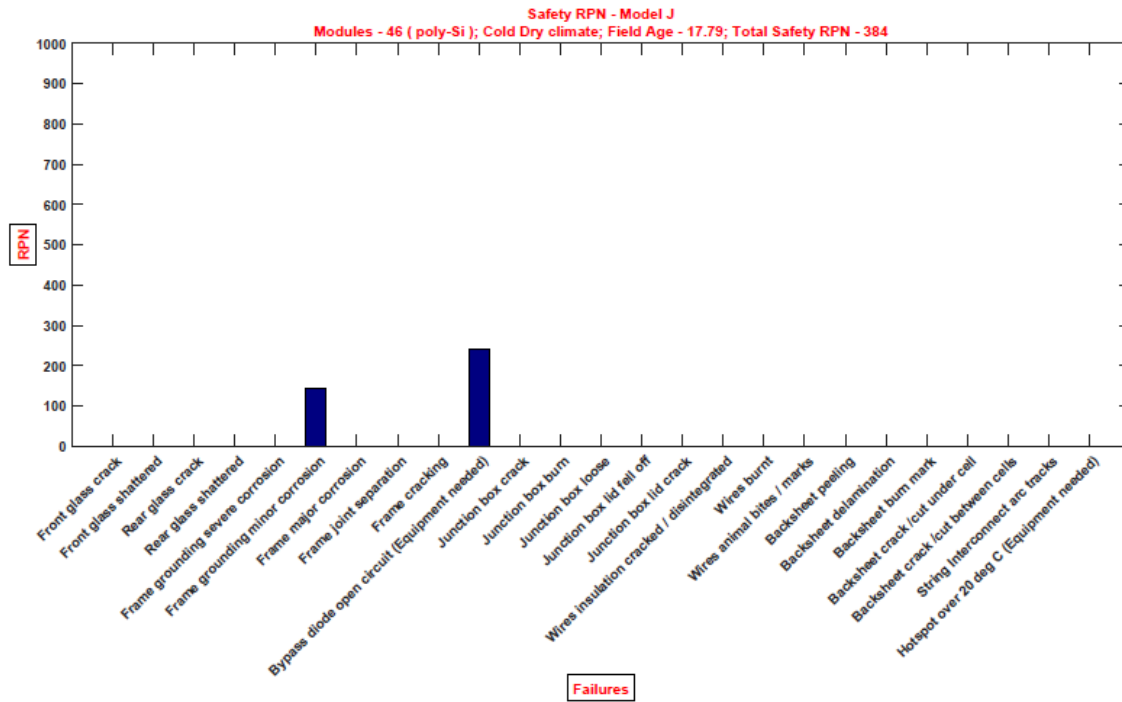


Figure 9: Safety RPN plot

Safety RPN can be calculated automatically using FMECA-RPN technique provided by Shrestha et.al [4] for the data set obtained from any PV power plant using severity calculated using Pmax degradation rate. Based on the results, bar plot is generated to

identify the Safety RPN for each of the 25 safety failures pertaining to any one PV power plant. From fig 9, we can identify the following:

1. Safety failures that are present in a particular PV power plant – which has bars in the plot.
2. Safety failures that are not present in a particular PV power plant – which doesn't have any bars in the plot.
3. Dominant Safety failure that is present in a particular PV power plant – failure having the maximum Safety RPN.
4. As they are color coded based on 4 different climatic conditions, it is also possible to group Safety failures for a particular climate, thus assisting the reliability improvement for PV modules based on climatic conditions [NREL climate based ratings for module]
5. Total Safety RPN is provided in the plot which can be useful in rating the PV power plants based on safety issues as suggested in [5] and [6].

1.3.6.4 Determination of Global RPN – Performance RPN + Safety RPN

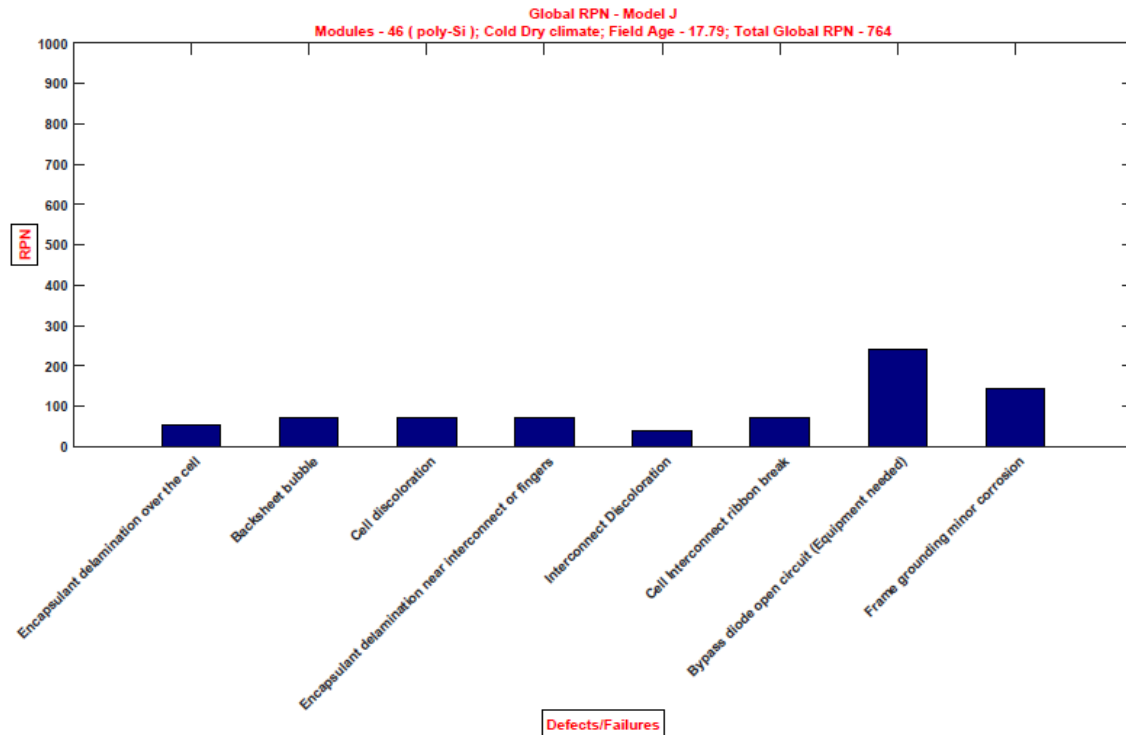


Figure 10: Global RPN plot

Global RPN is the sum of Performance RPN and Safety RPN as provided by Rajasekar et.al [5] [6]. Only RPN of defects/failures that are present in the PV power plant as safety failures or performance defects are provided as a bar plot as shown in fig. From fig 10, we can infer the following:

1. Dominant failure mode in a particular PV power plant which requires the immediate attention of the plant owner/operator to avoid performance loss, property loss and loss of personnel. It also helps PV module manufacturer to identify issues with the design, material selection and manufacturing issues.

2. As they are color coded based on climate, it will be useful in identifying defects/failures common to a particular climate thereby enabling module manufacturers to design modules resilient to those defects/failures for a particular climate and also helps PV power plant owners to identify modules resilient to those defects/failures thereby reducing loss and increasing their payback.
3. Total Global RPN for a particular PV power plant can be obtained which can lead to grading of PV power plants as reported in [5] and [6], once the database of PV power plants is established.

1.3.6.5 Global RPN Using Severity and Occurrence

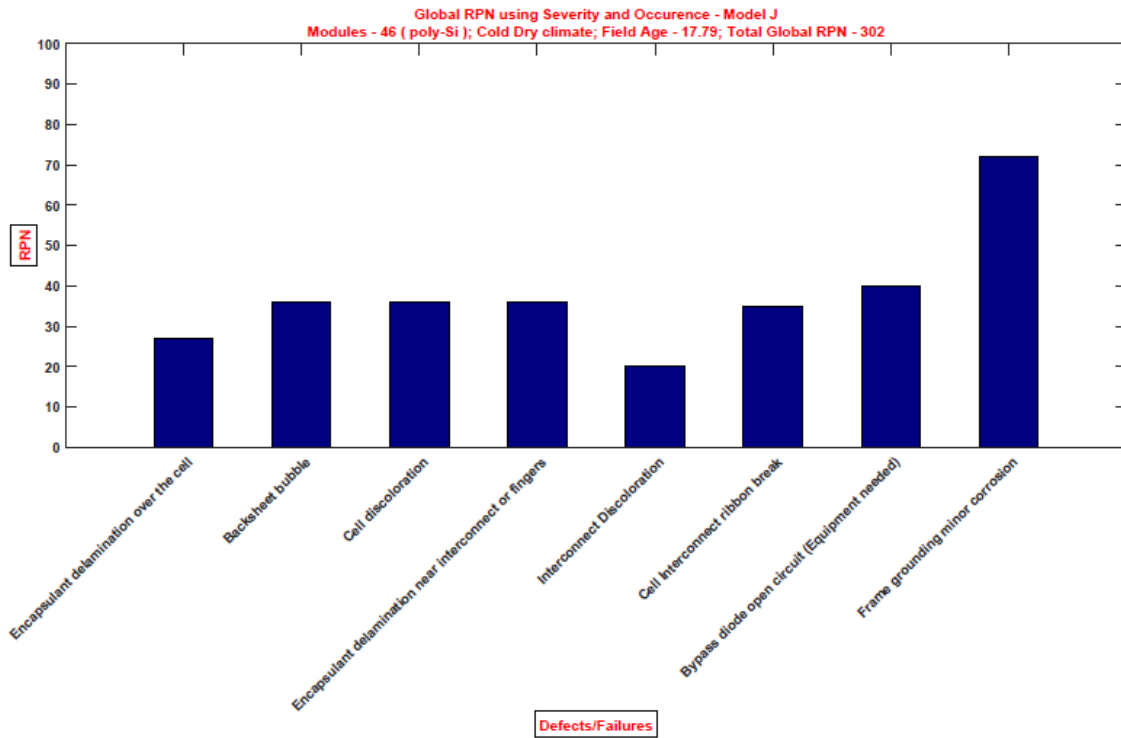


Figure 11: Global RPN plot using severity and occurrence

Global RPN was calculated using severity and occurrence neglecting detection by considering all defects/failures can be easily detected. From fig 11, we can infer the following:

1. Dominant failure mode in a particular PV power plant which requires the immediate attention of the plant owner/operator to avoid performance loss, property loss and loss of personnel. It also helps PV module manufacturer to identify issues with the design, material selection and manufacturing issues.
2. As they are color coded based on climate, it will be useful in identifying defects/failures common to a particular climate thereby enabling module manufacturers to design modules resilient to those defects/failures for a particular climate and also helps PV power plant owners to identify modules resilient to those defects/failures thereby reducing loss and increasing their payback.
3. Total Global RPN for a particular PV power plant can be obtained which can lead to grading of PV power plants as reported in [5] and [6], once the database of PV power plants is established.

1.3.6.6 Reliability Vs Durability Vs Safety Failures - Pie Chart

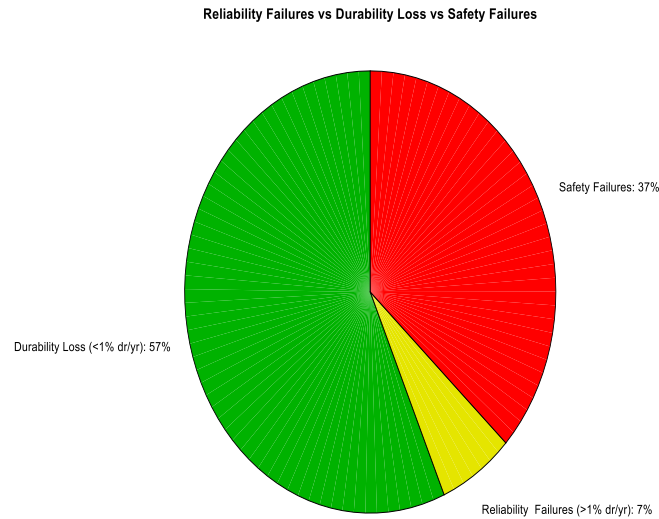


Figure 12: Pie chart

The Pie chart is used to show the proportion occupied by Reliability failures, Durability loss and Safety failures as shown in fig 12. It is generated using a separate MATLAB code to create the pie chart which is invoked when program for global RPN is run. MATLAB code was based on code developed for labelling pie chart in [17]. It can be useful in identifying

1. Percentage of modules which need to be replaced immediately to avoid loss of property and personnel (Safety failures).
2. Percentage of modules which can be covered under warranty for losing power at the rate of more than 1% / year (Reliability failures).
3. Percentage of modules which are still functioning well with power degradation rates less than 1% / year (Durability loss).

1.3.6.7 Severity Vs Occurrence Vs Detection Plot for Global RPN

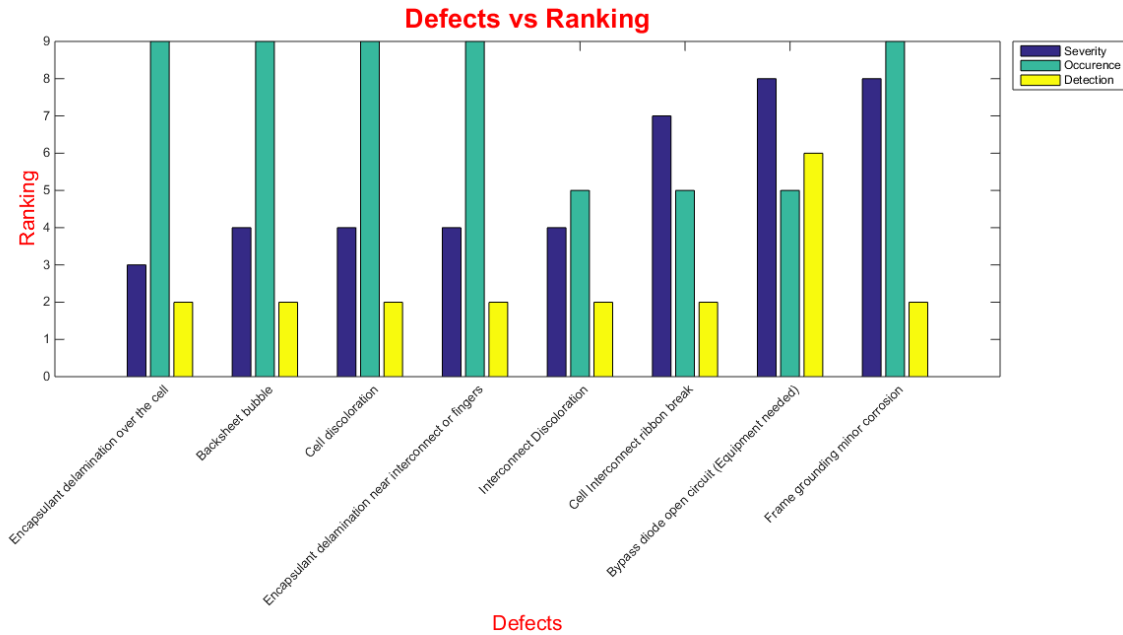


Figure 13: Defects Vs Ranking plot

Severity, occurrence and detection of defects/failures that are present in a power plant are plotted as shown in fig 13, where x-axis contains the defects/failures and y-axis contains the ranking of the defect/failure with respect to severity, occurrence and detection. This plot helps the researcher as follows:

1. It helps to identify the defects/failures with more performance/safety issues (i.e.) Severity in a visual format.
2. It helps in providing information in a visual format about defects/failures that occur more frequently (i.e.) occurrence in a particular PV power plant.
3. It helps in providing information about defects/failures that require the complex set of equipment/devices to identify them (i.e.) detection in the PV power plant in an easy way for the researcher or plant operator or plant owner.

1.3.7 Correlation Plots

1.3.7.1 Box Plot for Comparing IV Parameter Degradation Rates

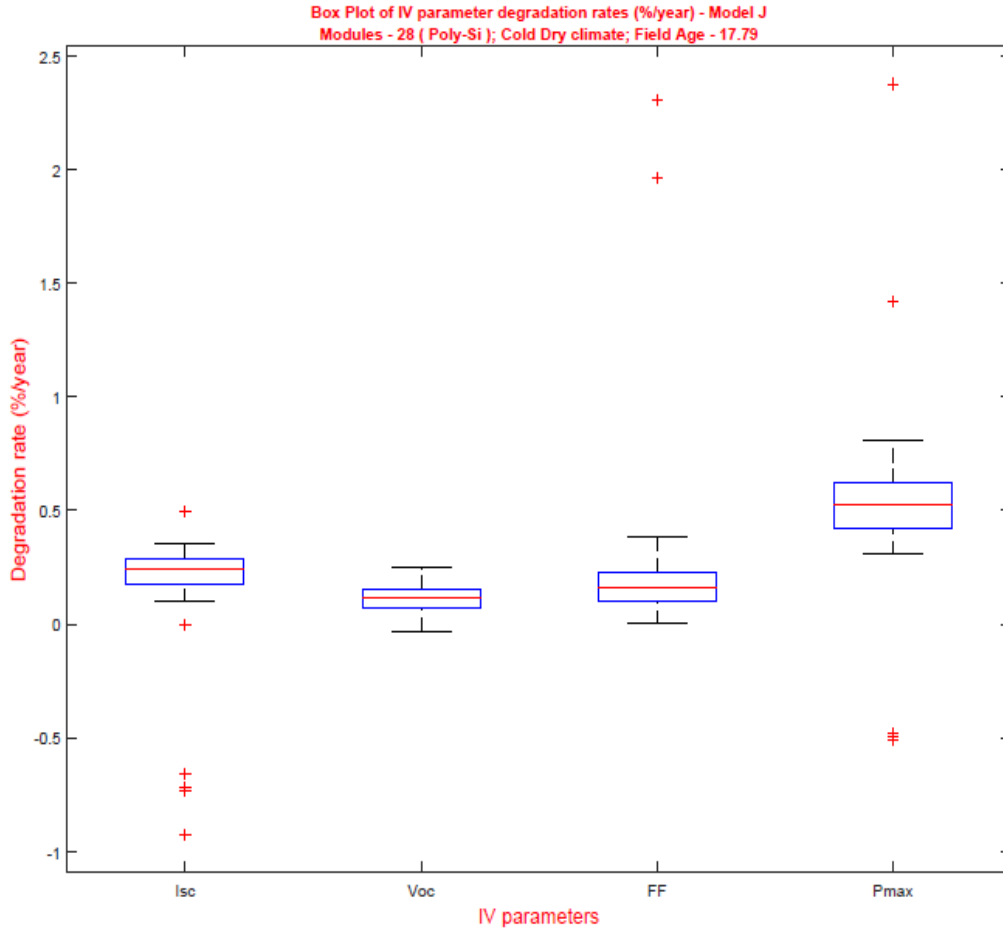


Figure 14: Box plot of degradation rates (%/year) for IV parameters

Box plot of the degradation rates (%/year), grouped by PV module IV parameters is plotted using MATLAB as shown in fig 14. It is to be noted that modules with safety failures and degradation rates greater than 2.5%/year were removed to avoid skewing of data because of outliers. It is helpful in finding

1. Correlation between Pmax degradation rates and other IV parameter (Voc, Isc and FF) degradation rates.
2. Dominant IV parameter which is responsible for degradation of Pmax in a particular PV power plant.

1.3.7.2 Linear Relation between Pmax Rd (%/year) Vs Isc Rd (%/year), Voc Rd (%/year) and FF Rd (%/year)

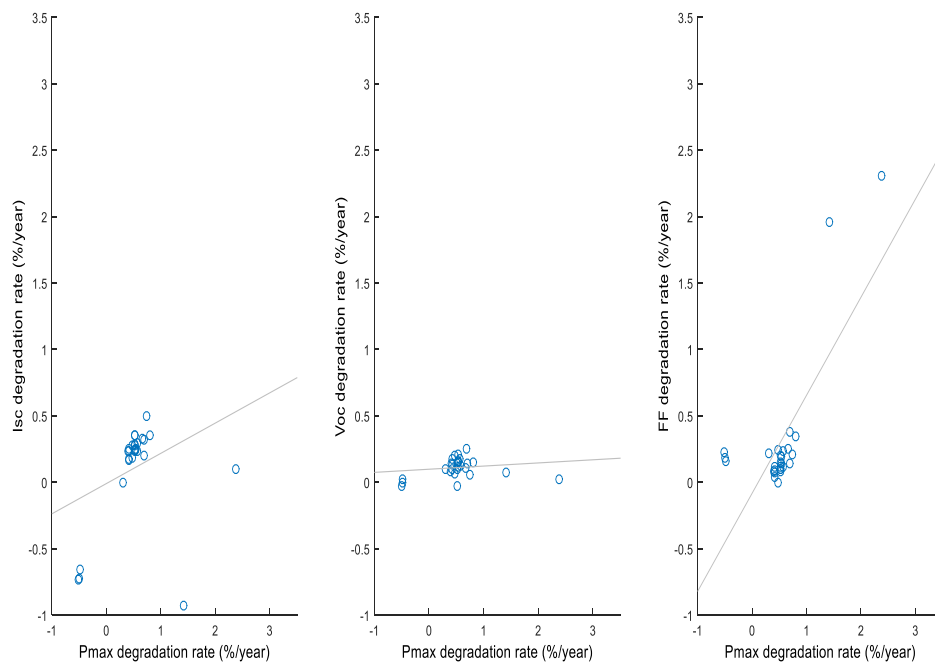


Figure 15: Linear relation between degradation rates (%/year) of Pmax and Isc, Voc, FF

The linear relation between Pmax Rd (%/year) and Rd (%/year) for Isc, Voc and FF is plotted as shown in fig 15. It helps us to understand the linear relationship between Pmax degradation rate and other three major IV parameters.

1.3.7.3 Linear Relation between Pmax Drop Vs Voc Drop, Isc Drop and FF Drop

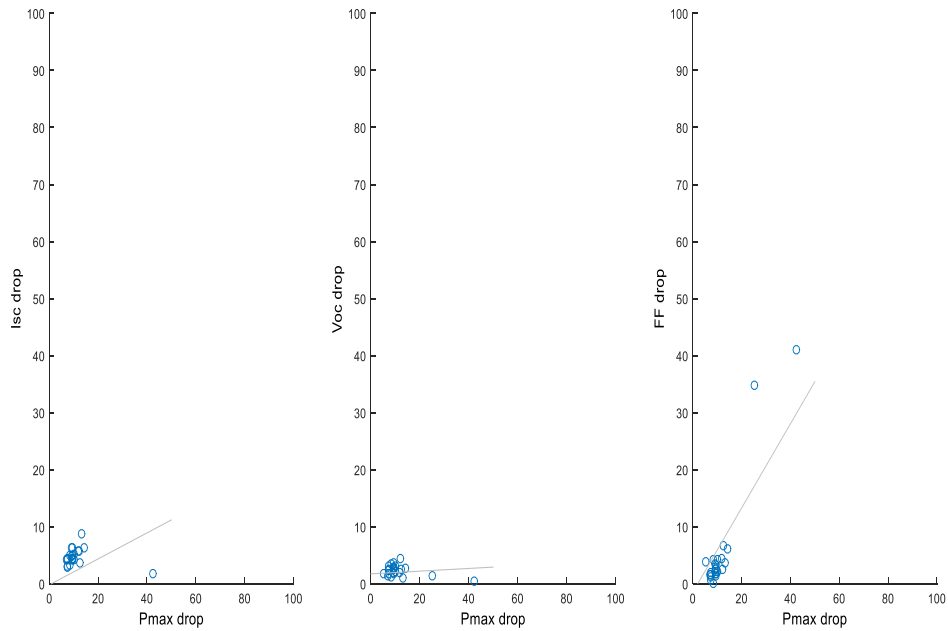


Figure 16: Linear relation between Pmax drop and Isc, Voc and FF drop

The linear relation between Pmax drop and drop in Isc, Voc and FF is plotted as shown in fig 16. It helps us to understand the linear relationship between Pmax drop and drop in other three major IV parameters as shown in [22].

1.3.7.4 Histogram for Pmax Rd

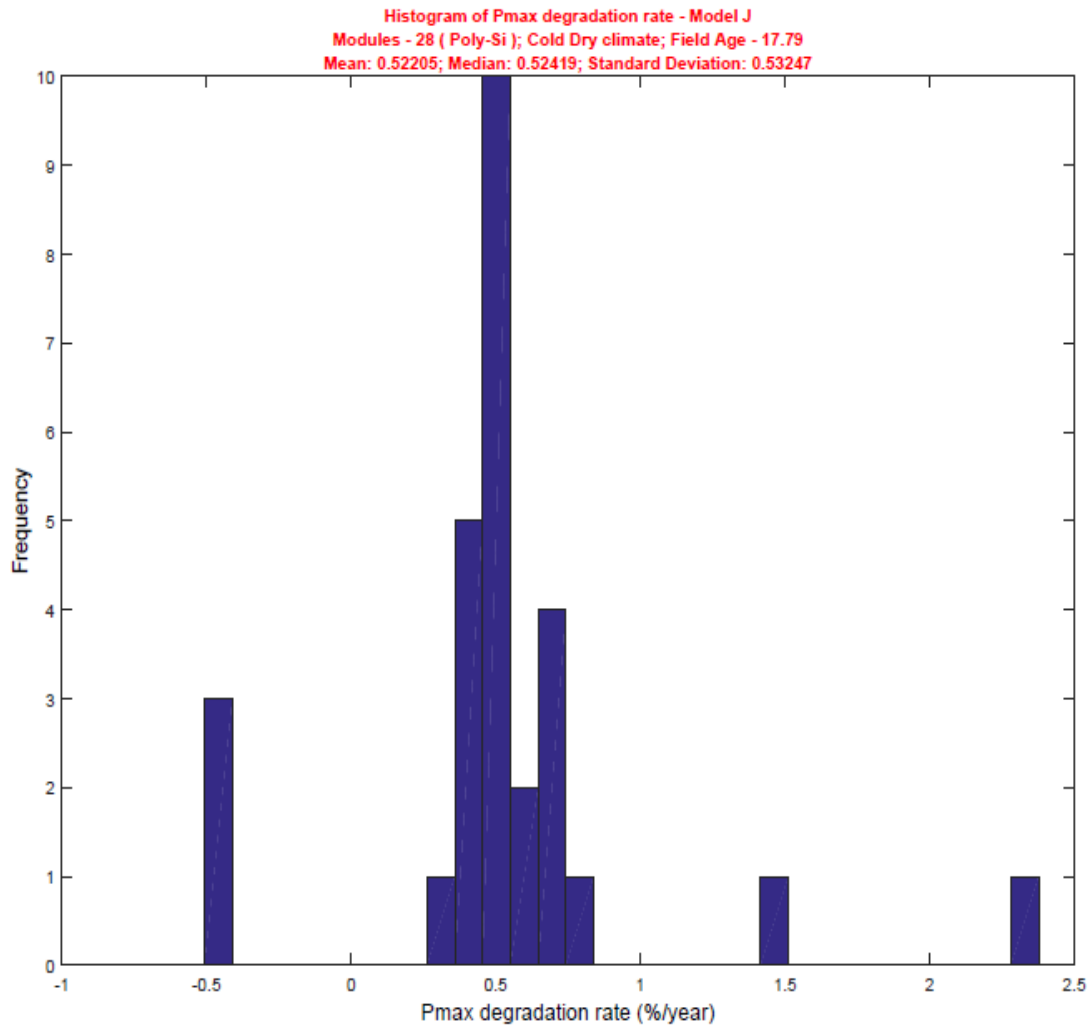


Figure 17: Histogram of Pmax degradation rate (%/year)

Histogram is plotted for Pmax rate of degradation (%/year) as shown in fig 17. This plot is helpful in identifying

1. Distribution of Pmax degradation rates in a PV power plant
2. Frequency or count of modules in y-axis for a particular degradation rate on x-axis

3. Number of modules which are to be replaced through warranty claims (i.e.)
Modules that are degrading at more than 1%/year.
4. Number of modules degrading at less than 1%/year, which are to be monitored to
find whether they are degrading at a rate exceeding 1%/year so that the PV power
plant owner can claim warranty for those modules in the future.

1.3.7.5 Pmax Degradation Rate (%/year) Vs Frequency (%)

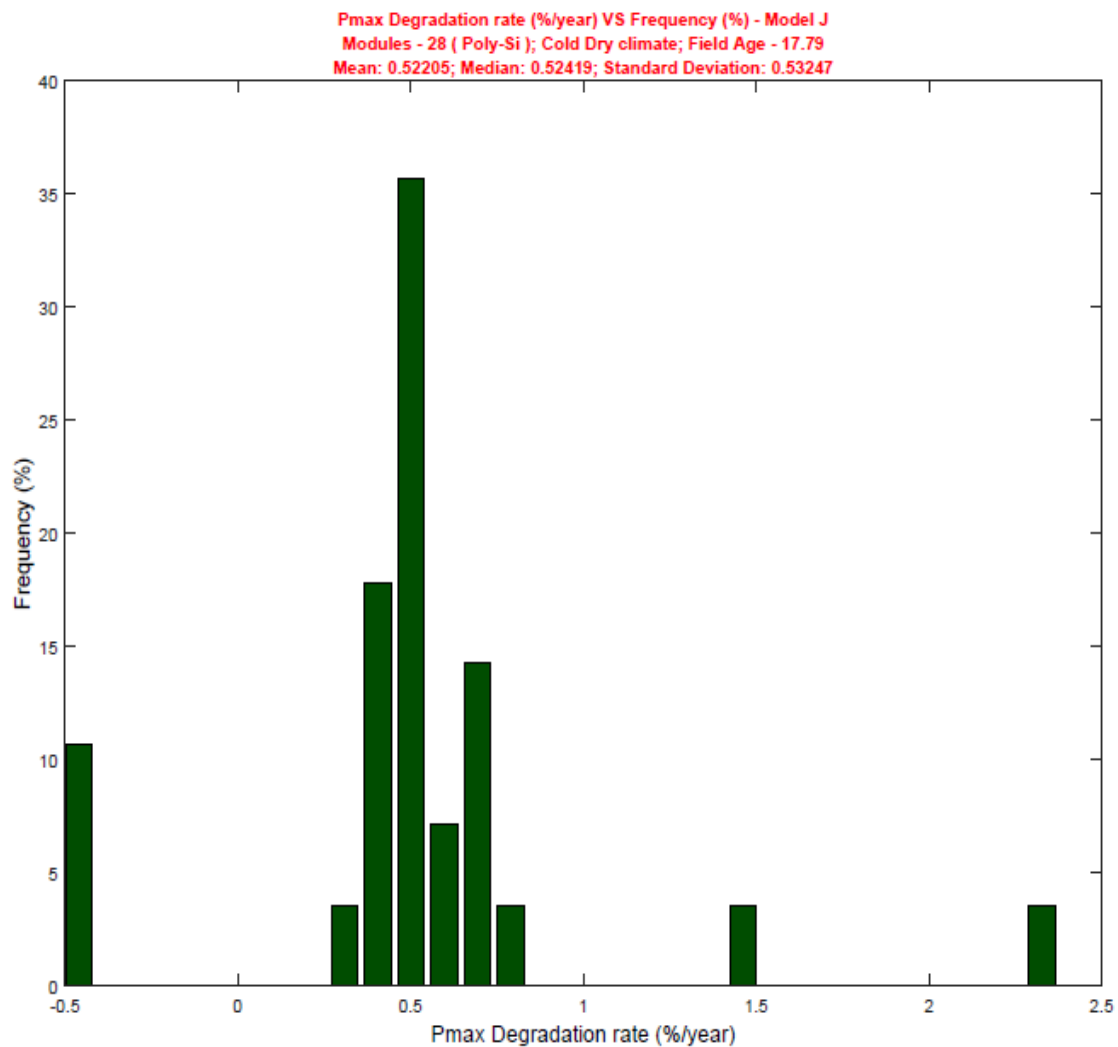


Figure 18: Histogram of Pmax degradation rate (%/year) with frequency in percentage

Histogram is plotted for Pmax rate of degradation (%/year) vs frequency (%) as shown in fig 18. Coding for generating frequency in percentage (%) was developed with coding idea provided in [18]. This plot is helpful in identifying

1. Distribution of Pmax degradation rates in a PV power plant
2. Frequency or count of modules in percentage along the y-axis for a particular degradation rate on x-axis
3. Percentage of modules which are to be replaced through warranty claims (i.e.) Modules that are degrading at more than 1%/year.
4. Percentage of modules degrading at less than 1%/year, which are to be monitored to find whether they are degrading at a rate exceeding 1%/year so that the PV power plant owner can claim warranty for those modules in the future.

1.3.7.6 Combined Histogram of Degradation Rates Vs Frequency

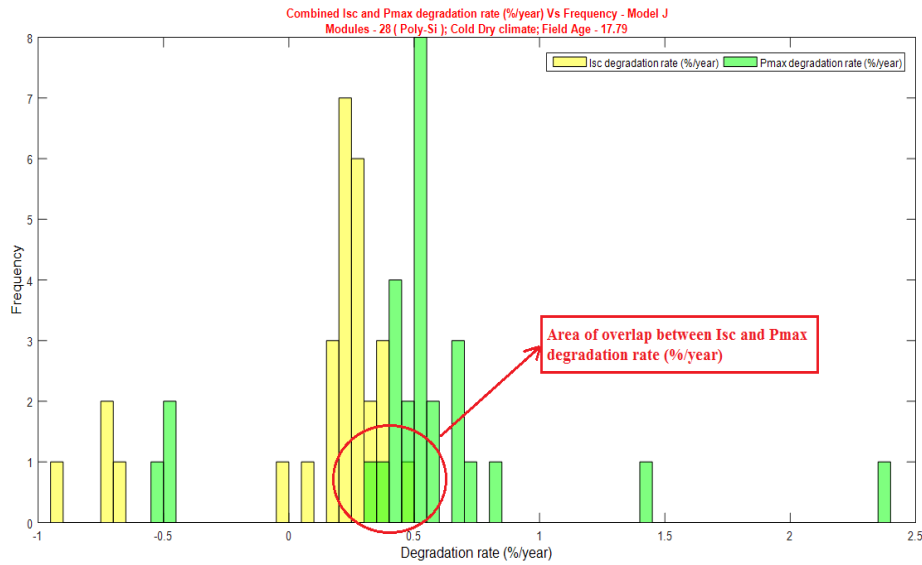


Figure 19: Combined histogram of Isc and Pmax degradation rate (%/year)

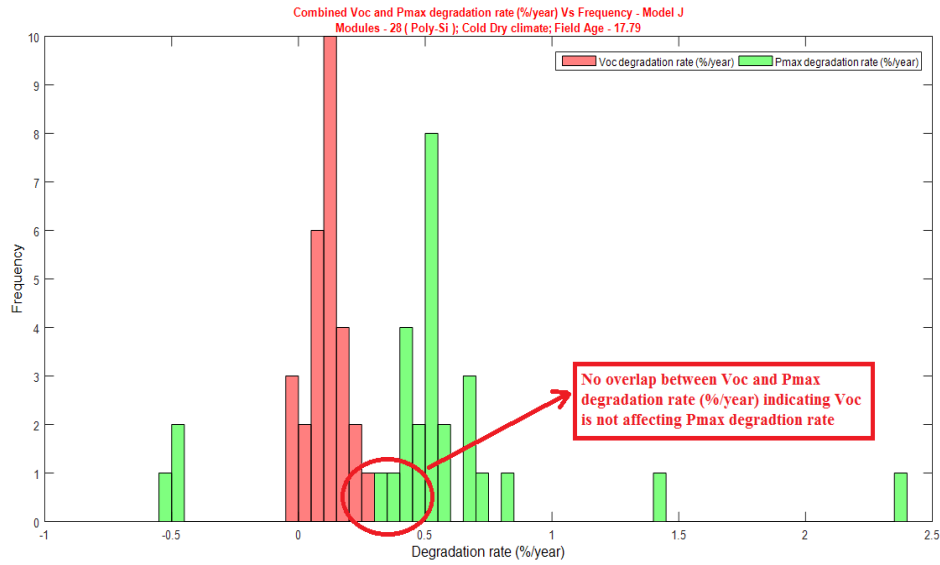


Figure 20: Combined histogram of Voc and Pmax degradation rate (%/year)

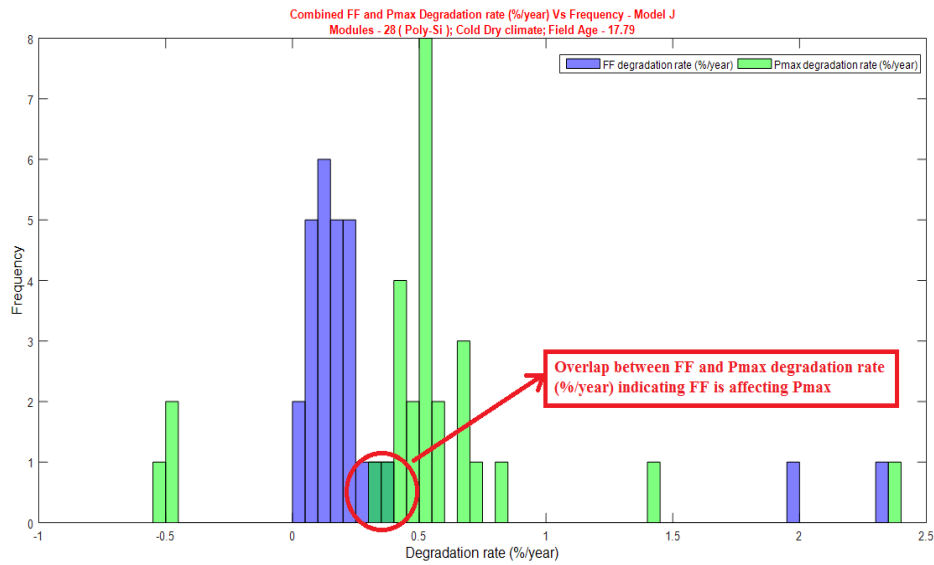


Figure 21: Combined histogram of FF and Pmax degradation rate (%/year)

Plotting histogram of Isc/Voc/FF degradation rate and Pmax degradation rate in the same plot will be useful in finding the effect of Isc/Voc/FF degradation rates on Pmax degradation rates in form of overlap of the histograms. It is evident from the fig 19 that

there is an overlap between I_{sc} and P_{max} degradation rates around 0.25 %/year to 0.5 %/year, which suggests that degradation of I_{sc} is affecting P_{max} . There is no overlap between V_{oc} and P_{max} degradation rates as shown in fig 20, which suggests that degradation of V_{oc} is not affecting P_{max} . Also, we can find that there is an overlap between FF degradation rates and P_{max} degradation rates in fig 21, around 0.3 %/year to 0.5%/year, which denotes even FF degradation has an effect on P_{max} , but not in the same scale as I_{sc} degradation which can be identified from the frequency or count of modules affected.

1.3.7.7 Comparison of Average Degradation Rates (%/year) of IV Parameters for Performance Defects

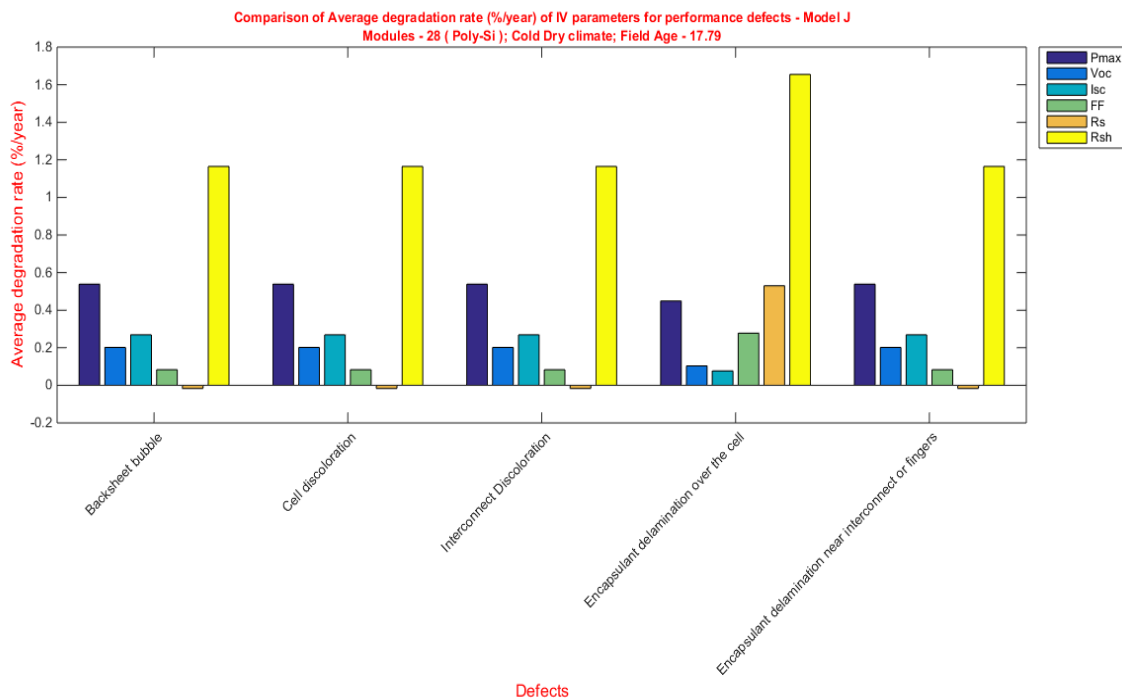


Figure 22: Comparison of average degradation rate (%/year) of IV parameters for performance defects

Average degradation rate (%/year) of IV parameters for different performance defects is plotted as shown in fig 22. Different IV parameters such as I_{sc} , V_{oc} , FF, R_s and R_{sh} are compared to identify the effect of these parameters on P_{max} based on defects. This plot is helpful in identifying

1. IV parameter which dominantly affects P_{max} degradation for a particular defect based on average degradation rate.
2. It is helpful in identifying the order of parameters affecting the P_{max} based on average degradation rates. For Eg: from the fig., it is evident that for interconnect discoloration, the order of parameters will be as follows: $R_{sh} \gg I_{sc} > V_{oc} > FF > R_s$.

1.3.7.8 Comparison of Median Degradation Rates (%/year) of IV Parameters for Performance Defects

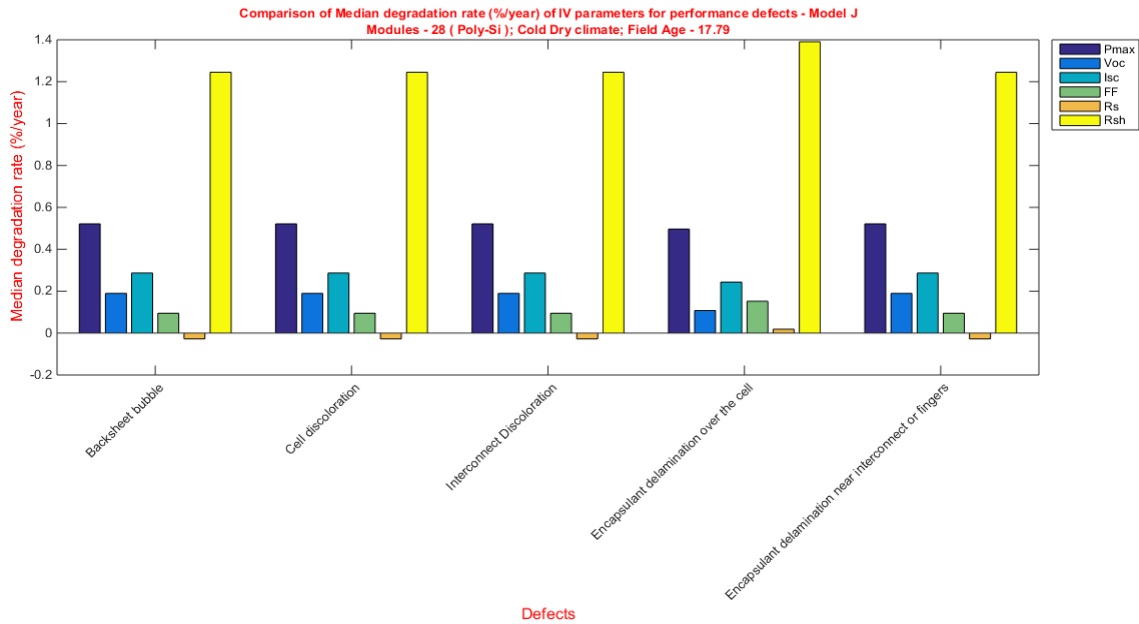


Figure 23: Comparison of median degradation rates (%/year) of IV parameters for performance defects

Median degradation rate (%/year) of IV parameters for different performance defects is plotted as shown in fig 23. Different IV parameters such as Isc, Voc, FF, Rs and Rsh are compared to identify the effect of these parameters on Pmax based on defects. This plot is helpful in identifying

1. IV parameter which dominantly affects Pmax degradation for a particular defect based on median degradation rate.
2. It is helpful in identifying the order of parameters affecting the Pmax based on median degradation rates. For Eg: from the fig., it is evident that for interconnect discoloration, the order of parameters will be as follows: Rsh >> Isc > Voc > FF > Rs following the same pattern as that identified using average degradation rates.

1.4 RESULTS AND DISCUSSION

1.4.1 Manual Vs Program Result Comparison – Model J

Model-J is a roof mounted PV power plant in cold-dry climate with 18 years of field exposure. 46 modules were tested in the field with IV data measurement, Visual Inspection and IR imaging.

Of the 46 modules, 28 modules were only considered for correlation analysis as around 18 modules were neglected in correlation study. 18 modules which were neglected, had either safety failures such as bypass diode open circuit failure or frame grounding minor corrosion or average Pmax degradation rate greater than 2.5%.

All 46 modules data were considered for FMECA-RPN analysis.

1.4.1.1 Correlation Results

1.4.1.1.1 Box Plot

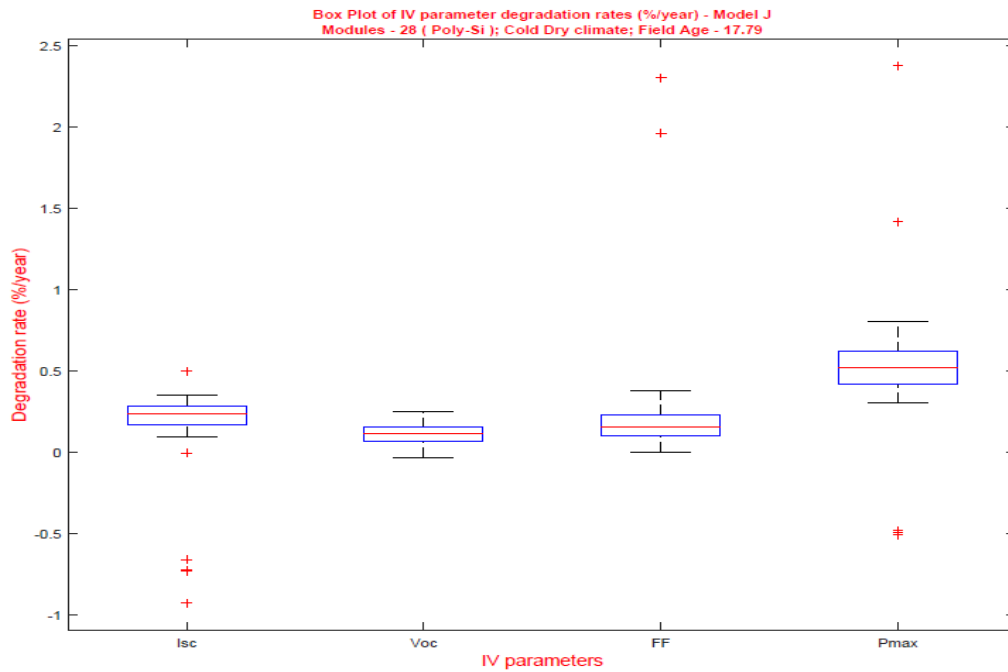


Figure 24: Matlab - Model J - Box Plot of IV parameter degradation rates (%/year)

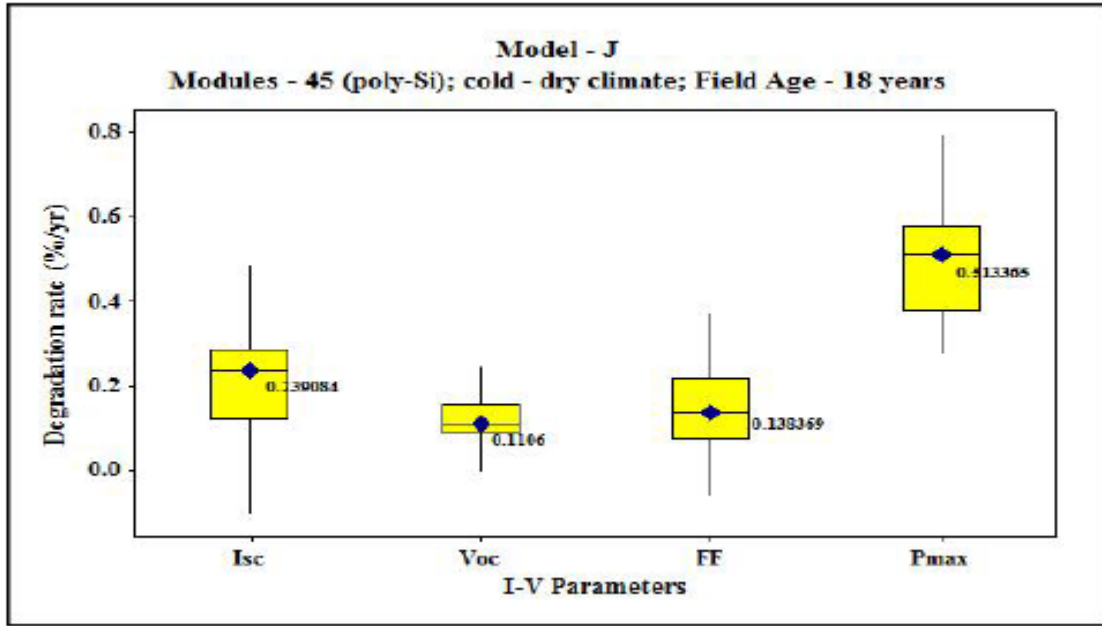


Figure 25: Manual - Model J - Box Plot of IV parameter degradation rates (%/year)

From fig 24, it is evident that Isc degradation rate (%/year) is affecting Pmax degradation (%/year). Order of IV parameters affecting Pmax degradation rate (%/year) is as follows: Isc > FF = Voc which is same as that reported by manual verification as shown in fig 25 with only difference 45 modules were considered when performing manually [9].

Comparison of median degradation rate (%/year) calculated for Isc, Voc, FF and Pmax manually and using MATLAB program are given below as table 6. Table 6 indicates that there is not much difference from the data calculated manually [9] and using MATLAB.

Table 6: Model J - Comparison of Matlab and Manual median degradation rates (%/year) for IV parameters

IV parameter	Median degradation rate (%/year)	
	Matlab	Manual
Isc	0.24	0.24
Voc	0.12	0.11
FF	0.16	0.14
Pmax	0.52	0.51

1.4.1.1.2 Correlation of Defects with Dominant IV Parameter Affected

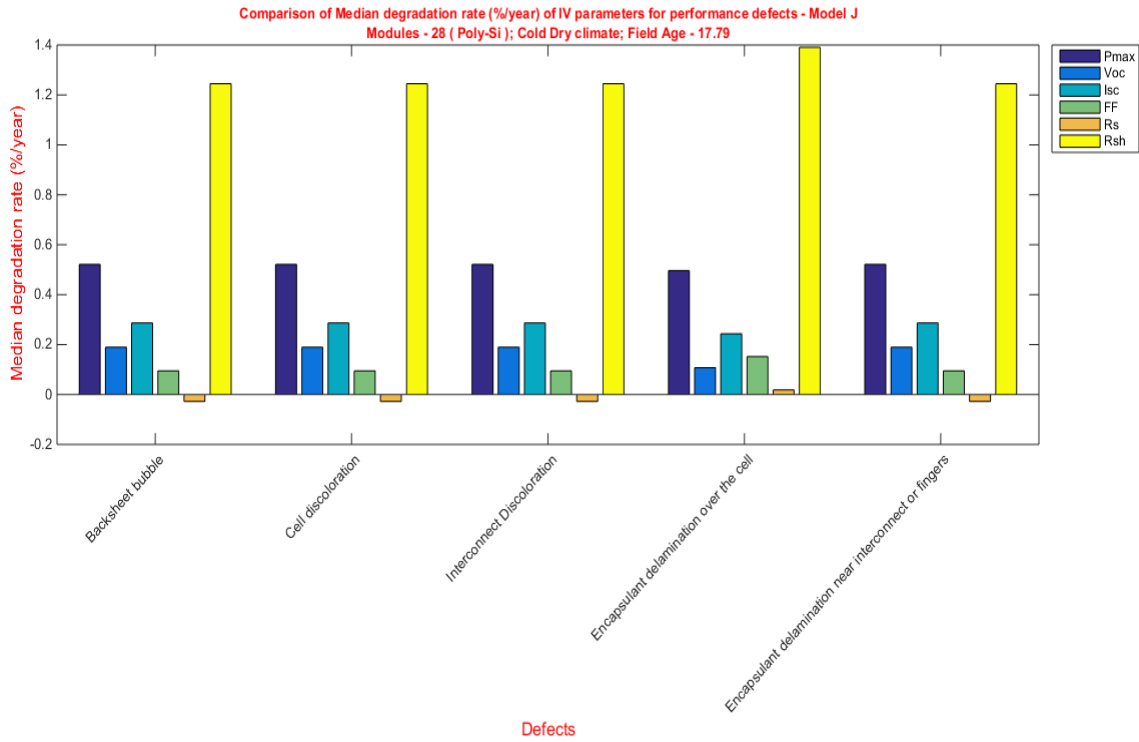


Figure 26: Model J - Comparison of median degradation rates (%/year) of IV parameters for performance defects

From fig 26, it is evident from median degradation data for all IV parameters for each individual defect, Isc is the dominant parameter affecting Pmax excluding the median degradation rates of Rsh and Rs. Median degradation rates of Isc calculated manually [9] and using MATLAB is shown as table 7 below. It is to be noted that for manual calculation [9] data from 45 modules were considered, whereas for MATLAB program based analysis, only 28 modules were considered leaving out safety failure modules and also modules with Pmax degradation rate (%/year) greater than 2.5%.

Table 7: Model J - Comparison of Matlab and Manual Isc degradation rates (%/year)

Defects	Median_RdIsc_Matlab	Median_RdIsc_Manual
Encapsulant delamination over the cell	0.24	0.24
Encapsulant delamination near interconnect or fingers	0.29	0.22
Cell discoloration	0.29	0.26
Backsheet bubble	0.29	0.28
Interconnect Discoloration	0.29	0.28

Based on median Isc degradation rate (%/year) calculated manually [9], Backsheet bubble and Interconnect discoloration have higher values, whereas along with these two defects, encapsulant delamination near interconnect or fingers and cell discoloration are found out to be affecting Isc from MATLAB correlation program results. Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting Isc.

Table 8: Model J - Comparison of Matlab and Manual Voc degradation rates (%/year)

Defects	Median_RdVoc_Matlab	Median_RdVoc_Manual
Encapsulant delamination over the cell	0.11	0.11
Encapsulant delamination near interconnect or fingers	0.19	0.12
Cell discoloration	0.19	0.17
Backsheet bubble	0.19	0.19
Interconnect Discoloration	0.19	0.19

Based on the median Voc degradation rate (%/year) calculated manually [9], Backsheet bubble and Interconnect discoloration have higher values, whereas along with these two defects, encapsulant delamination near interconnect or fingers and cell discoloration are found out to be affecting Voc from MATLAB correlation program results. Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting Voc.

Table 9: Model J - Comparison of Matlab and Manual FF degradation rates (%/year)

Defects	Median_RdFF_Matlab	Median_RdFF_Manual
Backsheet bubble	0.09	0.09
Cell discoloration	0.09	0.06
Interconnect Discoloration	0.09	0.09
Encapsulant delamination near interconnect or fingers	0.09	0.05
Encapsulant delamination over the cell	0.15	0.12

Based on the median FF degradation rate (%/year) calculated manually [9], Encapsulant delamination over the cell is the major defect affecting fill factor, which matches with results from MATLAB based correlation program. Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting FF.

1.4.1.2 RPN Results

1.4.1.2.1 Global RPN

Global RPN was calculated for Model – J as shown below. Total Global RPN calculated using the MATLAB RPN program is 764, whereas Global RPN calculated manually [5] is 468. Reason for the difference is explained below.

Table 10 shows the difference in RPN for each defect/failure calculated using MATLAB and manual processing [5].

Table 10: Model J - Global RPN comparison

Defects/Failures	RPN_Matlab	RPN_Manual
Backsheet bubble	72	16
Bypass diode open circuit (Equipment needed)	240	200
Cell discoloration	72	16
Cell Interconnect ribbon break	70	80
Encapsulant delamination near interconnect or fingers	72	54
Encapsulant delamination over the cell	54	90
Frame grounding minor corrosion	144	NA
Interconnect Discoloration	40	12

Fig 27 shows the global RPN for Model J calculated using MATLAB in a visual format.

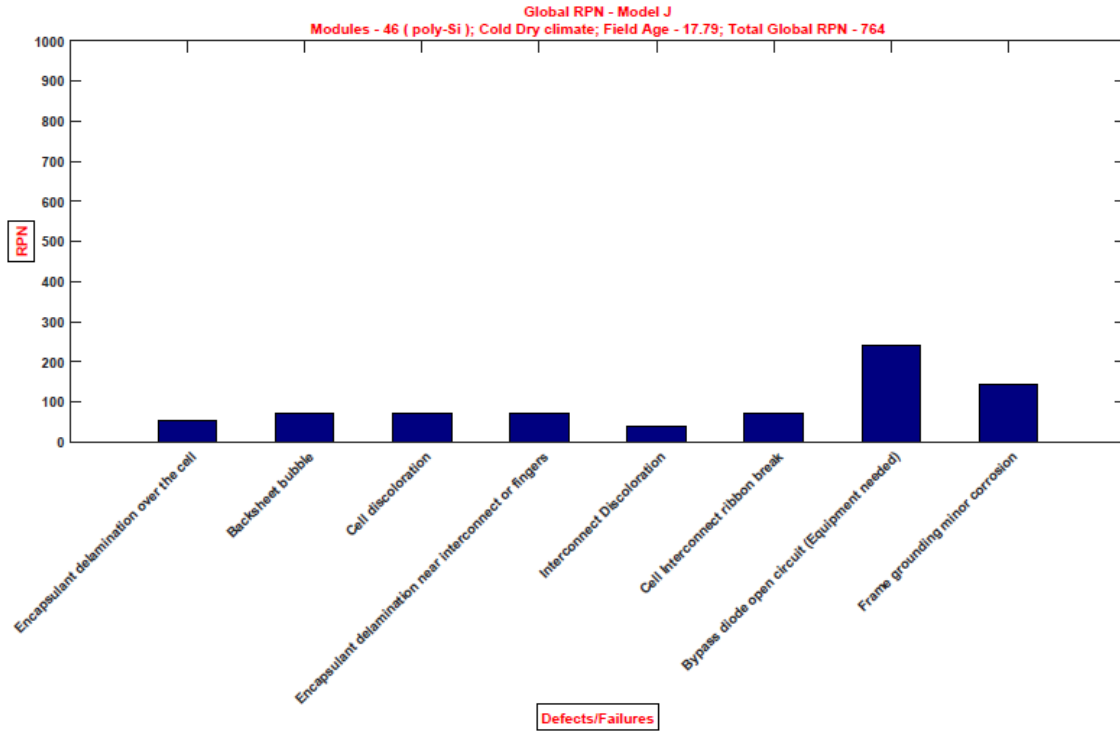


Figure 27: Model J - Global RPN plot using Matlab

Fig 28 shows the comparison of RPN calculated using MATLAB program and manual processing.

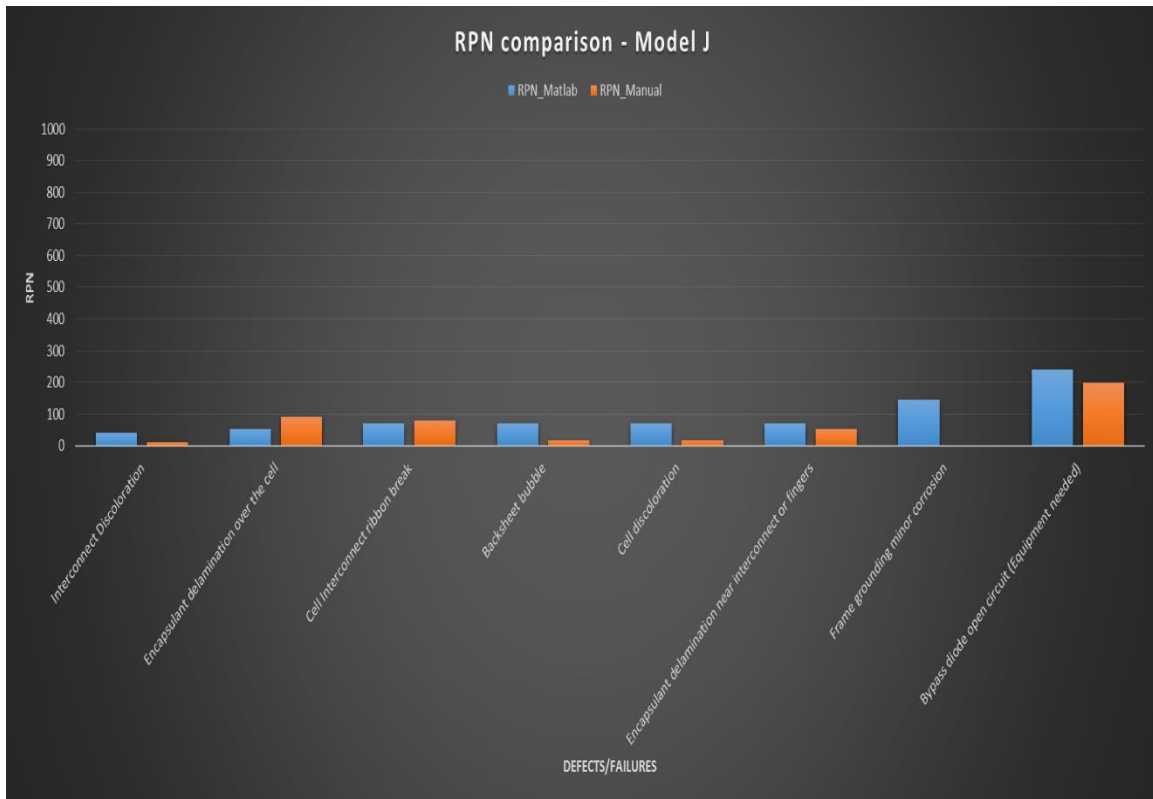


Figure 28: Model J - Global RPN results comparison

1.4.1.2.2 Difference in Severity Calculation

As shown in table 11, Average Pmax degradation rate (%/year) calculated using MATLAB and manual processing [5] had difference which lead to difference in severity calculation. Average Pmax degradation rate (%/year) calculated using manual processing had very low values, where average for each defect was taken for all 46 modules, whereas it should have been taken only for modules having the defects/failures. This lead to a major difference in Average Pmax degradation rate (%/year) calculated using MATLAB and manual processing [5]. Also, Bypass diode open circuit failure was given a severity rating of 10, whereas it should have been given only 8, as it is not a major safety failure. It is to be noted that frame grounding minor corrosion was neglected while

RPN was calculated manually [5]. It is evident from the table 11 that severity rankings are different for defects/failures calculated using both the methods, which was a major reason for difference in Global RPN calculated.

Table 11: Model J - Severity comparison

Defects/Failures	Matlab		Manual	
	Average RdPmax (%/year)	Severity	Average RdPmax (%/year)	Severity
Bypass diode open circuit (Equipment needed)	-0.53	8	0.1	10
Cell Interconnect ribbon break	1.48	7	0.3	8
Interconnect Discoloration	0.54	4	0.11	1
Cell discoloration	0.53	4	0.22	1
Backsheet bubble	0.51	4	0.21	1
Encapsulant delamination near interconnect or fingers	0.52	4	0.31	3
Encapsulant delamination over the cell	0.45	3	0.64	5
Frame grounding minor corrosion	0.51	8	NA	NA

1.4.1.2.3 Difference in Occurrence Calculation

There was no major difference in occurrence calculated as shown in table 12. Only two differences were identified. CNF/1000 of bypass diode open circuit failure in Model-J was identified as 1.28 instead of 1.36 reported in manual calculation [5]. This did not affect the occurrence rating as it was a minor difference which was primarily due to considering 18 bypass diode open circuit failure while performing manually [5], whereas there were only 17 bypass diode open circuit failure in Model-J. It is to be noted that frame grounding minor corrosion failure was neglected for manual occurrence calculation [5].

Table 12: Model J - Occurrence comparison

Defects/Failures	Matlab		Manual	
	CNF/1000	Occurrence	CNF/1000	Occurrence
Bypass diode open circuit (Equipment needed)	1.28	5	1.36	5
Cell Interconnect ribbon break	1.66	5	1.66	5
Interconnect Discoloration	1.89	5	1.89	5
Cell discoloration	21.61	9	21.61	9
Backsheet bubble	40.65	9	40.65	9
Encapsulant delamination near interconnect or fingers	42.54	9	42.54	9
Encapsulant delamination over the cell	47.60	9	47.60	9
Frame grounding minor corrosion	23.57	9	NA	NA

1.4.1.2.4 Difference in Detection Calculation

From table 13, it is evident that except for Bypass diode open circuit failure, all other defects/failures had same detection ratings for both the methods. From table for calculating detection provided by Shrestha et.al [4], it was identified that detection rating for bypass diode open circuit failure was 6 and not 4 as reported manually [5].

Table 13: Model J - Detection comparison

Defects/Failures	Detection	
	Matlab	Manual
Bypass diode open circuit (Equipment needed)	6	4
Cell Interconnect ribbon break	2	2
Interconnect Discoloration	2	2
Cell discoloration	2	2
Backsheet bubble	2	2
Encapsulant delamination near interconnect or fingers	2	2
Encapsulant delamination over the cell	2	2
Frame grounding minor corrosion	2	NA

1.4.1.2.5 Pie Chart

Table 14: Model J - Pie chart comparison

Loss/failure	Percentage_Matlab (%)	Percentage_Manual (%)
Durability Loss (<1% dr/yr)	57	86.3
Reliability failures (>1% dr/yr)	7	8.7
Safety failures	37	5.5

It is evident from the table 14, there is a major difference in pie chart calculated using MATLAB and manual methods. Major difference was due to not taking frame grounding corrosion (safety failure) into consideration while pie chart was plotted manually [5].

1.4.2 Manual Vs Program result comparison – Model JVA

Model-JVA is a roof mounted PV power plant in cold-dry climate with 19 years of field exposure. 128 modules were tested in the field with IV data measurement, Visual Inspection and IR imaging.

Of the 128 modules, 106 modules were only considered for correlation analysis as around 22 modules were neglected in correlation study. 22 modules which were neglected, had either safety failures such as bypass diode open circuit failure or frame grounding minor corrosion or average Pmax degradation rate greater than 2.5%.

All 128 module data were considered for FMECA-RPN analysis.

1.4.2.1 Correlation Results

1.4.2.1.1 Box Plot

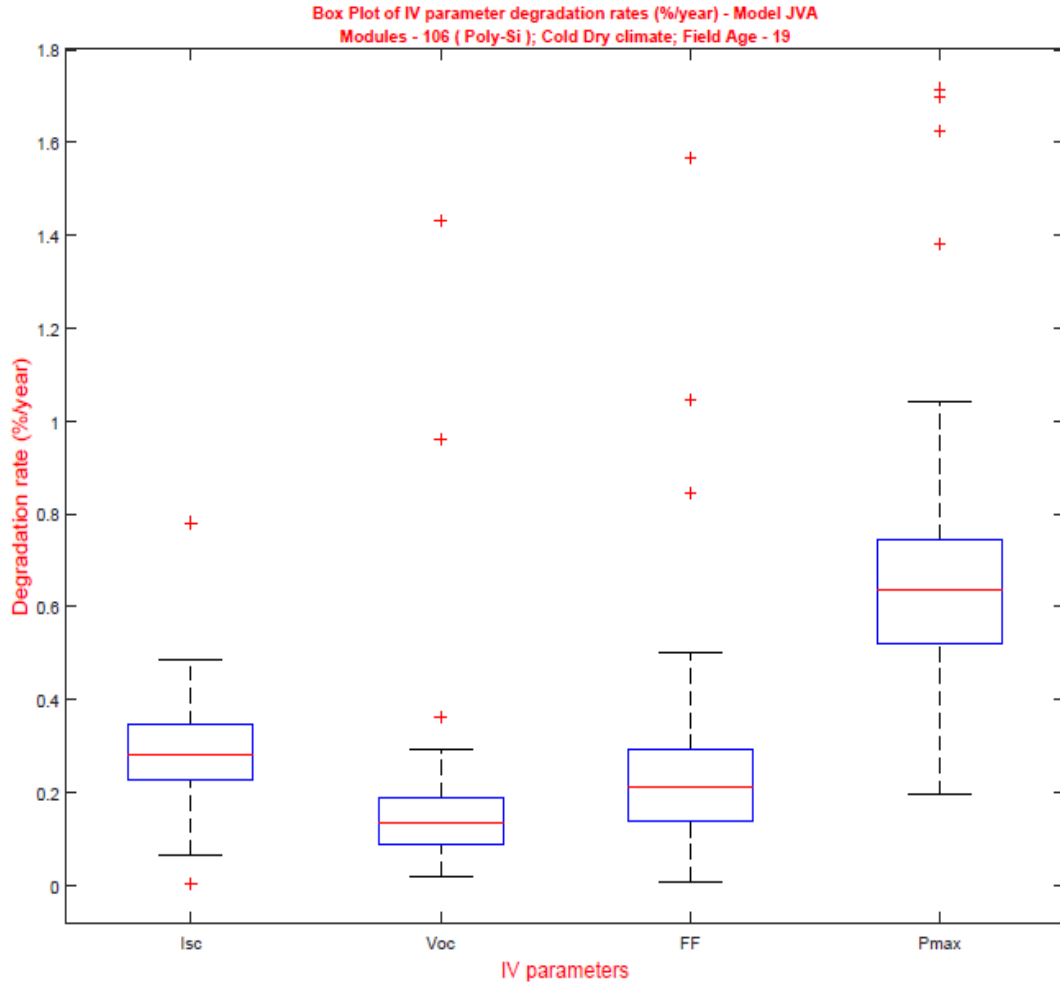


Figure 29: Model JVA - Box plot of IV parameter degradation rates (%/year) - Matlab

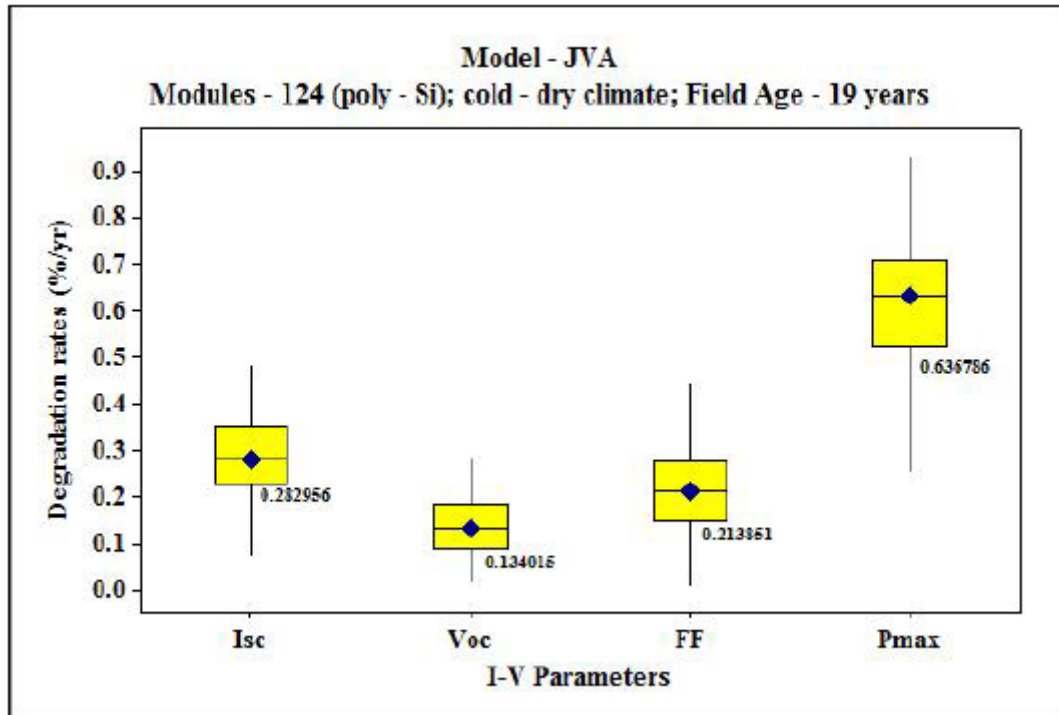


Figure 30: Model JVA - Box plot of IV parameter degradation rates (%/year) - Manual

From fig 29, it is evident that Isc degradation rate (%/year) is affecting Pmax degradation (%/year). Order of IV parameters affecting Pmax degradation rate (%/year) is as follows: Isc > FF > Voc which is same as that reported by manual verification [9] as shown in fig 30 with only difference - 124 modules were considered when performing manually.

Comparison of median degradation rate (%/year) calculated for Isc, Voc, FF and Pmax manually [9] and using the MATLAB program is given below. Table 15 indicates that there is no difference from the data calculated manually [9] and using MATLAB.

Table 15: Model JVA - Comparison of median degradation rate (%/year) for IV parameters

IV parameter	Median degradation rate (%/year)	
	Matlab	Manual
Isc	0.28	0.28
Voc	0.13	0.13
FF	0.21	0.21
Pmax	0.64	0.64

1.4.2.1.2 Correlation of Defects with Dominant IV Parameter Affected

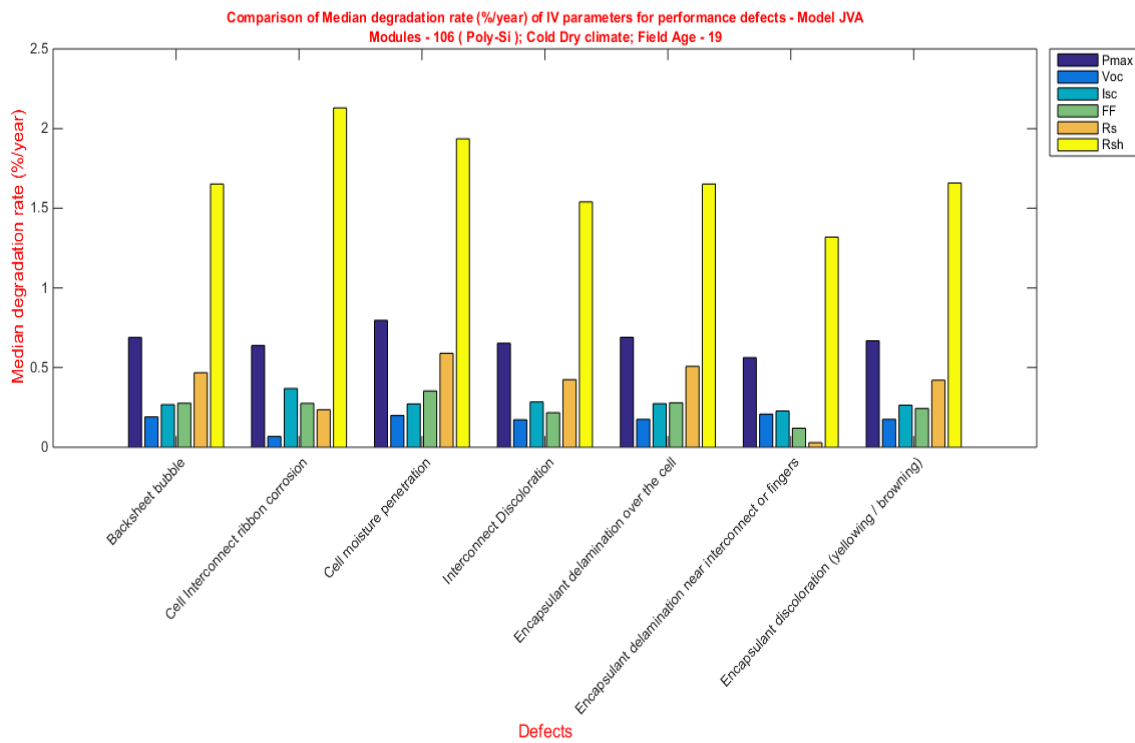


Figure 31: Model JVA - Comparison of median degradation rate (%/year) of IV parameters for performance defects using Matlab

From fig 31, it is evident from the median degradation data for all IV parameters for each individual defect, Isc is the dominant parameter affecting Pmax excluding the median degradation rates of Rsh and Rs. Median degradation rates of Isc calculated manually and

using MATLAB is shown as table 16 below. It is to be noted that for manual calculation data [9], 124 modules were considered, whereas for MATLAB program based analysis, only 106 modules were considered leaving out safety failure modules and also modules with Pmax degradation rate (%/year) greater than 2.5%.

Table 16: Model JVA - Comparison of Isc median degradation rate (%/year)

Defects	Median RdIsc_Matlab	Median RdIsc_Manual
Encapsulant delamination near interconnect or fingers	0.23	0.27
Encapsulant discoloration (yellowing / browning)	0.26	0.26
Backsheet bubble	0.27	0.27
Cell moisture penetration	0.27	0.26
Encapsulant delamination over the cell	0.27	0.28
Interconnect Discoloration	0.28	0.29
Cell Interconnect ribbon corrosion	0.37	NA

Based on the median Isc degradation rate (%/year) calculated manually [9], it is evident that Interconnect discoloration and Encapsulant delamination over the cell are the dominant defects causing Isc degradation, whereas cell interconnect ribbon corrosion (corrosion like) is the dominant defect causing Isc degradation from results obtained from MATLAB. It is to be noted that cell interconnect ribbon corrosion (corrosion like) was not considered for correlation study while performed manually. Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting Isc.

Table 17: Model JVA - Comparison of Voc median degradation rate (%/year)

Defects	Median RdVoc_Matlab	Median RdVoc_Manual
Cell Interconnect ribbon corrosion	0.07	NA
Interconnect Discoloration	0.17	0.17
Encapsulant discoloration (yellowing / browning)	0.18	0.17
Encapsulant delamination over the cell	0.18	0.18
Backsheet bubble	0.19	0.19
Cell moisture penetration	0.20	0.20
Encapsulant delamination near interconnect or fingers	0.21	0.21

Based on the median Voc degradation rate (%/year) calculated manually [9], Encapsulant delamination near interconnect or fingers and cell moisture penetration defects are the most dominant defects causing degradation of Voc. It is being validated by the MATLAB results as shown in table 17. Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting Voc.

Table 18: Model JVA - Comparison of FF median degradation rate (%/year)

Defects	Median RdFF_Matlab	Median RdFF_Manual
Encapsulant delamination near interconnect or fingers	0.12	0.17
Interconnect Discoloration	0.22	0.23
Encapsulant discoloration (yellowing / browning)	0.24	0.24
Cell Interconnect ribbon corrosion	0.28	NA
Backsheet bubble	0.28	0.24
Encapsulant delamination over the cell	0.28	0.24
Cell moisture penetration	0.35	0.34

Based on the median FF degradation rate (%/year) calculated manually [9], cell moisture penetration is the dominant defect causing FF degradation which is also the same from results calculated using the MATLAB correlation program. Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting FF.

1.4.2.2 RPN Results

1.4.2.2.1 Global RPN

Global RPN was calculated for Model – JVA as shown below. Total Global RPN calculated using the MATLAB RPN program is 1186, whereas Global RPN calculated manually [6] is 572. Reason for the difference is explained below.

Table 19 shows the difference in RPN for each defect/failure calculated using MATLAB and manual processing. It is to be noted that defects/failures like no frame grounding and circuit exposed due to backsheet scratches included in the manual RPN calculation [6] were neglected for RPN calculation using MATLAB.

Table 19: Model JVA - Comparison of Global RPN

Defects/Failures	RPN_Matlab	RPN_Manual
Backsheet bubble	80	16
Backsheet burn mark	48	48
Backsheet crack /cut under cell	120	48
Backsheet delamination	120	12
Bypass diode open circuit (Equipment needed)	240	160
Cell Interconnect ribbon burn mark	30	48
Cell Interconnect ribbon corrosion	60	36
Cell moisture penetration	72	NA
Encapsulant delamination near interconnect or fingers	60	12
Encapsulant delamination over the cell	80	48
Encapsulant discoloration (yellowing/browning)	90	72
Frame grounding minor corrosion	96	NA
Interconnect Discoloration	90	72

Fig 32 shows the global RPN calculated using MATLAB in a visual format.

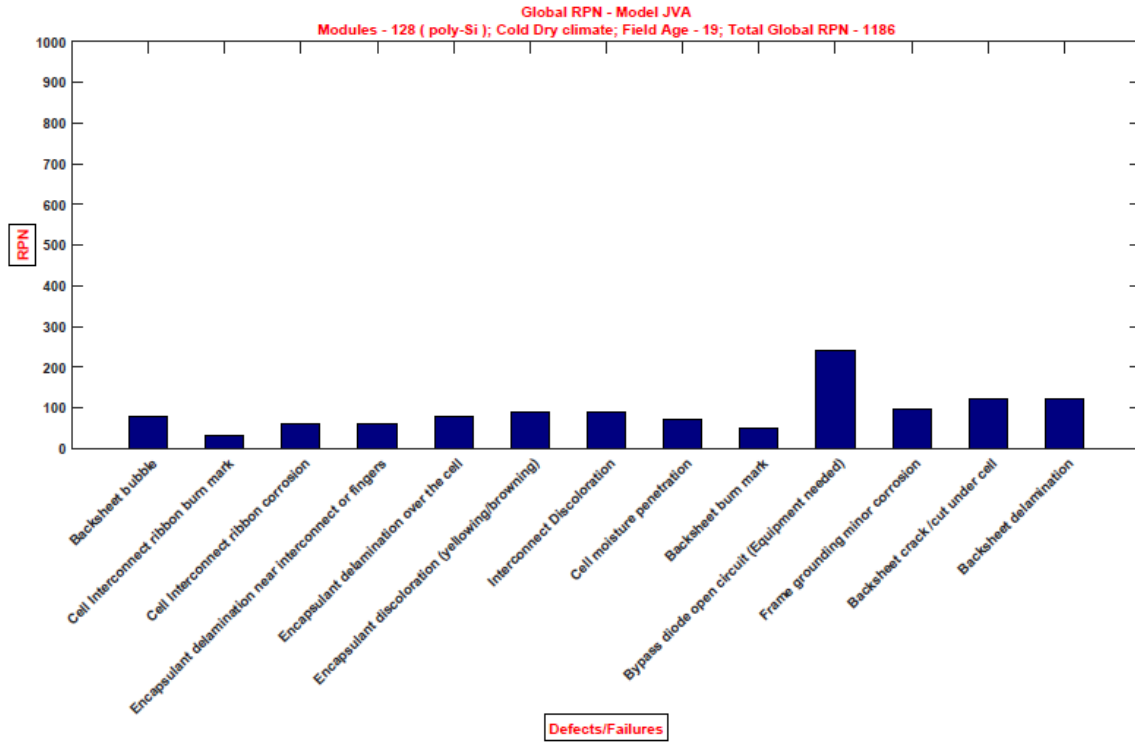


Figure 32: Model JVA - Global RPN plot

Fig.33 shows the comparison of RPN calculated using MATLAB program and manual processing.

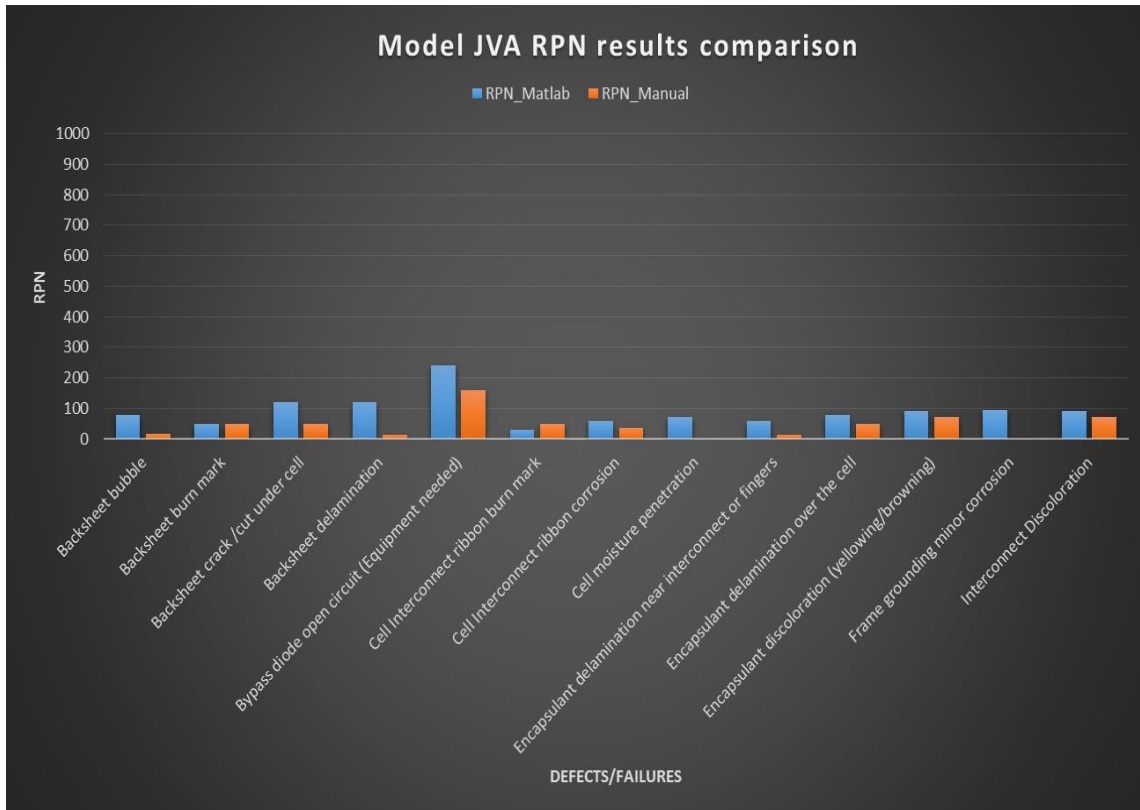


Figure 33: Model JVA - Comparison of Matlab and Manual RPN results

1.4.2.2.2 Difference in Severity Calculation

As shown in table 20, Average Pmax degradation rate (%/year) calculated using MATLAB and manual processing had difference which lead to difference in severity calculation. Average Pmax degradation rate (%/year) calculated using manual processing had very low values, where average for each defect was taken for all 128 modules, whereas it should have been taken only for modules having that particular defect/failure. This lead to a major difference in Average Pmax degradation rate (%/year) calculated using MATLAB and manual processing. Also, Bypass diode open circuit failure was given a severity rating of 10, whereas it should have been given only 8, as it is not a major safety failure. It is to be noted that frame grounding minor corrosion and cell

moisture penetration were neglected while RPN was calculated manually. It is evident from the table that severity rankings are different for defects/failures calculated using both the methods, which was a major reason for difference in Global RPN calculated.

Table 20: Model JVA - Comparison of severity

Defects/Failures	Matlab		Manual	
	RdPmax (%/year)	Severity	RdPmax (%/year)	Severity
Backsheet bubble	0.74	5	0.29	1
Backsheet burn mark	0.67	8	0.14	8
Backsheet crack /cut under cell	1.01	10	0.5	4
Backsheet delamination	0.64	10	0.13	1
Bypass diode open circuit (Equipment needed)	0.49	8	0.1	10
Cell Interconnect ribbon burn mark	0.62	5	0.12	8
Cell Interconnect ribbon corrosion	0.75	5	0.33	3
Cell moisture penetration	0.83	6	NA	NA
Encapsulant delamination near interconnect or fingers	0.80	5	0.15	1
Encapsulant delamination over the cell	0.75	5	0.42	3
Encapsulant discoloration (yellowing/browning)	0.73	5	0.56	4
Frame grounding minor corrosion	0.64	8	NA	NA
Interconnect Discoloration	0.72	5	0.55	4

1.4.2.2.3 Difference in Occurrence Calculation

There was no major difference in occurrence calculated as shown in table. Only three differences were identified. CNF/1000 value of bypass diode open circuit failure in Model-JVA was identified as 1.06 instead of 0.91 reported in manual calculation [6]. This did not affect the occurrence rating as it was a minor difference which was primarily due to considering 6 bypass diode open circuit failure while performing manually, whereas there were 7 bypass diode open circuit failure in Model-JVA. It is to be noted that frame grounding minor corrosion failure and cell moisture penetration were neglected for manual occurrence calculation [6].

Table 21: Model JVA - Comparison of Occurrence

Defects/Failures	Matlab		Manual	
	CNF/1000	Occurrence	CNF/1000	Occurrence
Backsheet bubble	13.01	8	13.01	8
Backsheet burn mark	0.30	3	0.30	3
Backsheet crack /cut under cell	3.18	6	3.18	6
Backsheet delamination	3.02	6	3.02	6
Bypass diode open circuit (Equipment needed)	1.06	5	0.91	4
Cell Interconnect ribbon burn mark	0.30	3	0.30	3
Cell Interconnect ribbon corrosion	2.72	6	2.72	6
Cell moisture penetration	4.08	6	NA	NA
Encapsulant delamination near interconnect or fingers	4.54	6	4.54	6
Encapsulant delamination over the cell	17.39	8	17.39	8
Encapsulant discoloration (yellowing/browning)	24.05	9	24.05	9
Frame grounding minor corrosion	3.93	6	NA	NA
Interconnect Discoloration	26.32	9	26.32	9

1.4.2.2.4 Difference in Detection Calculation

From table 22, it is evident that except for Bypass diode open circuit failure, all other defects/failures had same detection ratings for both the methods. From table for calculating detection provided by Shrestha et.al [4], it was identified that detection rating for bypass diode open circuit failure was 6 and not 4 as reported manually [6].

Table 22: Model JVA - Comparison of Detection

Defects/Failures	Detection	
	Matlab	Manual
Backsheet bubble	2	2
Backsheet burn mark	2	2
Backsheet crack /cut under cell	2	2
Backsheet delamination	2	2
Bypass diode open circuit (Equipment needed)	6	4
Cell Interconnect ribbon burn mark	2	2
Cell Interconnect ribbon corrosion	2	2
Cell moisture penetration	2	NA
Encapsulant delamination near interconnect or fingers	2	2
Encapsulant delamination over the cell	2	2
Encapsulant discoloration (yellowing/browning)	2	2
Frame grounding minor corrosion	2	NA
Interconnect Discoloration	2	2

1.4.2.2.5 Pie Chart

Table 23: Model JVA - Pie chart comparison

Loss/Failure	Percentage_Matlab (%)	Percentage_Manual (%)
Durability Loss (<1% dr/yr)	78	89.6
Reliability failures (>1% dr/yr)	5	4.3
Safety failures	17	6.1

It is evident from the table 23, there is a major difference in pie chart calculated using MATLAB and manual methods [6] for Model-JVA. Major difference was due to not taking frame grounding corrosion (safety failure) into consideration while pie chart was plotted manually [6].

1.4.3 Manual Vs Program Result Comparison – Model HP

Model-HP is a roof mounted PV power plant in hot-dry climate with 5 years of field exposure. 84 modules were tested in the field with IV data measurement, Visual Inspection and IR imaging.

Of the 84 modules, 76 modules were only considered for correlation analysis as around 8 modules were neglected in correlation study. 8 modules which were neglected, had either safety failures such as backsheet bubble or hotspot over 20°C or average Pmax degradation rate greater than 2.5%.

All 84 module data were considered for FMECA-RPN analysis.

1.4.3.1 Correlation Results

1.4.3.1.1 Box Plot

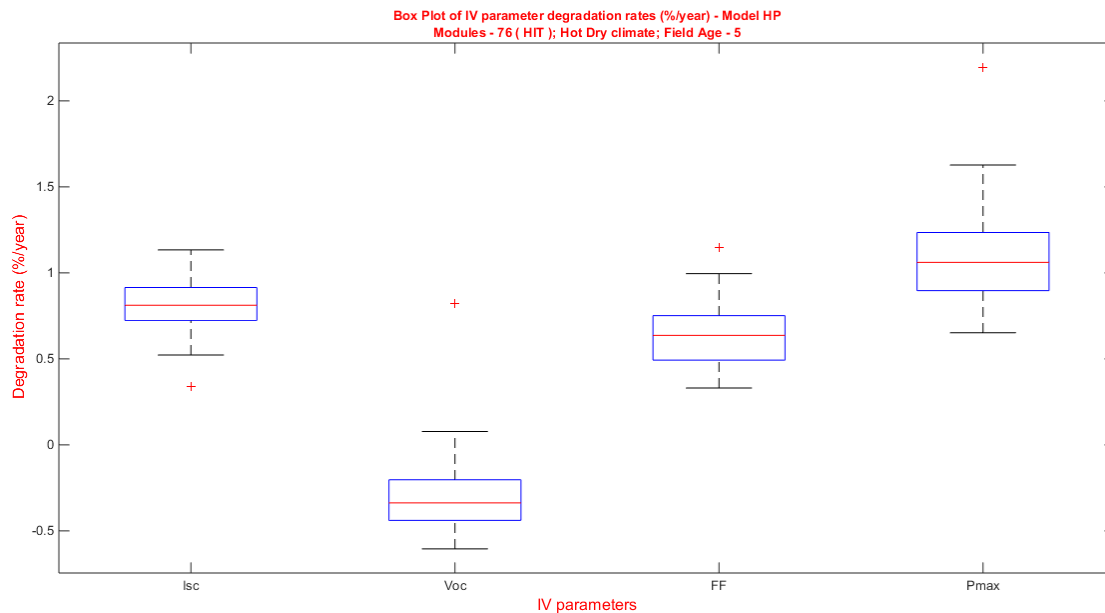


Figure 34: Model HP - Box plot of IV parameter degradation rates (%/year) using Matlab

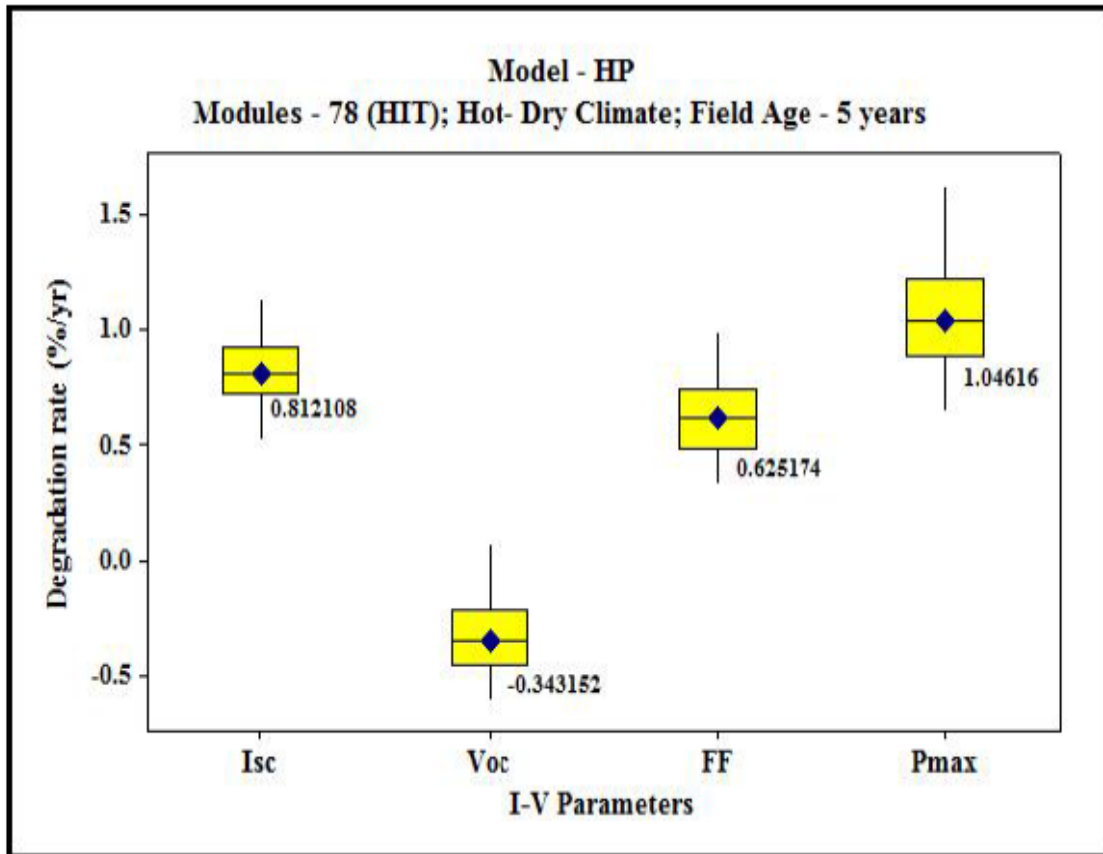


Figure 35: Model HP - Box Plot of IV parameter degradation rates (%/year) - Manual

From the fig 34, it is evident that Isc degradation rate (%/year) is affecting Pmax degradation (%/year). Order of IV parameters affecting Pmax degradation rate (%/year) is as follows: Isc > FF > Voc which is same as that reported by manual processing [9] as shown in fig 35.

Comparison of median degradation rate (%/year) calculated for Isc, Voc, FF and Pmax manually [9] and using the MATLAB program is given below. Table 24 indicates that there is no difference from the data calculated manually and using MATLAB.

Table 24: Model HP - Comparison of median degradation rates (%/year) for IV parameters

IV parameter	Median degradation rate (%/year)	
	Matlab	Manual
Isc	0.81	0.81
Voc	-0.33	-0.33
FF	0.64	0.65
Pmax	1.06	1.07

1.4.3.1.2 Correlation of Defects with Dominant IV Parameter Affected

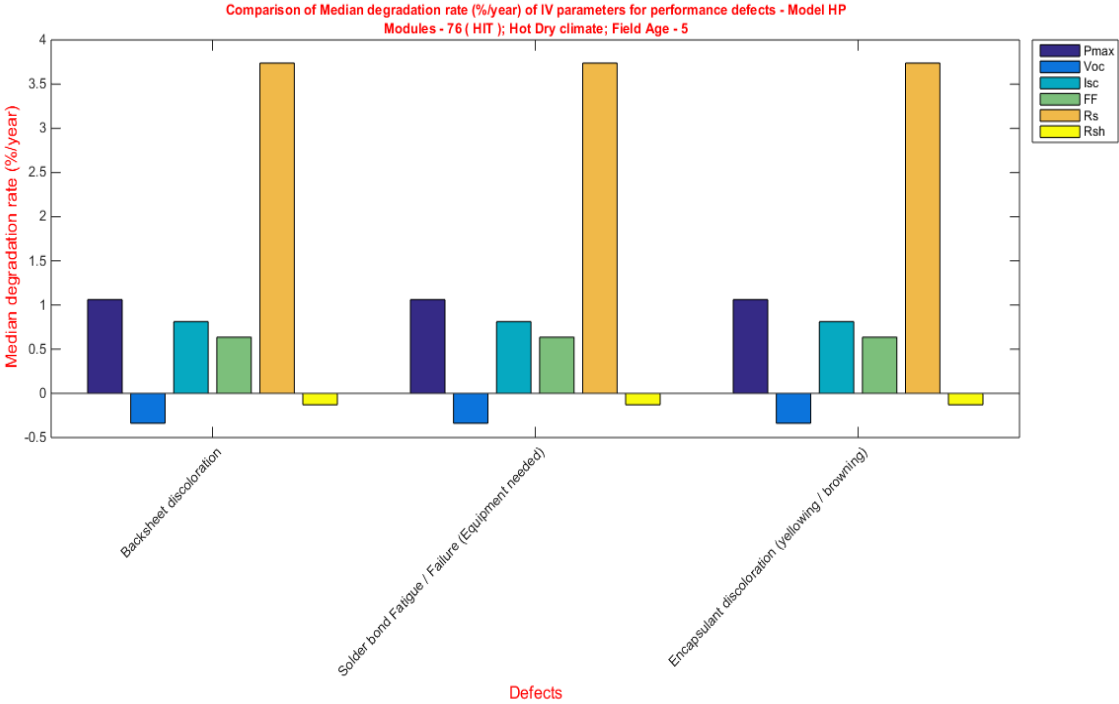


Figure 36: Model HP - Comparison of median degradation rate (%/year) of IV parameters for performance defects using Matlab

From fig 36, it is evident from median degradation data for all IV parameters for each individual defect, Isc is the dominant parameter affecting Pmax excluding the median

degradation rates of Rsh and Rs. Median degradation rates of Isc calculated manually [9] and using MATLAB is shown as table 25 below.

Table 25: Model HP - Comparison of median Isc degradation rate (%/year)

Defects	Median RdIsc_Matlab	Median RdIsc_Manual
Backsheet discoloration	0.81	0.81
Solder bond Fatigue / Failure (Equipment needed)	0.81	0.81
Encapsulant discoloration (yellowing / browning)	0.81	0.81

Based on the median Isc degradation rate (%/year) calculated manually [9] and using MATLAB, it is evident that all three defects are causing Isc degradation equally which is mainly due to the presence of all 3 defects in all 76 modules which were considered for correlation study. It is difficult to identify the defect which is exactly causing Isc degradation based on the data obtained as all defects have exactly same Isc degradation rate (%/year). Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting Isc.

Table 26: Model HP - Comparison of median Voc degradation rate (%/year)

Defects	Median RdVoc_Matlab	Median RdVoc_Manual
Backsheet discoloration	-0.33	-0.33
Solder bond Fatigue / Failure (Equipment needed)	-0.33	-0.33
Encapsulant discoloration (yellowing / browning)	-0.33	-0.33

Based on the median Voc degradation rate (%/year) calculated manually [9] and using MATLAB, it is evident that Voc is not the parameter that is affecting Pmax degradation.

Table 27: Model HP - Comparison of median FF degradation rate (%/year)

Defects	Median RdFF_Matlab	Median RdFF_Manual
Backsheet discoloration	0.64	0.65
Solder bond Fatigue / Failure (Equipment needed)	0.64	0.65
Encapsulant discoloration (yellowing / browning)	0.64	0.65

Based on the median FF degradation rate (%/year) calculated manually [9] and using MATLAB, it is evident that all three defects are causing FF degradation equally which is mainly due to the presence of all 3 defects in all 76 modules which were considered for correlation study. It is difficult to identify the defect which is exactly causing FF degradation based on the data obtained as all defects have exactly same FF degradation rate (%/year). Further study is to be done using vertical degradation spread as outlined in [9] to find out the exact defects affecting FF.

1.4.3.2 RPN Results

1.4.3.2.1 Global RPN

Global RPN was calculated for Model – HP as shown below. Total Global RPN calculated using the MATLAB RPN program is 1224, whereas Global RPN calculated manually [4] is 730. Reason for the difference is explained below.

Table 28 shows the difference in RPN for each defect/failure calculated using MATLAB and manual processing [4].

Table 28: Model HP - Comparison of Global RPN results

Defects/Failures	RPN_Matlab	RPN_Manual
Backsheet bubble	72	48
Backsheet discoloration	160	40
Encapsulant delamination over the cell	72	54
Encapsulant discoloration (yellowing/browning)	160	60
Hotspot over 20 deg C (Equipment needed)	120	128
Solder bond Fatigue / Failure (Equipment needed)	640	400

Fig 37 shows the global RPN calculated using MATLAB in a visual format.

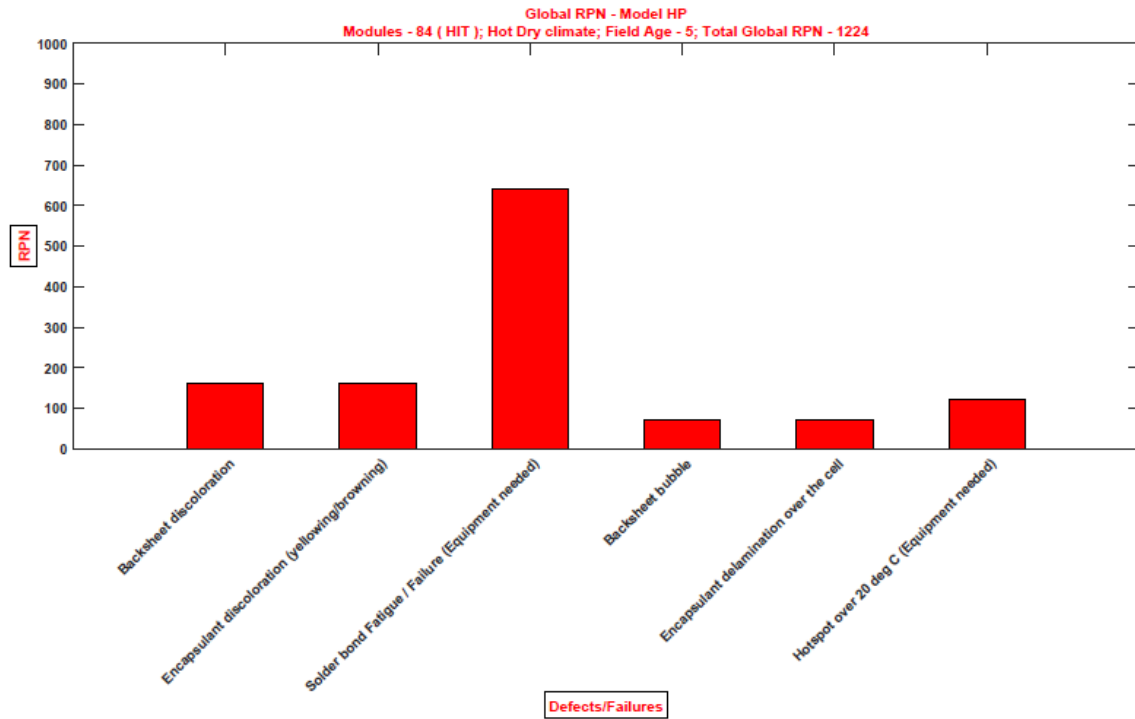


Figure 37: Model HP - Global RPN plot using Matlab

Fig 38 shows the comparison of RPN calculated using MATLAB program and manual processing.

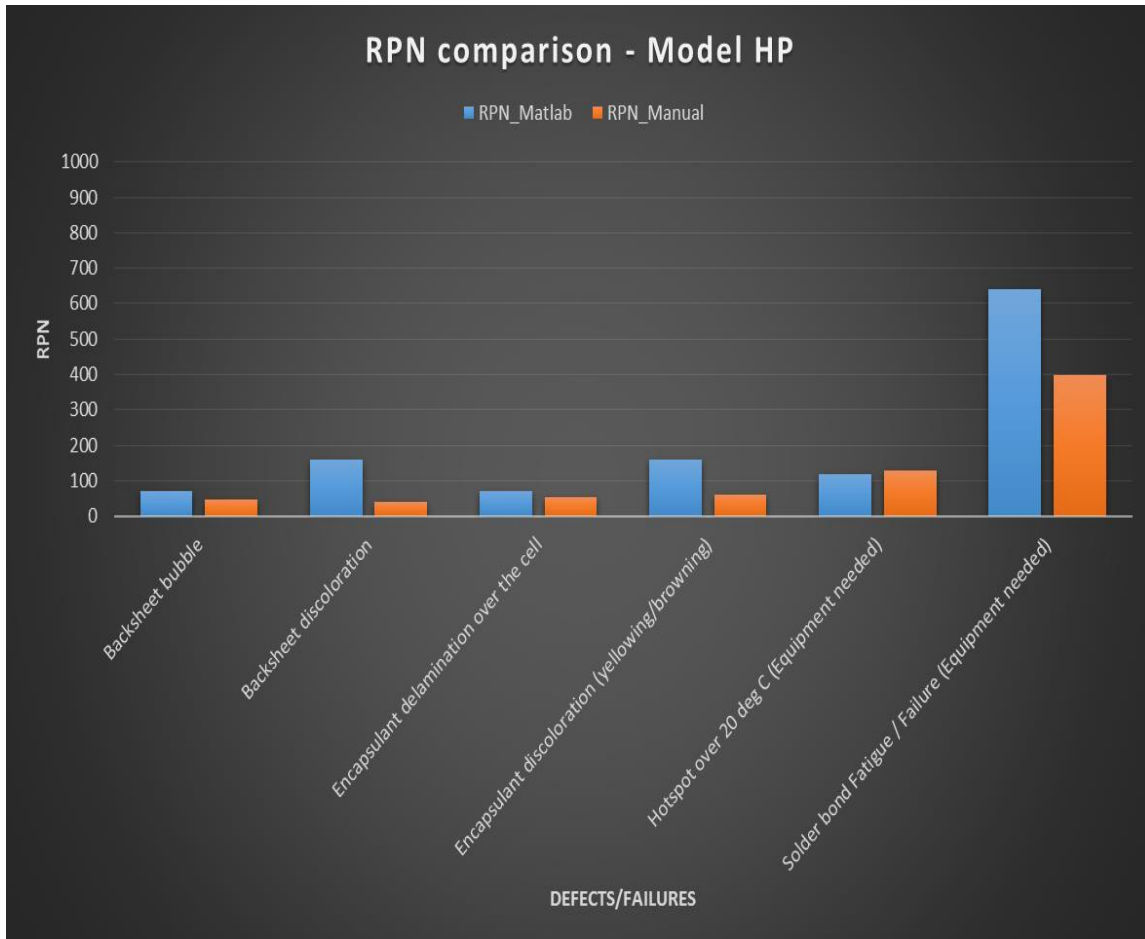


Figure 38: Model HP - Comparison of Global RPN results

1.4.3.2.2 Difference in Severity Calculation

As shown in table 29, Severity calculated using MATLAB and manual processing [4] are different. As Average Pmax degradation rate (%/year) is not available for each defect/failure from manual calculation [4], it is difficult to compare the results.

Table 29: Model HP - Comparison of severity

Defects/Failures	Matlab		Manual	
	Rd Pmax (%/year)	Severity	Rd Pmax (%/year)	Severity
Backsheet discoloration	1.57	8	NA	2
Encapsulant discoloration (yellowing/browning)	1.57	8	NA	3
Solder bond Fatigue / Failure (Equipment needed)	1.57	8	NA	5
Backsheet bubble	8.01	9	NA	8
Encapsulant delamination over the cell	8.01	9	NA	9
Hotspot over 20 deg C (Equipment needed)	5.67	10	NA	8

1.4.3.2.3 Difference in Occurrence Calculation

There is a major difference in occurrence calculated as shown in table 30. While CNF/1000 was calculated manually [4], field age of 6 years was used, whereas field age was reported as 5 years which lead to the difference in occurrence calculated. MATLAB program was run with field age of 5 years.

Table 30: Model HP - Comparison of Occurrence

Defects/Failures	Matlab		Manual	
	CNF/1000	Occurrence	CNF/1000	Occurrence
Backsheet discoloration	200	10	166.67	10
Encapsulant discoloration (yellowing/browning)	200	10	166.67	10
Solder bond Fatigue / Failure (Equipment needed)	200	10	166.67	10
Backsheet bubble	0.79	4	0.66	3
Encapsulant delamination over the cell	0.79	4	0.66	3
Hotspot over 20 deg C (Equipment needed)	0.40	3	1.32	4

1.4.3.2.4 Difference in Detection Calculation

From table 31, it is evident that except for Backsheet discoloration, all other defects/failures had same detection ratings for both the methods. From table for calculating detection provided by Shrestha et.al [4], it was identified that the detection rating for Backsheet discoloration was 2 and not 1 as reported manually [4], as rank 1 is

usually given to defects/failures which can be detected by the field control mechanism itself, which is not the case with Backsheet discoloration as it was identified using visual inspection. So, Rank 2 was given for Backsheet discoloration using the MATLAB RPN program.

Table 31: Model HP - Comparison of detection

Defects/Failures	Detection	
	Matlab	Manual
Backsheet discoloration	2	1
Encapsulant discoloration (yellowing/browning)	2	2
Solder bond Fatigue / Failure (Equipment needed)	8	8
Backsheet bubble	2	2
Encapsulant delamination over the cell	2	2
Hotspot over 20 deg C (Equipment needed)	4	4

1.4.3.2.5 Pie Chart

Table 32: Model HP - Comparison of pie chart results

Loss/Failure	Percentage_Matlab (%)	Percentage_Manual (%)
Durability loss	36	NA
Reliability failures	63	NA
Safety failures	1	NA

As there was no pie chart generated manually [4], values for respective loss/failure are not provided here.

1.5 CONCLUSION

Automation of Risk Priority Number (RPN) Calculation of Photovoltaic Modules with statistical risk analysis and correlation analysis will be of great help to researchers working in the photovoltaic power plant inspection and evaluation by reducing the time involved in manual processing of the data. It also helps PV power plant operators to find the safety failed and reliability failed modules which are needed to be replaced in order to avoid loss of property or personnel and also loss of energy production. It will be prime help to PV module manufacturers to find out the flaws in their design affecting a module with respect to climatic conditions, enabling them to come up with climate resilient PV modules. In this project, an automated statistical processing through RPN calculations has been successfully developed and demonstrated. The Primary achievement of this project is the automatic generation of Risk Priority Number (RPN) for each defect based on two Excel spreadsheets: Defect spreadsheet; Degradation rate spreadsheet. The automation developed and presented in this project generates about 20 different reliability risk plots in about 3-4 minutes without the need of several manual labor hours traditionally spent for these analyses. There is a lot of potential for future work such as:

1. Comparing parameters of PV modules measured with soil and after cleaning the soil to find out energy loss due to soiling.
2. With the possibility of new defects/failures detected through research and field experience, program can be altered to accommodate new defects/failures.
3. The Rate of degradation of IV parameters for each defect can be plotted in the form of distribution to further study the effect of defects on performance of PV module.

4. RPN can be calculated for each module separately to find out the effects of defects on each single module.
5. With the availability of AC performance data, finding Performance index, efficiency of PV power plant, etc., can be automated.
6. Results can be published in a report format using publish option in MATLAB. It was not implemented in this work because of issues with image sizing.

PART 2: EVALUATION OF MODULE LEVEL POWER ELECTRONICS (MLPE)

2.1 INTRODUCTION

2.1.1 Background

Photovoltaics (PV) industry is striving hard to become cost competitive with other traditional forms of energy. One part of reducing the cost is reducing the costs associated with balance of system (BOS). Inverters are a major part of the cost associated with balance of system. Inverter design is currently being guided into three directions: large, centralized, utility-scale inverters (>500 kW), medium, residential-scale string inverters (<100 kW), and small, module level (~250 W) power electronics (MLPE). MLPE [21] offers a lot of advantages over its counterparts such as safety, ease of system operation and maintenance (O&M) with monitoring capability, increase in energy yield due to module level power point tracking and lower power handling requirements. It also suffers from major disadvantages [21]: Exposure to extreme environment conditions (high temperatures, temperature cycling due to difference in temperature in day and night, moisture/humidity, etc.) based on the proximity to PV modules can negatively affect the reliability of MLPE and also tracking and repairing the units out of service will be challenging in power plants where several thousands to millions of PV modules are employed. It is of prime importance to identify the reliability of MLPE as disadvantages identified can be rectified with estimation of lifetime with the help of accelerated stress tests. It can play an important role in bringing down the costs associated with O&M of MLPE, thereby reducing the costs associated with photovoltaics installation and increasing the confidence of the investors and system owners [21].

2.1.2 Statement of the Problem

Safety standards are available for PV modules and various generic inverter types, but there are no qualification standards available specifically for MLPE as it is a very new industry. There are no agreed upon reliability standards existing for any of these technologies including MLPE [21]. There is a need to develop a reliability protocol for MLPE [21]. In order to come up with a standardized reliability protocol for MLPE, Accelerated Lifetime Testing (ALT) has to be performed on MLPE [14]. Accelerated Lifetime testing [14] involves three major steps – Pre-Characterization, Stress tests and Post-Characterization. Pre-characterization [14] involves characterizing MLPE units (i.e. measuring input and output parameters associated with MLPE) under standard test conditions before carrying out stress tests on them. Stress tests [14] involves testing the MLPE units under various test conditions such as high temperature, thermal cycling, damp heat testing, etc. Post-characterization [14] involves characterizing the MLPE units in a similar fashion to Pre-Characterization after stress tests have concluded.

2.1.3 Objective

This thesis mainly focuses on pre-characterizing around 100 MLPE units to evaluate their input and output parameters before performing accelerated stress tests on them. Input parameters such as DC voltage, DC current, DC power, and output parameters such as AC voltage, AC current, AC power, efficiency, CEC efficiency, power factor and harmonics have to be measured under industry required test conditions. Based on this project, the accelerated tests were initiated and they are still ongoing at the time of this write up. This report analyzes and compares only the pre-stress characterization data for five different dominant MLPE manufacturers.

2.2 LITERATURE REVIEW

Stefan Krauter et.al [10] performed outdoor and indoor tests on seven different micro inverters. They compared euro efficiency for all seven micro inverters from seven different manufacturers. Southern California Edison [11] provided various testing methods for utility inverters, which can be employed to test micro inverters. Joe Schwartz provided an outline about different MLPE manufacturers [12] and their products and also generated views from integrator's on advancements, NEC requirements and economics associated with MLPE [13].

TamizhMani [14] deals with the need for development of Qualification Standards for MLPE based on environment stresses. He also discussed about results of performing FMEA on MLPE failures and reliability evaluation of 17 year old AC modules.

C.Chaudhari [20] conducted a limited study to evaluate the effect of stress testing on the performance of micro inverter and DC-DC converters, where one micro inverter and two DC-DC converters from different manufacturers were tested. All 3 units were pre-characterized before undergoing 75 cycles of thermal cycling test. After completion of the thermal cycling stress test, all 3 units were post-characterized. At the end of post-characterization, it was identified that there were degradation in performance of all 3 units. The results were further compared with simplified version of inverter performance model developed by Sandia National Laboratories.

2.3 METHODOLOGY

MLPE pre-characterization was carried out before performing ALT (Accelerated Lifetime Testing) in order to have a reference for comparing the results after post-characterization. Five different manufacturers MLPE – UUT A, UUT B, UUT C, UUT D and UUT E were pre-characterized, where UUT stands for Unit under Test.

2.3.1 UUT A Pre-Characterization Procedure

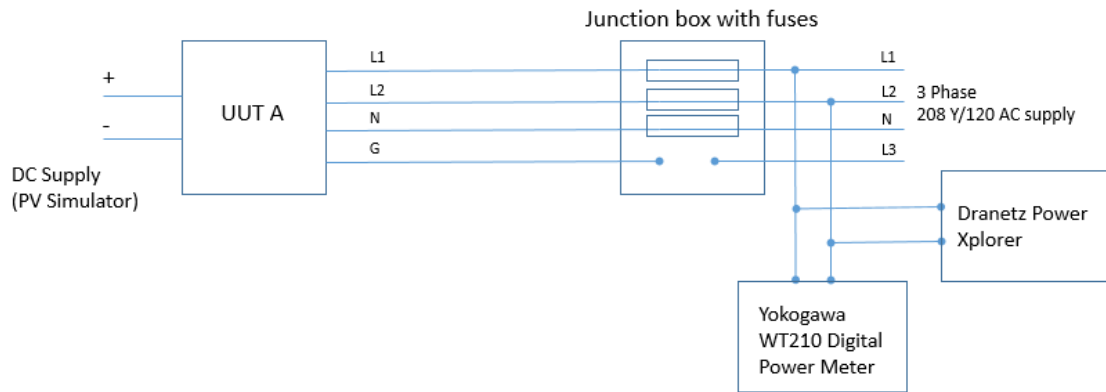


Figure 39: UUT A pre-characterization setup

2.3.1.1 Steps

1. Connections are to be made as shown in fig 39.
2. AC output from the UUT A should be connected to the grid only after DC connections are made.
3. DC input to the UUT A is provided using TerraSAS PV Simulator as shown in fig 39.
4. Irradiance is changed accordingly in the PV simulator to get the power output from the micro inverter at 10%, 20%, 30%, 50%, 75% and 100% load.

5. Photovoltaic curve used in the PV simulator was BP Solar 3230T.
6. Irradiance values are as follows: 107 W/m², 217 W/m², 323 W/m², 539 W/m², 813 W/m² and 1092 W/m² for 10%, 20%, 30%, 50%, 75% and 100% load.
7. Input DC values such as Voltage, Current and Power were logged using data logger available in TerraSAS Solar Array Simulator software and also noted down manually.
8. Output AC values such as Voltage, Current, Power, Power Factor were measured and logged using Yokogawa WT210 Digital Power meter.
9. Harmonic parameters such as Vthd% and Ithd% were measured and noted down for a sample of 5 units using Dranetz Power Xplorer.
10. 27 units were tested using steps 1-8 and 5 units were tested in step 9.

2.3.1.2 Problems Encountered

1. Power recorded at low load% such as 10% and 20% were not reliable as current output from the UUT A was very low with low power factor and high distortion. So, CEC efficiency calculation cannot be reliable.

2.3.2 UUT B Pre-Characterization Procedure

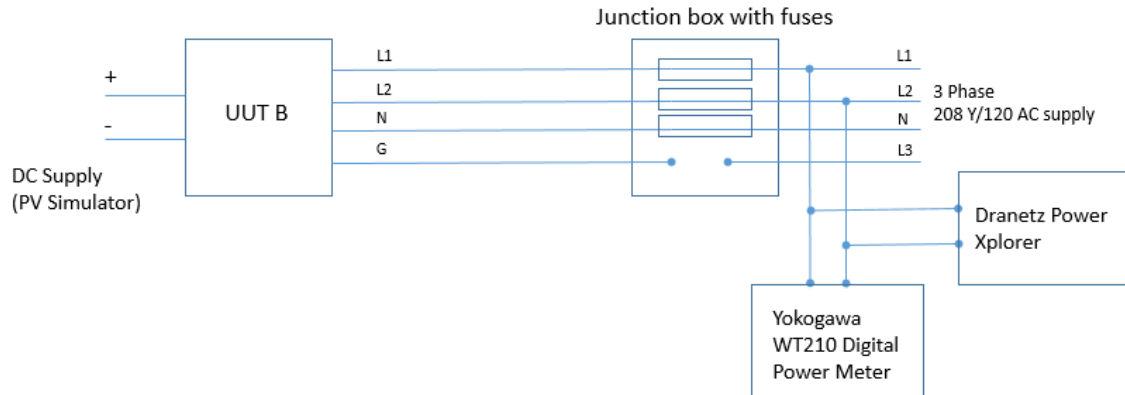


Figure 40: UUT B - pre-characterization setup

2.3.2.1 Steps

1. Connections are to be made as shown in fig 40.
2. AC output from UUT B should be connected to the grid only after DC connections are made.
3. DC input to the UUT B is provided using TerraSAS PV Simulator as shown in fig 40.
4. Irradiance is changed accordingly in the PV simulator to get the power output from the micro inverter at 10%, 20%, 30%, 50%, 75% and 100% load.
5. Photovoltaic curve used in the PV simulator was Sunviva Titan 240 (2009 E).
6. Irradiance values are as follows: 120 W/m², 225 W/m², 330 W/m², 547 W/m², 809 -825 W/m² and 1075 W/m² for 10%, 20%, 30%, 50%, 75% and 100% load.

7. Input DC values such as Voltage, Current and Power were logged using data logger available in TerraSAS Solar Array Simulator software and also noted down manually.
8. Output AC values such as Voltage, Current, Power, Power Factor were measured and logged using Yokogawa WT210 Digital Power meter.
9. Harmonic parameters such as $V_{thd}\%$ and $I_{thd}\%$ were measured and noted down for a sample of 5 units using Dranetz Power Xplorer.
10. 27 units were tested using steps 1-8 and 5 units were tested in step 9.

2.3.2.2 Problems Encountered

1. Power recorded at low load% such as 10% and 20% were not reliable as current output from UUT B was very low with low power factor and high distortion. So, CEC efficiency calculation cannot be reliable.

2.3.3 UUT C Pre-Characterization Procedure

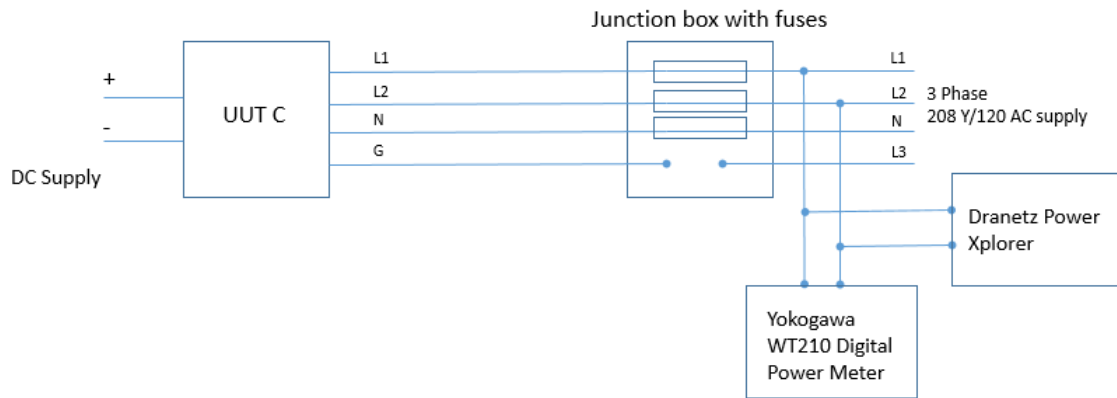


Figure 41: UUT C - pre-characterization setup

2.3.3.1 Steps

1. Connections are to be made as shown in fig 41.
2. AC output from UUT C should be connected to the grid only after DC connections are made.
3. DC input to UUT C is provided using DC Power supply as shown in fig.
4. Input DC values such as Voltage, Current were noted down manually from the DC power supply.
5. Output AC values such as Voltage, Current, Power, Power Factor were measured and logged using Yokogawa WT210 Digital Power meter.
6. Harmonic parameters such as $V_{thd}\%$ and $I_{thd}\%$ were measured and noted down for a sample of 5 units using Dranetz Power Xplorer.
7. 28 units were tested using steps 1-8 and 5 units were tested in step 9.

2.3.3.2 Problems Encountered

1. UUT C micro inverters stopped working with PV Simulator, though initially we were able to record output from the micro inverter using input from the PV simulator for 4 units. Reason for the problem is unknown as different PV curves from the PV Simulator were tried leading to no output from the micro inverter.
2. DC Power supply was tried to lower the current value to find power output at 10%, 20%, 30%, 50% and 75% load conditions, which resulted in a severe fluctuation of AC output from the micro inverter as well as DC input from the power supply. So, it was decided to record only one power value (maximum). As a result, CEC efficiency was not calculated.

3. Though the rated power output from the micro inverter was greater than 220W, we were only able to achieve a maximum of 220 W with the help of DC power supply.

2.3.4 UUT D Pre-Characterization Procedure

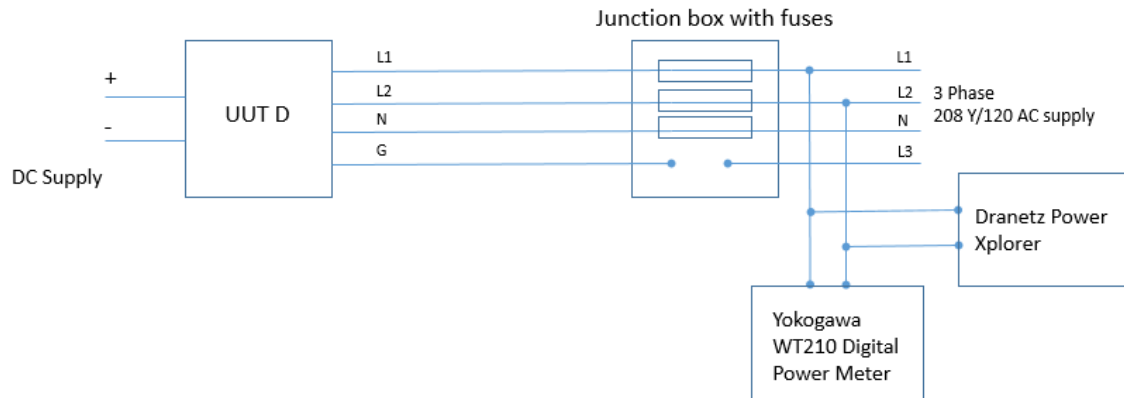


Figure 42: UUT D - pre-characterization setup

2.3.4.1 Steps

1. Connections are to be made as shown in fig 42.
2. AC output from UUT D should be connected to the grid only after DC connections are made.
3. DC input to the micro inverter is provided using DC Power supply as shown in fig 42.
4. Input DC values such as Voltage, Current were noted down manually from the DC power supply.
5. Output AC values such as Voltage, Current, Power, Power Factor were measured and logged using Yokogawa WT210 Digital Power meter.

6. Harmonic parameters such as $V_{thd}\%$ and $I_{thd}\%$ were measured and noted down for a sample of 5 units using Dranetz Power Xplorer.
7. 8 units were tested using steps 1-8 and 5 units were tested in step 9.

2.3.4.2 Problems Encountered

1. UUT D micro inverters didn't work with PV Simulator. Reason for the problem is unknown as different PV curves from the PV Simulator were tried leading to no output from the micro inverter, although it is suspected to be MPPT tracking problems.
2. DC Power supply was tried to lower the current value to find power output at 10%, 20%, 30%, 50% and 75% load conditions, which resulted in no AC output from the micro inverter as the micro inverter stopped drawing power from PV Simulator. So, it was decided to record only one power value (maximum). As a result, CEC efficiency was not calculated.

2.3.5 UUT E Pre-Characterization Procedure

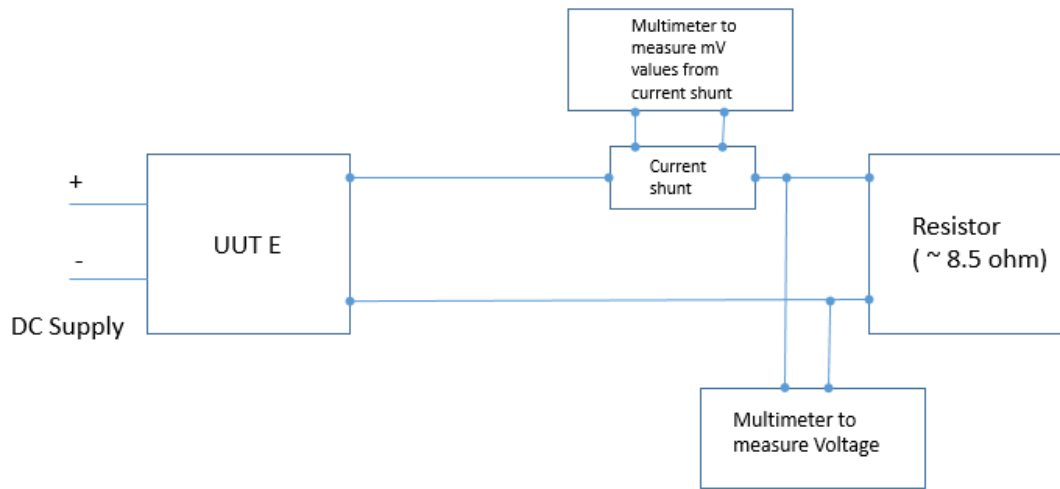


Figure 43: UUT E - pre-characterization setup

2.3.5.1 Steps

1. Connections are to be made as shown in fig 43.
2. UUT E requires DC power supply as input as shown in fig 43.
3. Output of UUT E is connected to a resistor (~8.5 ohms) acting as a load to dissipate power from the DC-DC optimizer. A resistor of around 8.5 ohms was selected in order to obtain around maximum power output from the DC-DC optimizer.
4. Calibrated current shunt was connected in between the resistor load and DC output from the DC-DC optimizer to enable accurate measurement of DC current. mV values recorded using a calibrated multi meter from the current shunt were

later processed with the resistance of the current shunt around 10.204 ohms to obtain the DC current values.

5. Another Multi meter was used to obtain the DC voltage output from the DC-DC optimizer across the resistor load.
6. DC Power Output was calculated from the values obtained from steps 4 and 5.
7. The efficiency of the DC-DC optimizer was calculated later with values obtained from steps 2, 4 and 5.
8. 27 units were tested using the steps above.

2.3.5.2 Problems Encountered

1. Fan was required to cool down the resistor load.

2.4 RESULTS AND DISCUSSION

Various parameters were obtained from 5 different MLPE such as Efficiency, CEC Efficiency, Harmonics (Vthd% and Ithd%) and Power factor.

2.4.1 Efficiency Comparison

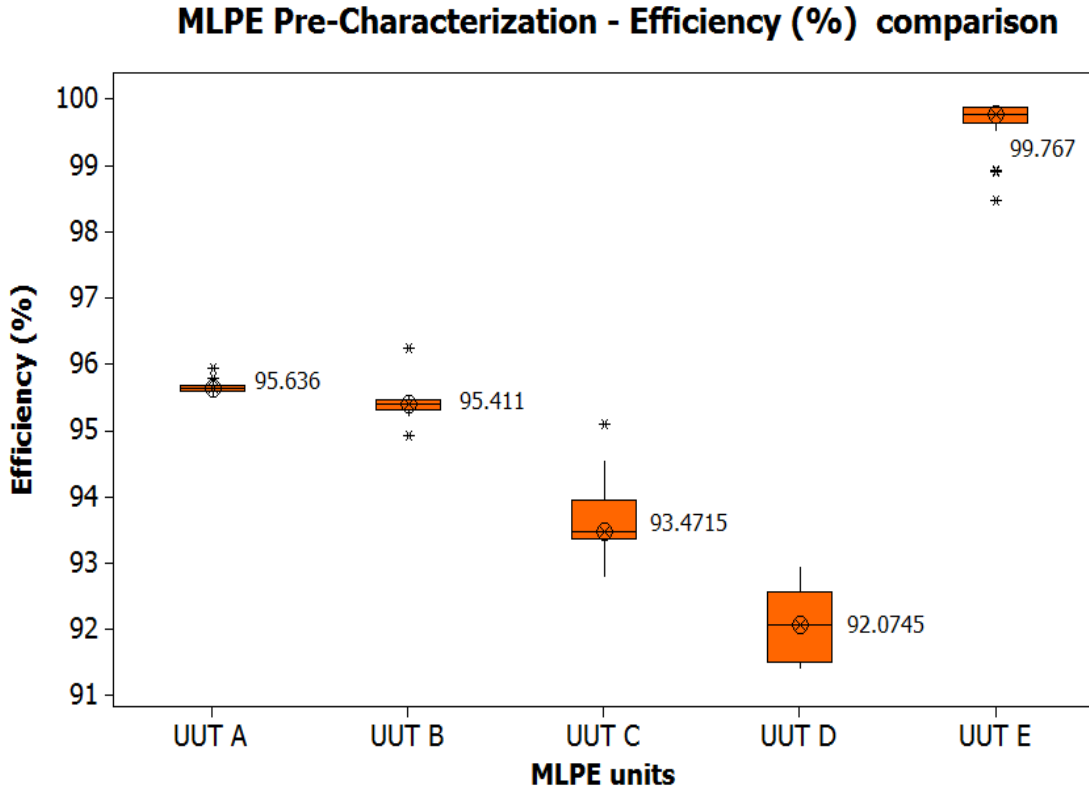


Figure 44: MLPE efficiency comparison

UUT E which is a DC-DC optimizer had highest median efficiency of 99.767%. Among the micro inverters, UUT A and UUT B had nearly the same median efficiency of 95%, followed by UUT C (93.47%) and UUT D (92%). It is to be noted that UUT C and UUT D were not operating at their maximum rated power due to MPPT tracking issues.

Average measured efficiency (%) of all MLPE units is provided as table 33 below. It is to be noted that only 8 samples were tested for UUT D.

Table 33: MLPE efficiency comparison

Model	Rated or Peak Inverter Efficiency (%)	Average Measured Efficiency (%)	Number of Samples
UUT A	~ 96	95.6	27
UUT B	~ 96	95.4	27
UUT C	~ 96	93.6	28
UUT D	~ 96	92	8
UUT E	NA	99.6	27

27 samples were tested from UUT A, UUT B and UUT E, 28 samples were tested from UUT C and 8 samples were tested from UUT D as shown in table 33. Average measured efficiency ranges from 92% to 95.6% for micro inverters depending on the manufacturers and 99.6% for UUT E (DC-DC optimizer).

2.4.2 Harmonics – Vthd (%) Comparison

Total Harmonic distortion with respect to voltage were measured using Power Quality Analyzer. Box plot of Vthd (%) is provided below.

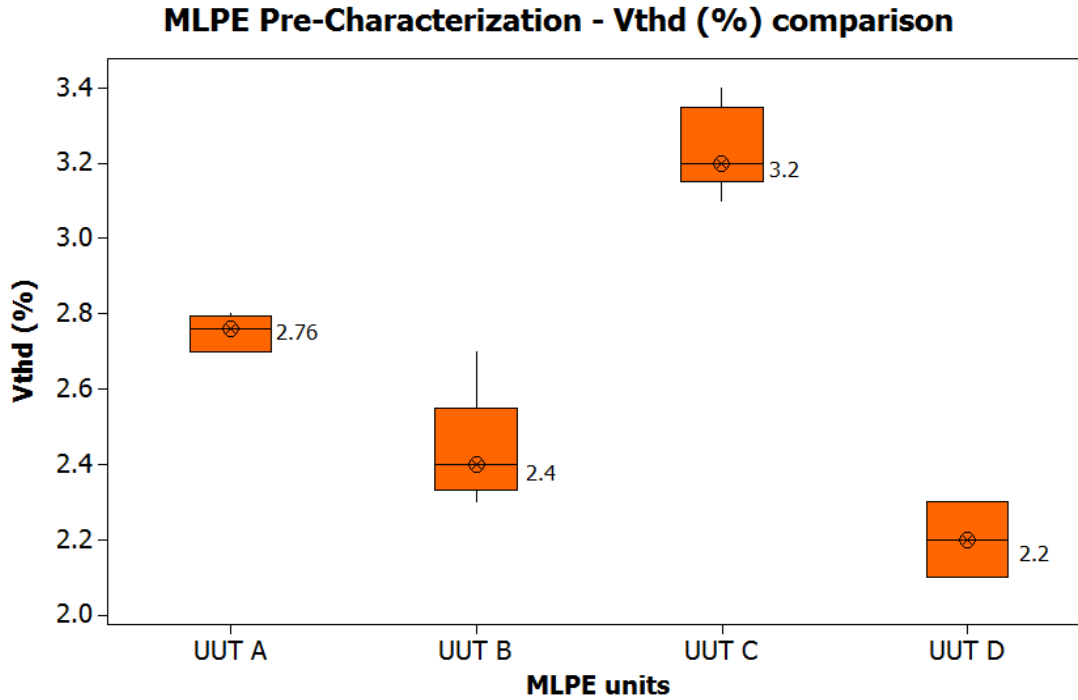


Figure 45: MLPE Vthd (%) comparison

It is to be noted for UUT E, it is not possible to measure harmonics as it is a DC-DC optimizer.

UUT C had higher median Vthd(%) of 3.2%, followed by UUT A (2.7%), UUT B (2.4%) and UUT D (2.2%). All Vthd (%) are well below the permissible limit of 5% for Vthd (%) as per IEEE 519 standards.

Average Vthd (%) for all units are provided as table 34 below.

Table 34: MLPE Vthd(%) comparison

Model	Rated	Measured (Average)	Number of samples
	Vthd%	Vthd%	
UUT A	< 5	2.75	5
UUT B	< 5	2.432	5
UUT C	< 5	3.24	5
UUT D	< 5	2.2	4
UUT E	NA	NA	NA

5 samples were tested from UUT A, UUT B and UUT C and 4 samples were tested from UUT D as shown in table 33. Average Vthd (%) ranges from 2.2 % to 3.24% for micro inverters depending on the manufacturers.

2.4.3 Harmonics – Ithd (%) Comparison

Total Harmonic distortion with respect to current were measured using Power Quality Analyzer. Box plot of Ithd (%) is provided below.

MLPE Pre-Characterization - Ithd (%) comparison

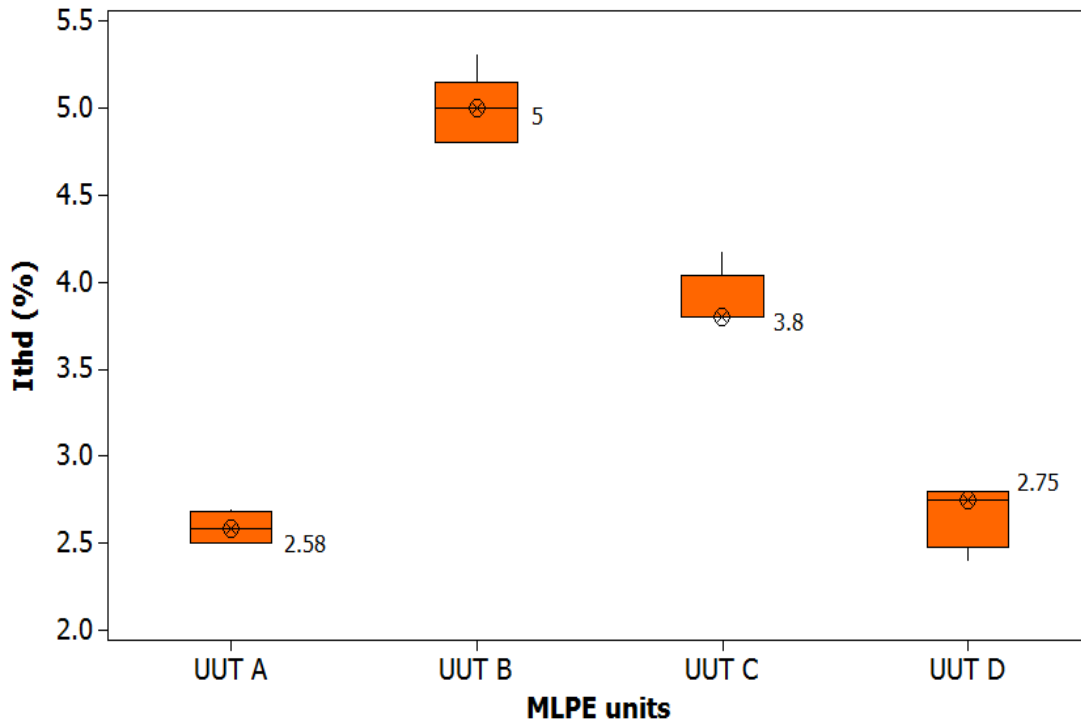


Figure 46: MLPE Ithd(%) comparison

For UUT E, Ithd (%) was not measured for the same reason outlined for Vthd (%). UUT B showed higher median Ithd (%) of 5%, followed by UUT C (3.8%), UUT D (2.75%) and UUT A (2.5%). All units were functioning well below within the IEEE 519 permissible limit of 5% Ithd with only UUT B showing signs of exceeding the permissible values when connected to the AC grid. Reason for UUT B showing higher Ithd (%) is unknown, but it is suspected the AC grid to which the units were connected may have caused the problems.

Average Ithd (%) for each unit is provided as table 35 below.

Table 35: MLPE Ithd(%) comparison

Model	Rated	Measured (Average)	Number of samples
	Ithd%	Ithd%	
UUT A	< 5	2.59	5
UUT B	< 5	4.98	5
UUT C	< 5	3.894	5
UUT D	< 5	2.675	4
UUT E	NA	NA	NA

5 samples were tested from UUT A, UUT B and UUT C and 4 samples were tested from UUT D as shown in table 34. Average Vthd (%) ranges from 2.59 % to 4.98% for micro inverters depending on the manufacturers.

2.4.4 CEC Efficiency Comparison

CEC (California Energy Commission) efficiency [15] was calculated by measuring efficiency at 6 different power levels based on 10%, 20%, 30%, 50%, 75% and 100% of rated AC output power from the micro inverters.

CEC efficiency [15] is a weighted average calculated as per table 36 provided below:

Table 36: CEC weightage table

Micro Inverter AC power level (%)	Weightage
10	0.04
20	0.05
30	0.12
50	0.21
75	0.53
100	0.05

CEC efficiency was calculated for only UUT A and UUT B. UUT C and UUT D had issues with responding to the PV array Simulator as well as DC power supply at low voltage and current (i.e. 10%, 20%, 30%, 50% and 75%). So CEC efficiency was not calculated for UUT C and UUT D.

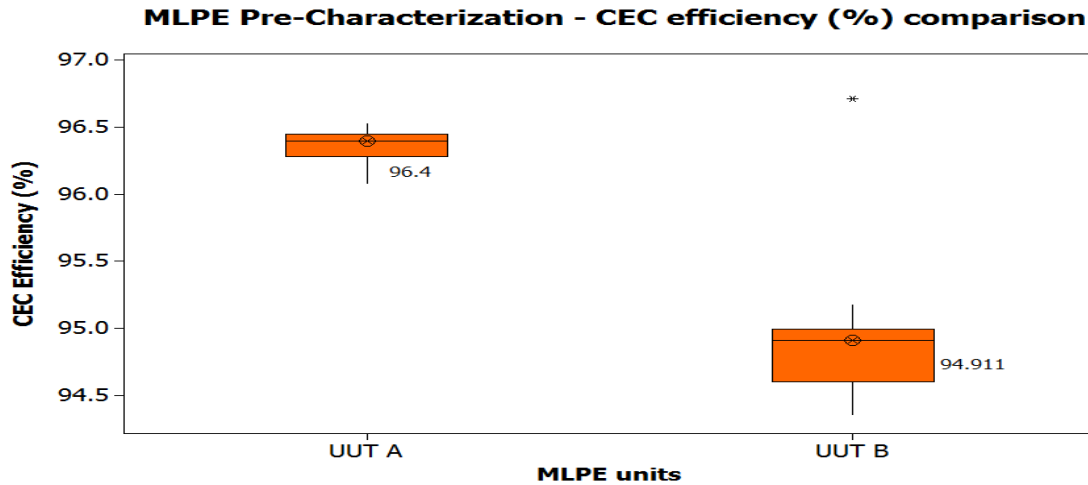


Figure 47: MLPE CEC efficiency comparison

It is evident from the fig 47 that the median CEC efficiency of UUT A was around 96.4%, whereas median CEC efficiency of UUT B was around 94.9%.

Average CEC efficiency values for all UUT's are provided as table 37 below.

Table 37: MLPE CEC efficiency comparison

Model	Rated CEC efficiency (%)	Average Measured CEC efficiency (%)	Number of Samples
UUT A	~ 96	96	27
UUT B	~ 96	94.9	27
UUT C	~ 96	NA	NA
UUT D	~ 96	NA	NA
UUT E	NA	NA	NA

27 samples were tested from UUT A and UUT B as shown in table 37. Average CEC efficiency (%) ranges from 94.9% to 96% for micro inverters depending on the manufacturers. UUT C and UUT D had issues with MPPT tracking under low power conditions, which resulted in not being able to measure CEC efficiency.

2.4.5 Power Factor Comparison

Power factor was measured for all micro-inverters using Power Quality Analyzer.

MLPE Pre-Characterization - Power Factor comparison

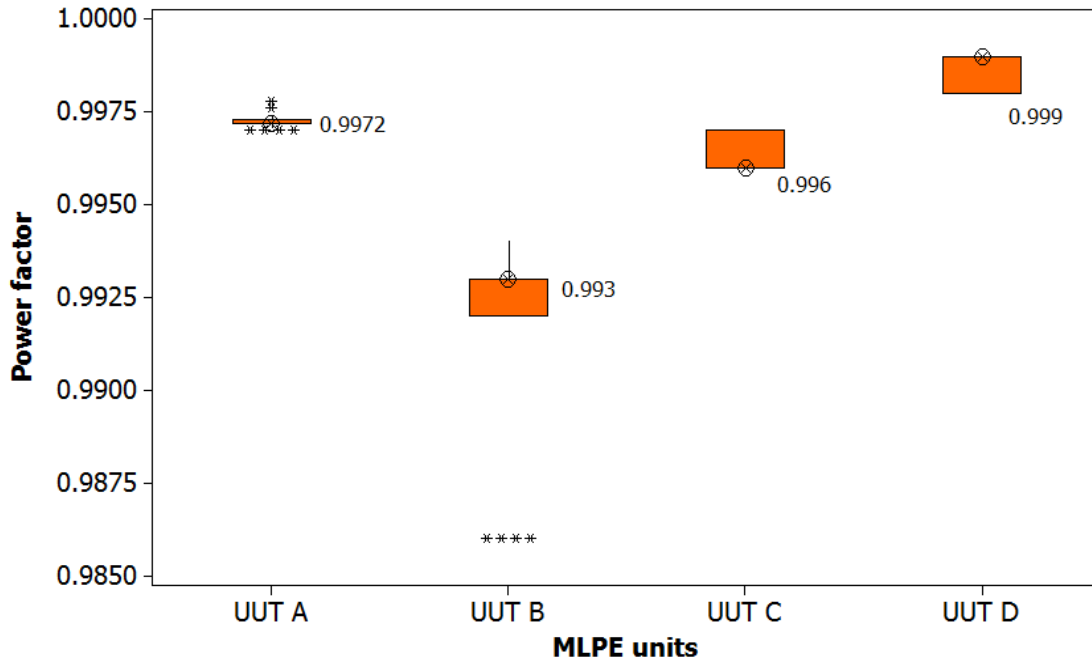


Figure 48: MLPE power factor comparison

From fig 48, it is evident that all micro-inverters had no issues with the quality of power at maximum rated power or power nearer to the maximum rated value. All UUT had median power factor of around 0.99 which validates the quality of power at rated maximum AC power output.

The average power factor of different UUT's is provided as table 38 below.

Table 38: MLPE power factor comparison

Model	Rated Power factor	Average Measured Power factor	Number of samples
UUT A	> 0.95	0.997	27
UUT B	> 0.95	0.992	27
UUT C	> 0.95	0.996	28
UUT D	> 0.95	0.999	8
UUT E	NA	NA	NA

27 samples were tested from UUT A, UUT B and UUT E, 28 samples were tested from UUT C and 8 samples were tested from UUT D as shown in table 38. Average measured power factor ranges from 0.992 to 0.997 for micro inverters depending on the manufacturers. It is to be noted UUT E was a DC-DC optimizer for which power factor cannot be measured.

2.5 CONCLUSION

Thus Pre-characterization was successfully performed for about 100 MLPE units from 5 different manufacturers. Accelerated Lifetime testing (ALT) has been started and it's a work in progress, so results from ALT is not provided in this report. ALT testing includes Damp Heat testing, Static Temperature testing at 3 different temperatures and Thermal Cycling testing. After completion of stress tests, Post-characterization will be performed using the same procedure outlined in Pre-Characterization. The key findings in Pre-characterizations are presented below:

- Measured efficiencies have been found to be closely matching with the manufacturer rated efficiencies for all the tested 117 MLPE units from 5 different manufacturers.
- Measured total harmonic distortion (THD) with respect to voltage and current have been determined to meet or exceed the manufacturer rated THDs for all the microinverters.
- CEC efficiencies were determined for only UUT A and UUT B and they were found to be closely matching with manufacturer rated CEC efficiencies. UUT C and UUT D had issues with responding to the PV array simulator as well as DC power supply at low voltage and current (i.e. 10%, 20%, 30%, 50% and 75%). So CEC efficiency was not calculated for UUT C and UUT D
- Measured power factors have been found to be meeting or exceeding the manufacturer rated power factors for all the microinvertes.

All these pre-characterization data will be used in the time-to-failure accelerated tests which are currently being conducted.

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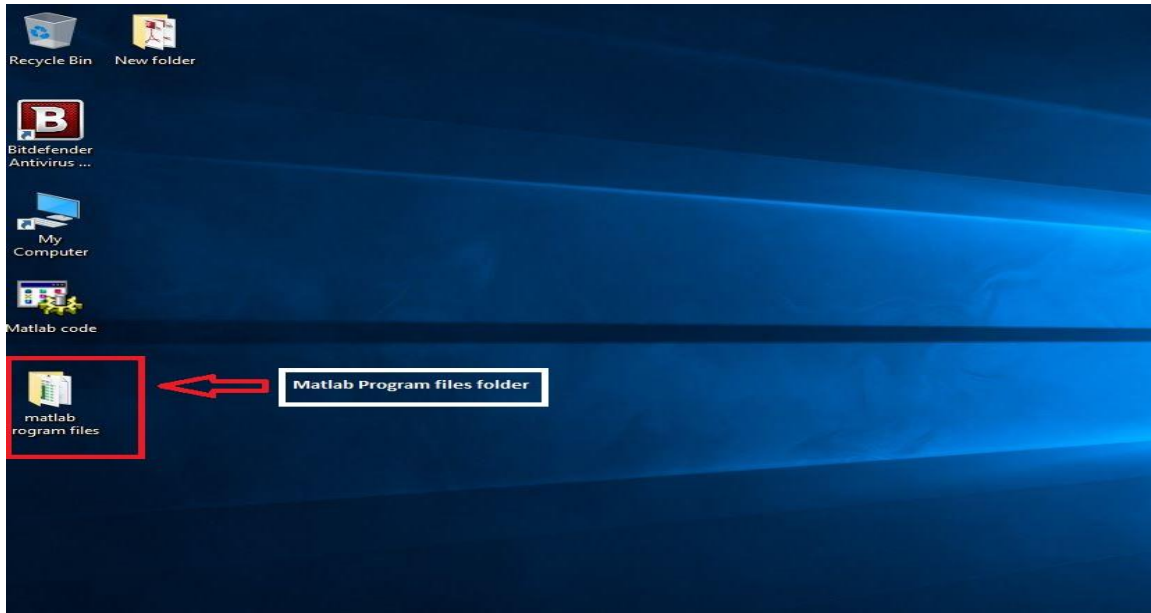
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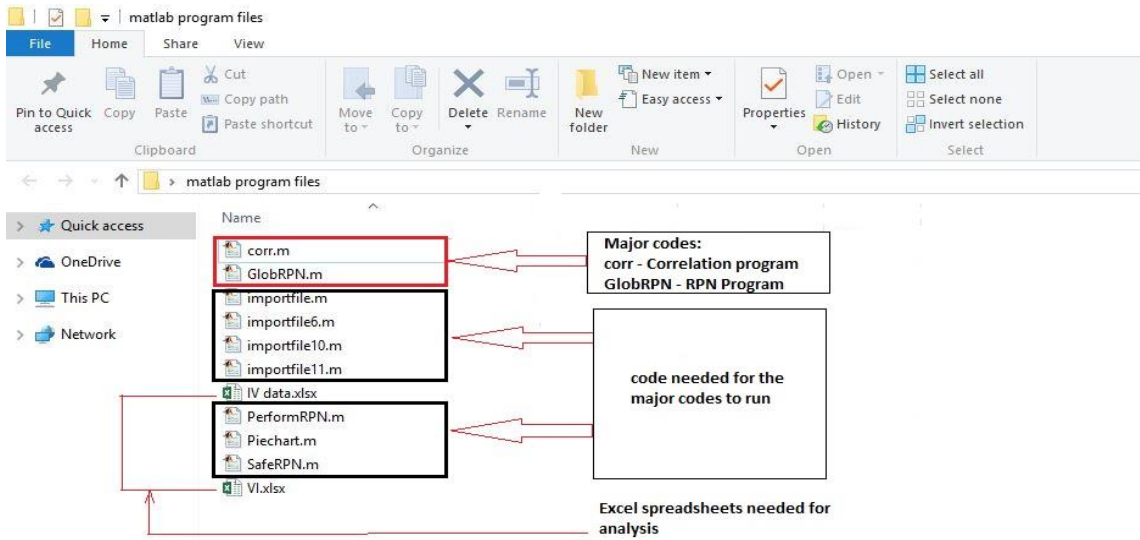
APPENDIX A

STANDARD OPERATING PROCEDURE FOR MATLAB PROGRAM

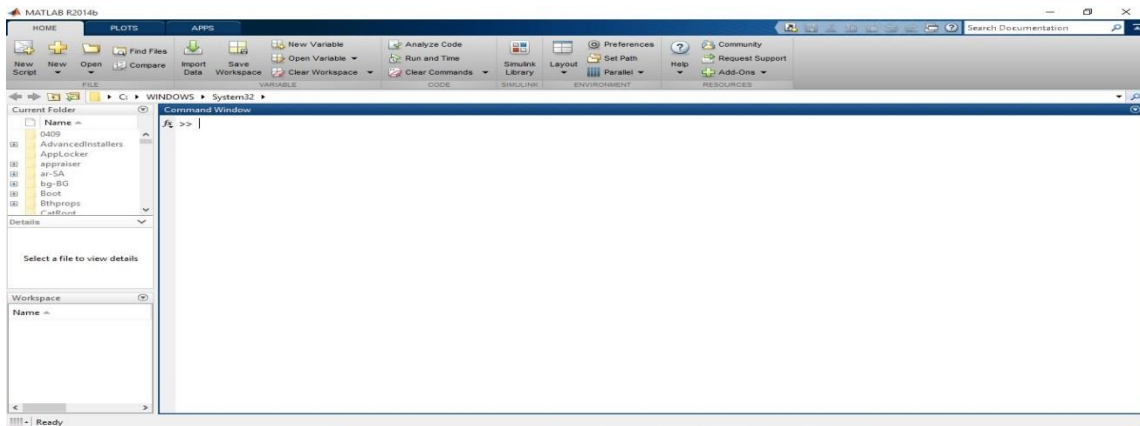
Step 1: Create a folder for matlab programs to be stored in desktop or wherever you can easily locate as shown in fig below.



Step 2: Following Matlab code files, as shown in fig below, should be inside the folder created for storing the matlab programs. Major codes that are needed are corr.m and GlobRPN.m as shown in fig below. Other codes needed for the major codes to run are also highlighted. Excel spreadsheets IV data.xlsx and VI.xlsx are to be changed every time different power plant data is to be analyzed, but the naming of those spreadsheets should be maintained as IV data.xlsx and VI.xlsx. If there is any change in the naming, Program won't work.



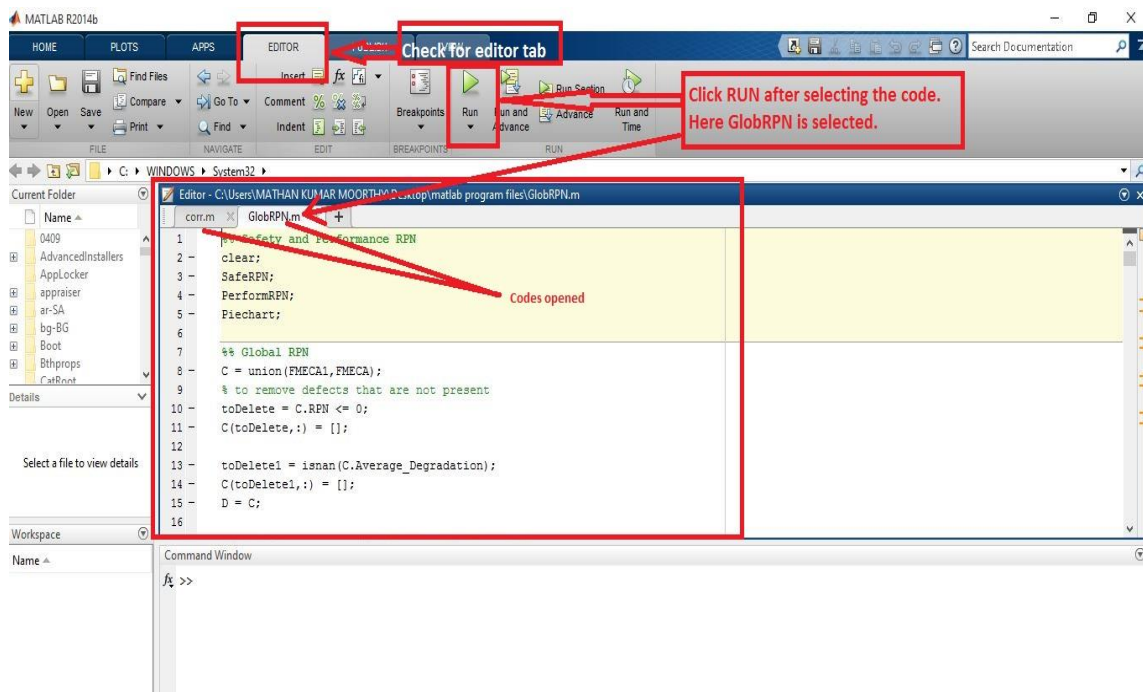
Step 3: MATLAB window will be as shown below, when opened. There will be no editor tab until you open a code as it can be found that there are only HOME, PLOTS and APPS tab available when you open MATLAB initially.



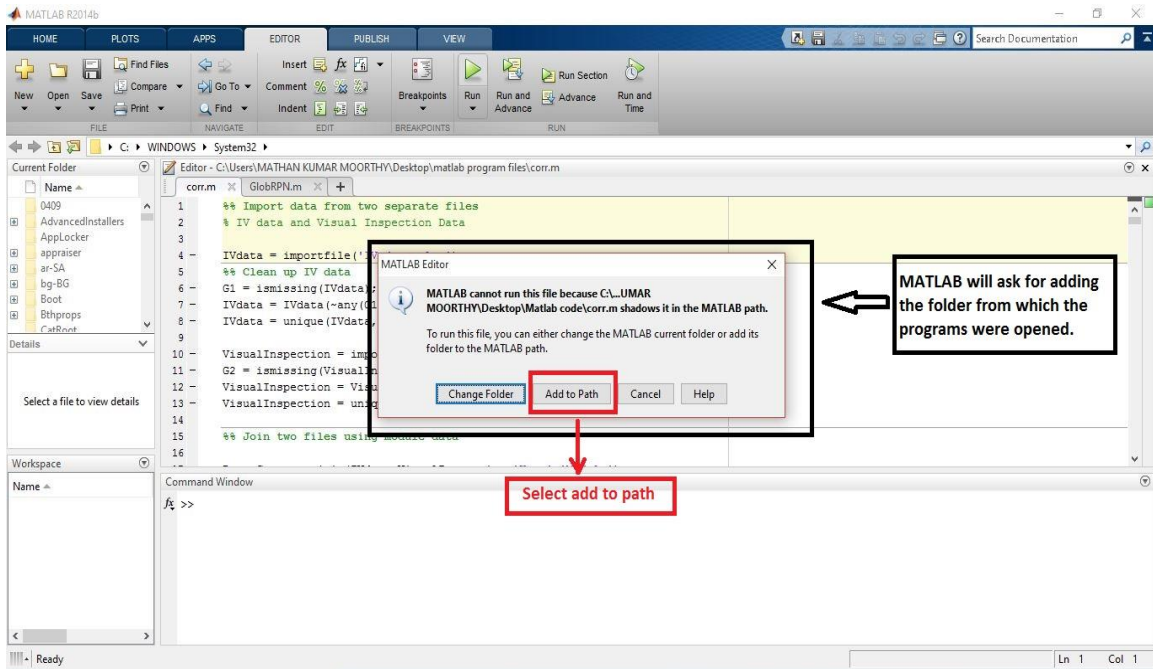
Step 4: Open codes corr.m and GlobRPN.m from the folder from step 1 as shown in fig below.



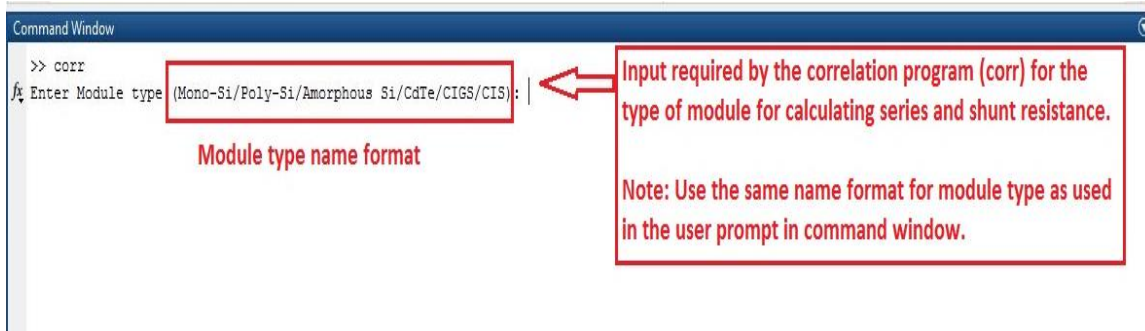
Step 5: After opening the codes corr.m and GlobRPN.m files from the folder from step 1, MATLAB window will be similar as shown in fig below. It can be noticed that EDITOR tab is now available along with other tabs. Once the EDITOR tab is available, RUN button will be visible as shown in fig below. It should be used to run the program required either corr.m or GlobRPN.m to generate correlation plots and RPN plots respectively.



Step 6: When code corr.m is run initially, MATLAB will ask for adding the folder to its path so that it can recognize the code. Click **Add to path** to add the folder to MATLAB path. *Note: Skip this step if path has been already added.*



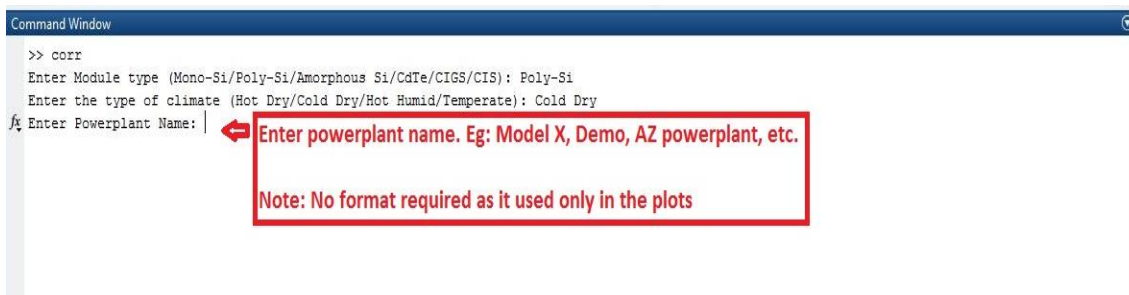
Step 7: When code corr.m is run, user prompt will appear asking to enter type of module in the PV power plant. Eg: Mono-Si, Poly-Si, etc. User should make sure to use the same naming format that the user prompt shows as shown in fig below, as it is required for calculating series and shunt resistance for the PV modules in that particular PV power plant. *Note: Program will exit if different naming formats are used.*



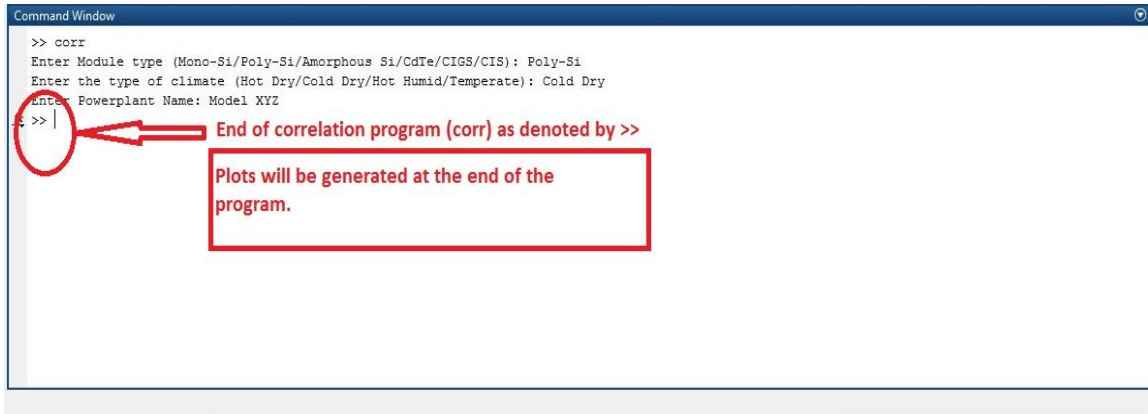
Step 8: After entering the module type, click ENTER in the keyboard. Next, prompt to enter type of climate will appear. User can enter the type of climate as Hot Dry, Cold Dry, etc. *Note: No Naming format is required here.*



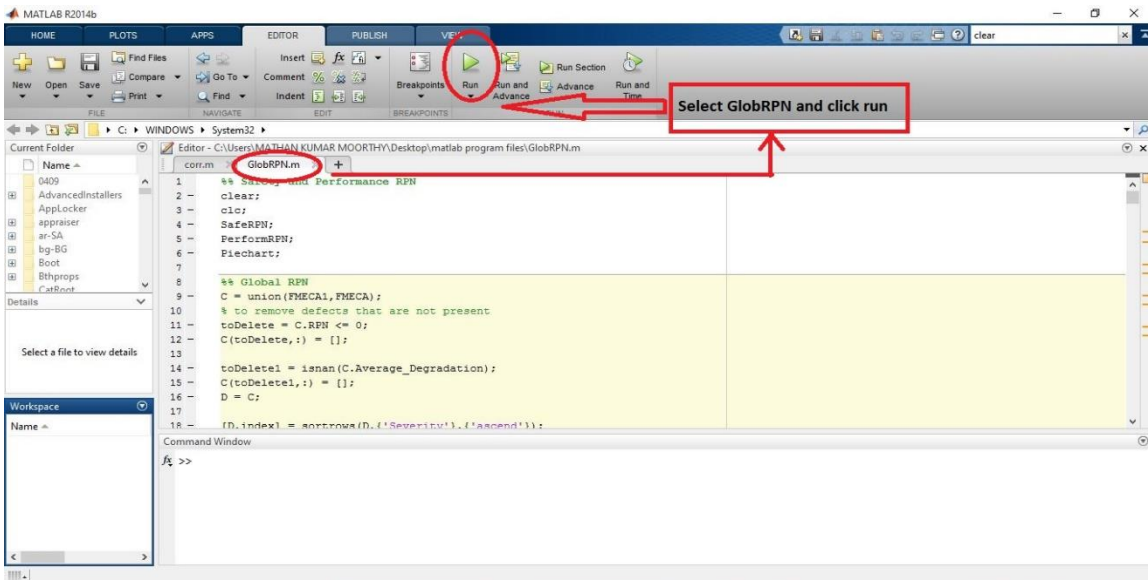
Step 9: After entering the type of climate, click ENTER in keyboard. Next, prompt to enter power plant name will appear as shown in fig below. User can enter the name of power plant in any way needed. Eg: Model XYZ, Demo, Arizona PV Power Plant, etc. *Note: No Naming format is required here.*



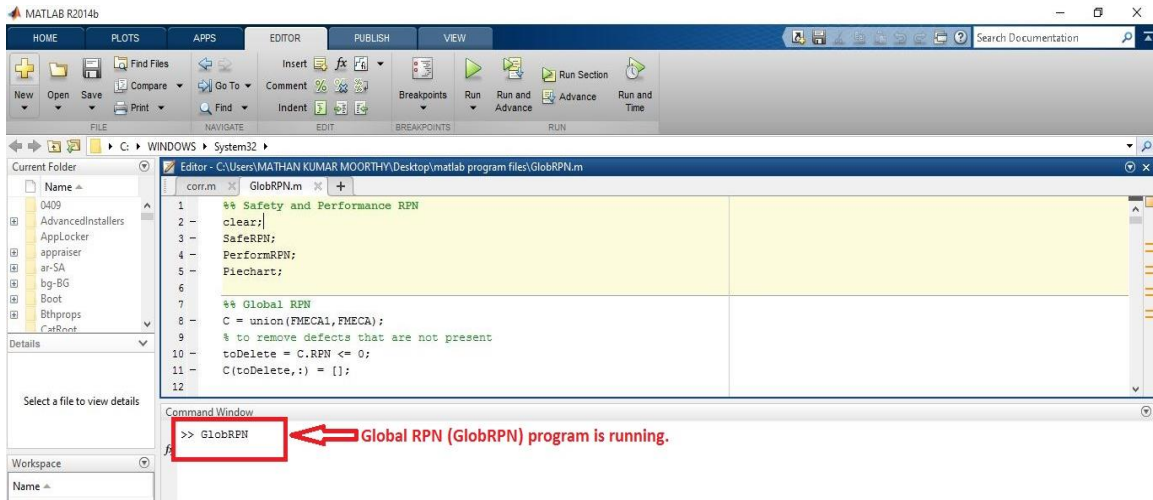
Step 10: After entering power plant name, click ENTER in keyboard. Correlation plots will be generated at the end of the running of corr.m code denoted by >> as shown in fig below.



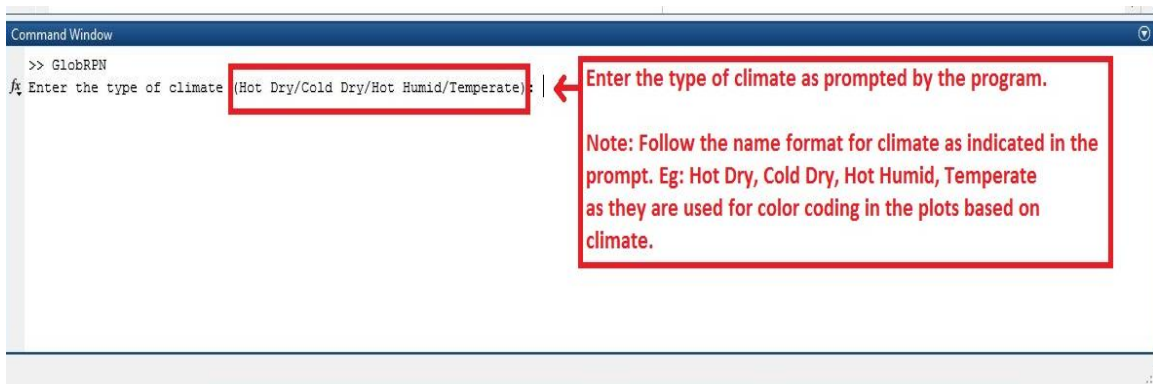
Step 11: After getting output plots from run corr.m, select GlobRPN.m tab and click RUN as shown in fig below. Note: It is recommended to clear the workspace before running the program.



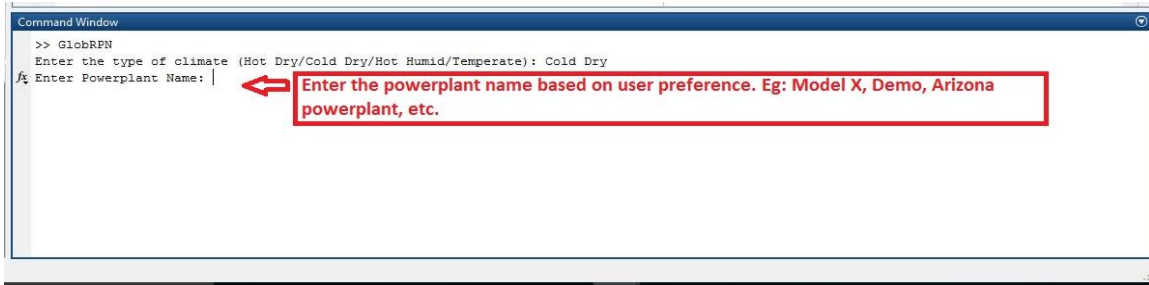
Step 12: Start of the program GlobRPN.m is indicated by >> as shown in fig below.



Step 13: Once the GlobRPN.m program is started, user prompt for entering the type of climate will pop up in the command window, as shown in fig below. *Note: It is to be noted that naming format for the climate should be similar to that shown in the user prompt. Eg: Use Hot Dry to denote hot dry conditions as indicated in the prompt and nothing like hot dry or hotdry or hot-dry, etc., as it will cause the program to exit.*



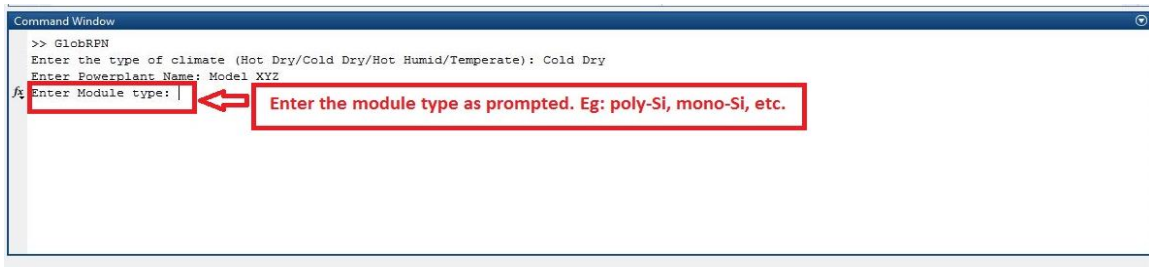
Step 14: After entering the type of climate, click ENTER in the keyboard. Prompt for entering power plant name will appear, as shown in fig below. *Note: User can enter any name without any restriction on naming format.*



```
Command Window
>> GlobRPN
Enter the type of climate (Hot Dry/Cold Dry/Hot Humid/Temperate): Cold Dry
Enter Powerplant Name: |
```

Enter the powerplant name based on user preference. Eg: Model X, Demo, Arizona powerplant, etc.

Step 15: After entering power plant name, click ENTER in keyboard. Prompt to enter module type will appear. User can enter the type of module. Eg; Mono-Si, mono Si, mono-Si, etc. *Note: User can follow any naming format.*



```
Command Window
>> GlobRPN
Enter the type of climate (Hot Dry/Cold Dry/Hot Humid/Temperate): Cold Dry
Enter Powerplant Name: Model XYZ
Enter Module type: |
```

Enter the module type as prompted. Eg: poly-Si, mono-Si, etc.

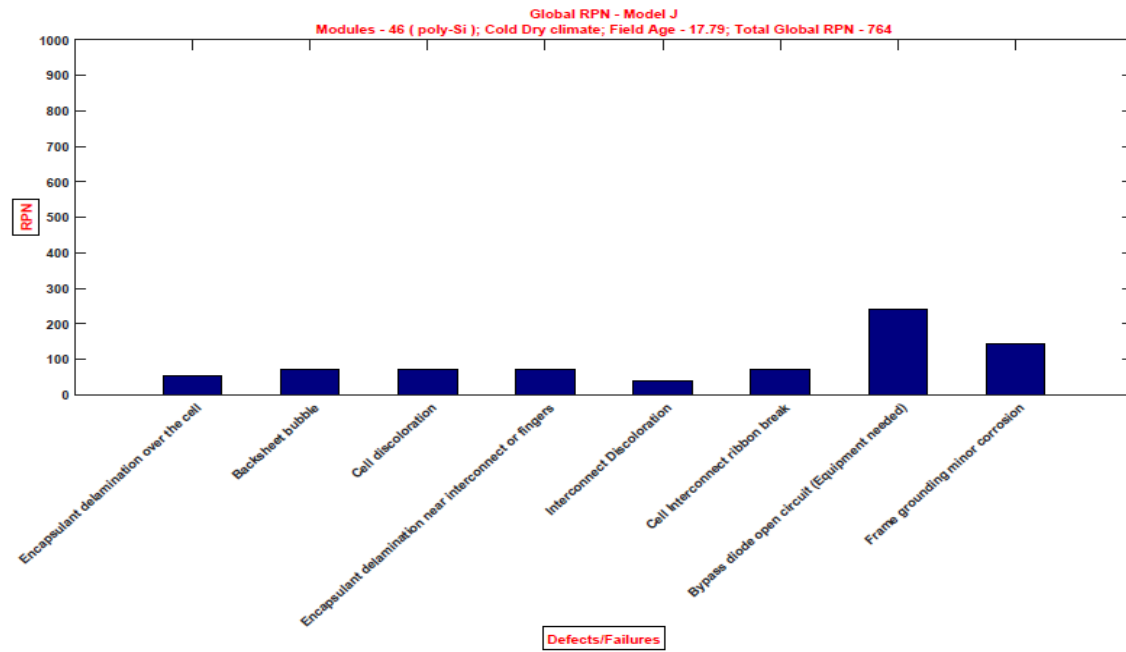
Step 16: After entering module type, click ENTER in keyboard. It will generate plots concerned with RPN and program will end denoted by >> as shown in fig below.

APPENDIX B

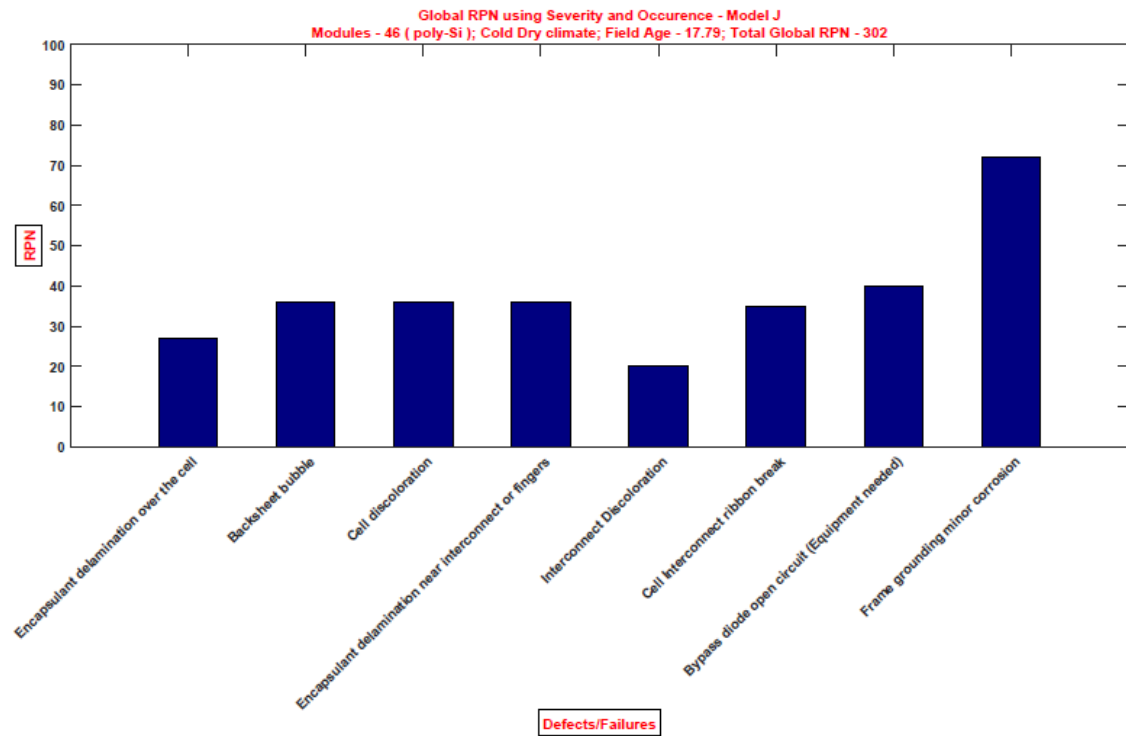
PLOTS FROM MODEL J

RPN results

Global RPN plot

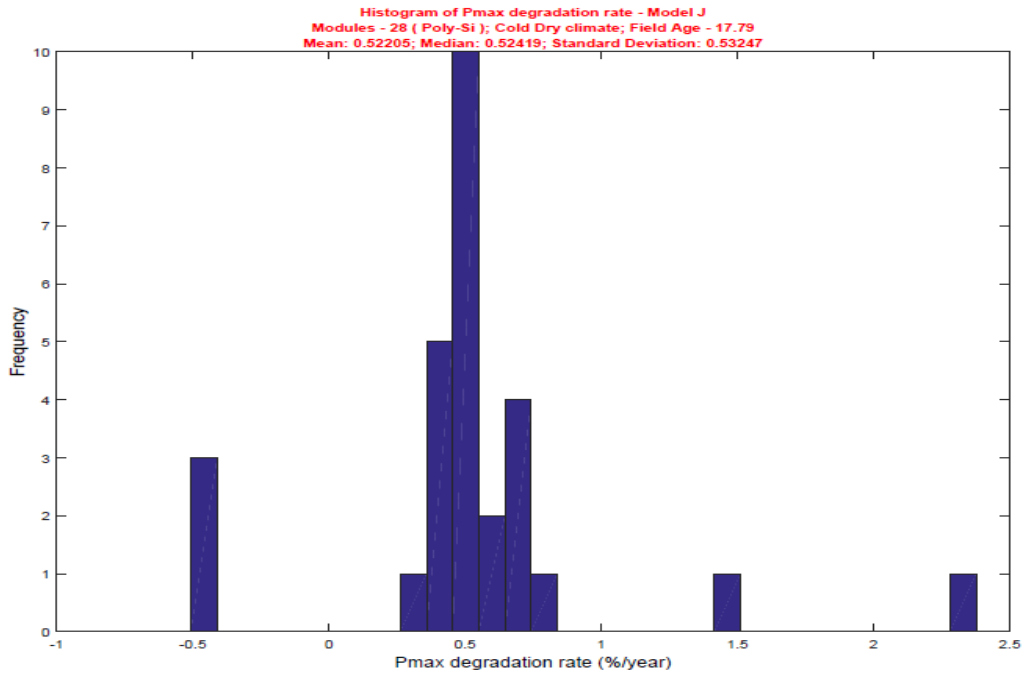


Global RPN plot using severity and Occurrence

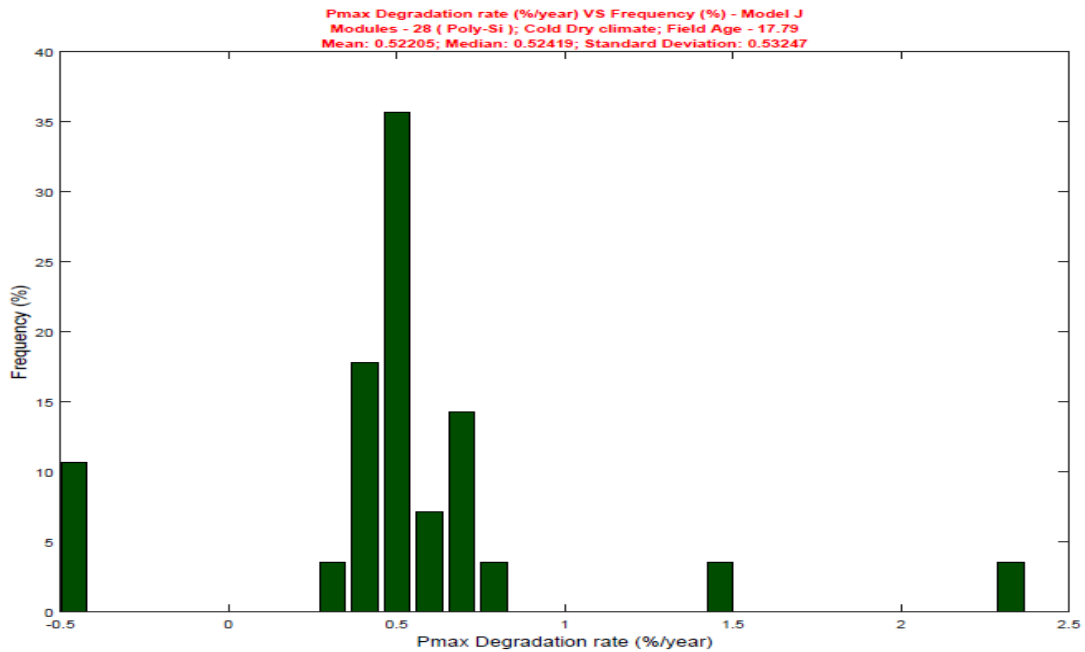


Correlation results

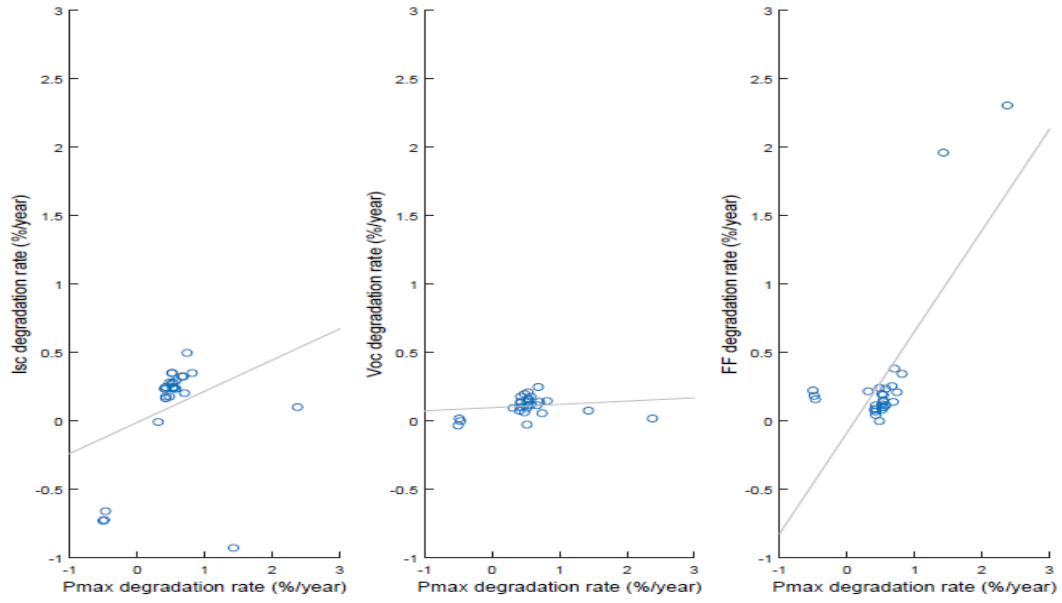
Histogram of Pmax degradation rate (%/year)



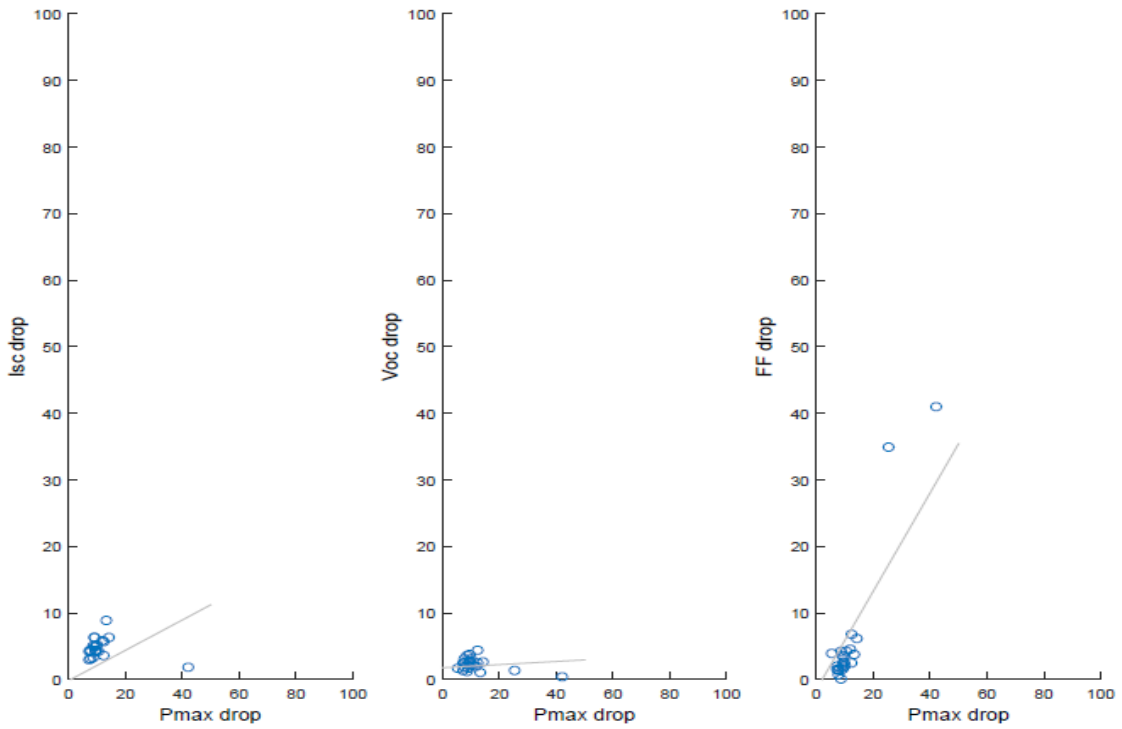
Histogram of Pmax degradation rate (%/year) Vs Frequency (%)



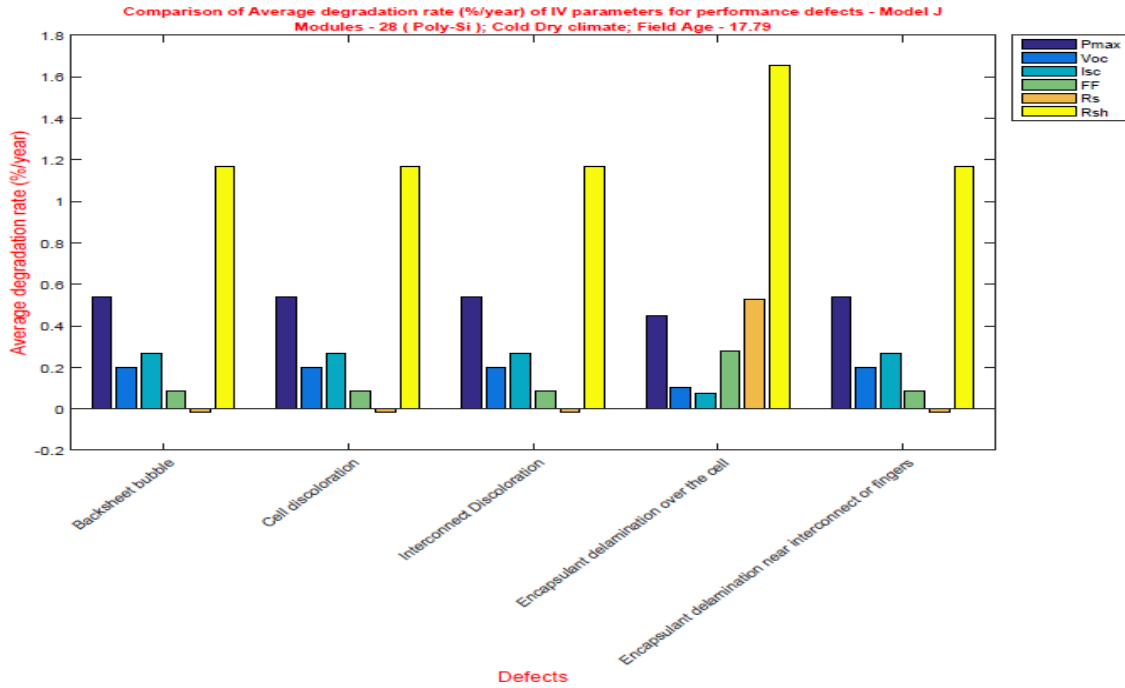
Linear relation plot 1



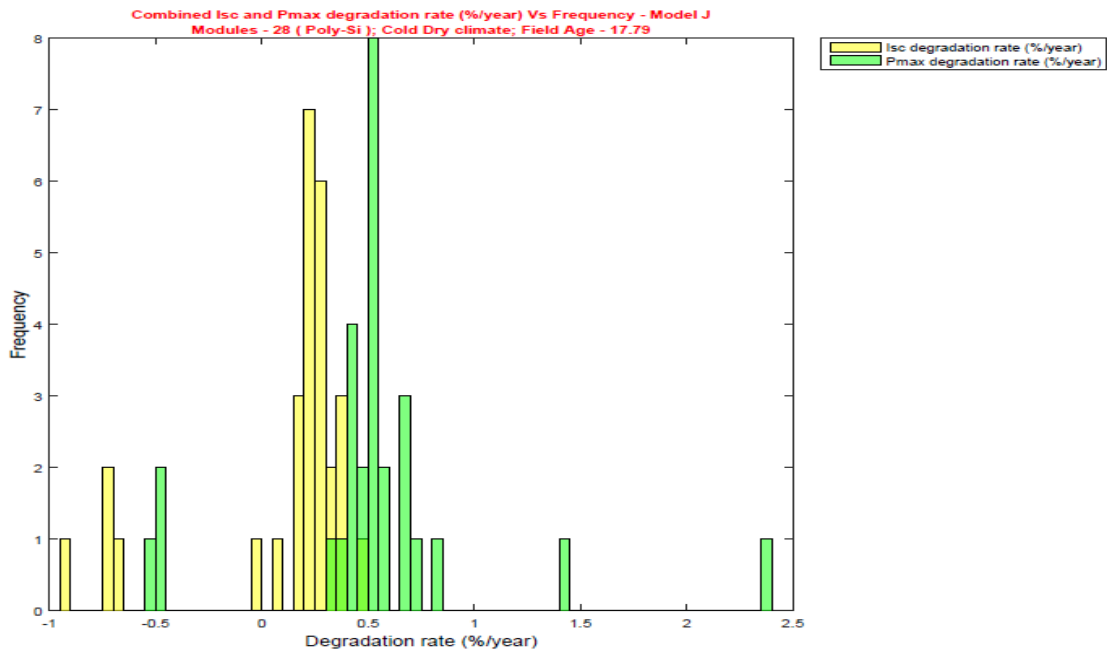
Linear relation plot 2



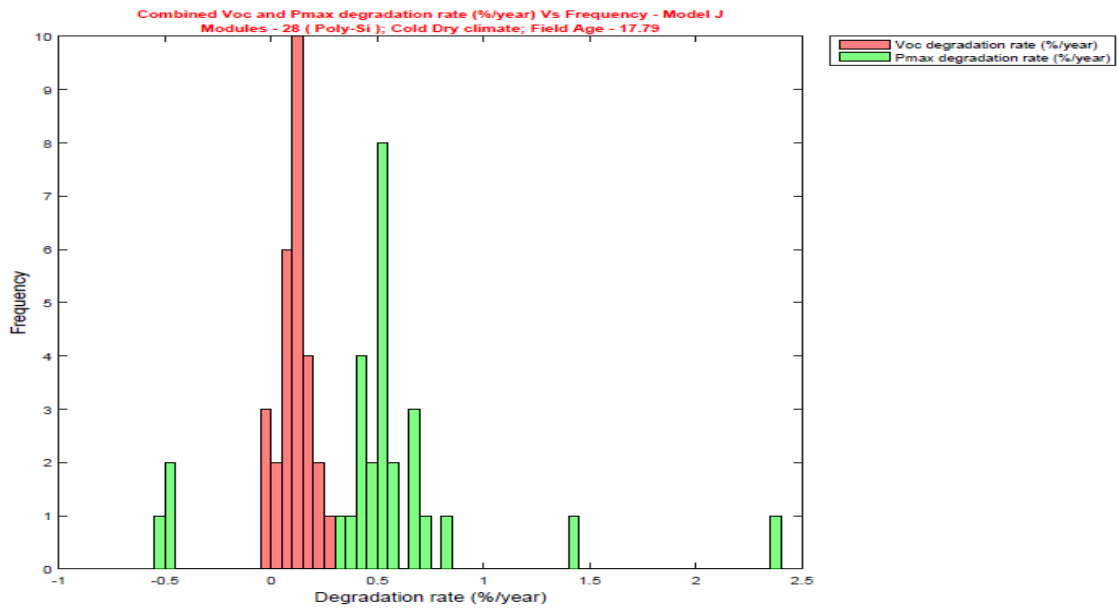
Comparison of average degradation rate (%/year) of IV parameters



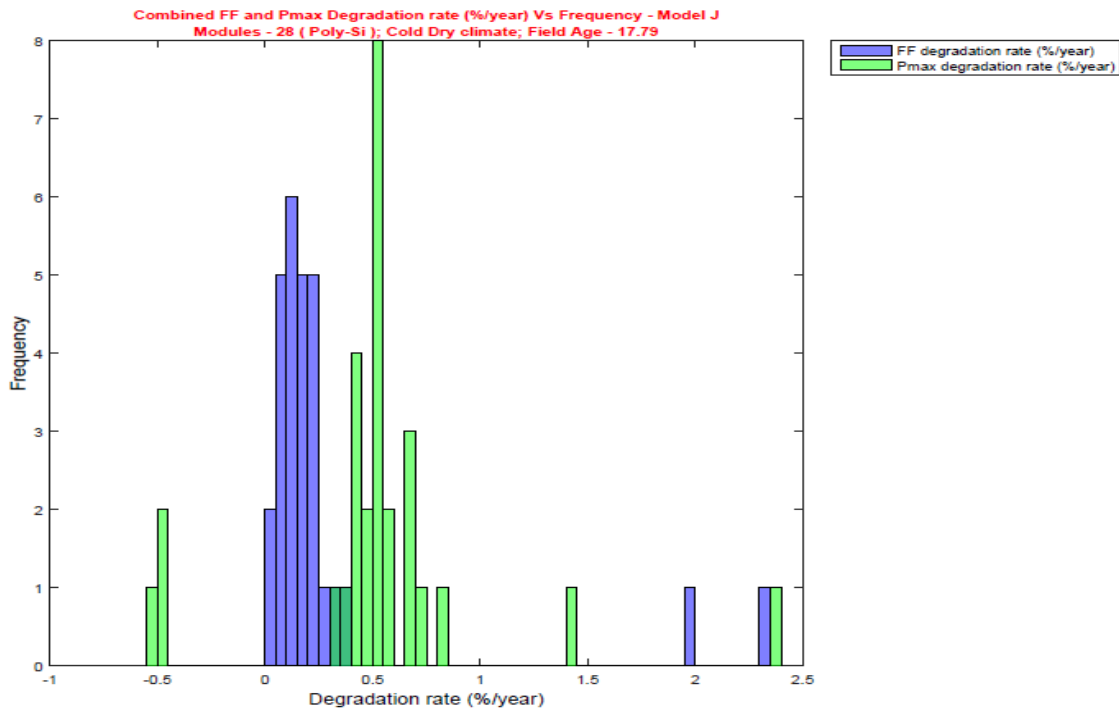
Combined histogram of Isc and Pmax degradation rates (%/year)



Combined histogram of Voc and Pmax degradation rate(%/year)



Combined histogram of FF and Pmax degradation rates (%/year)

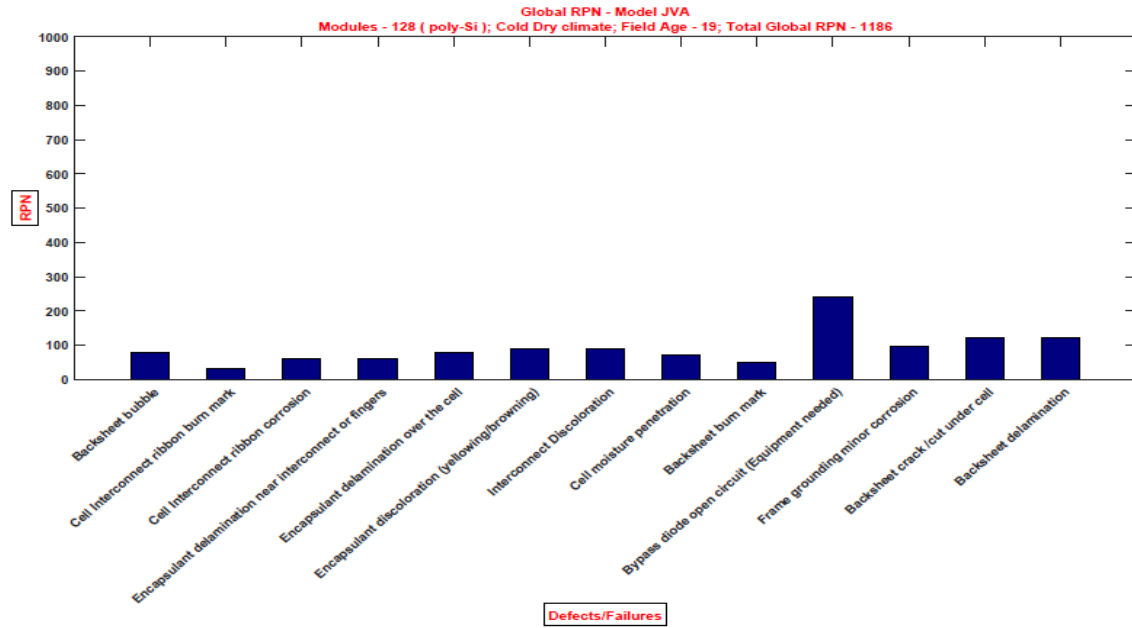


APPENDIX C

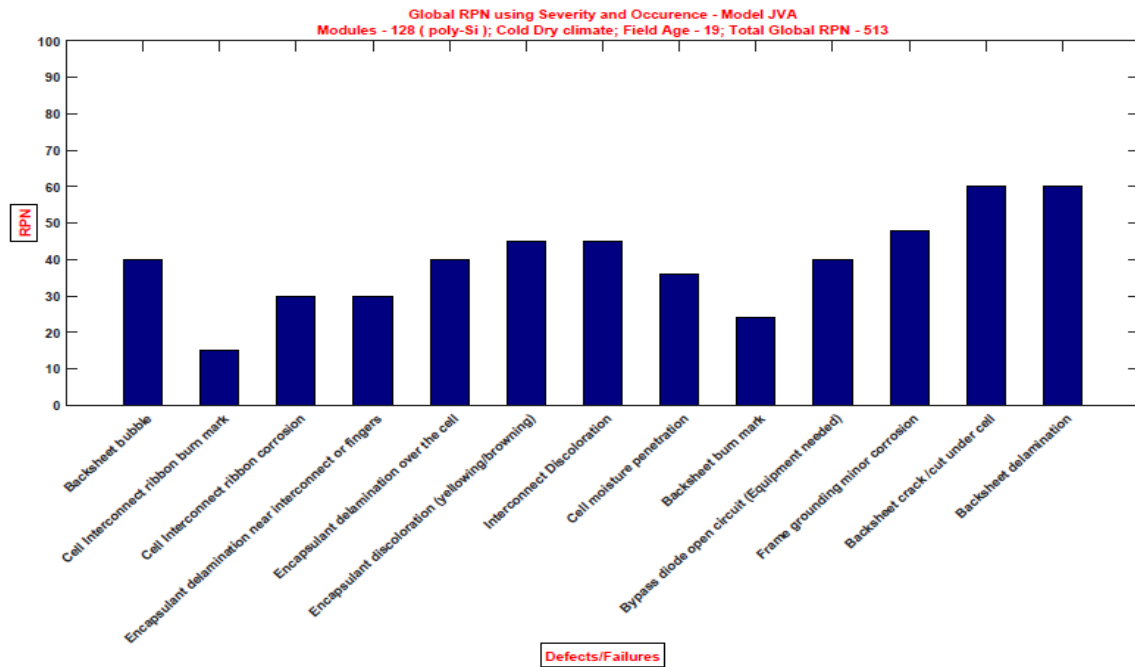
PLOTS FROM MODEL JVA

RPN results

Global RPN

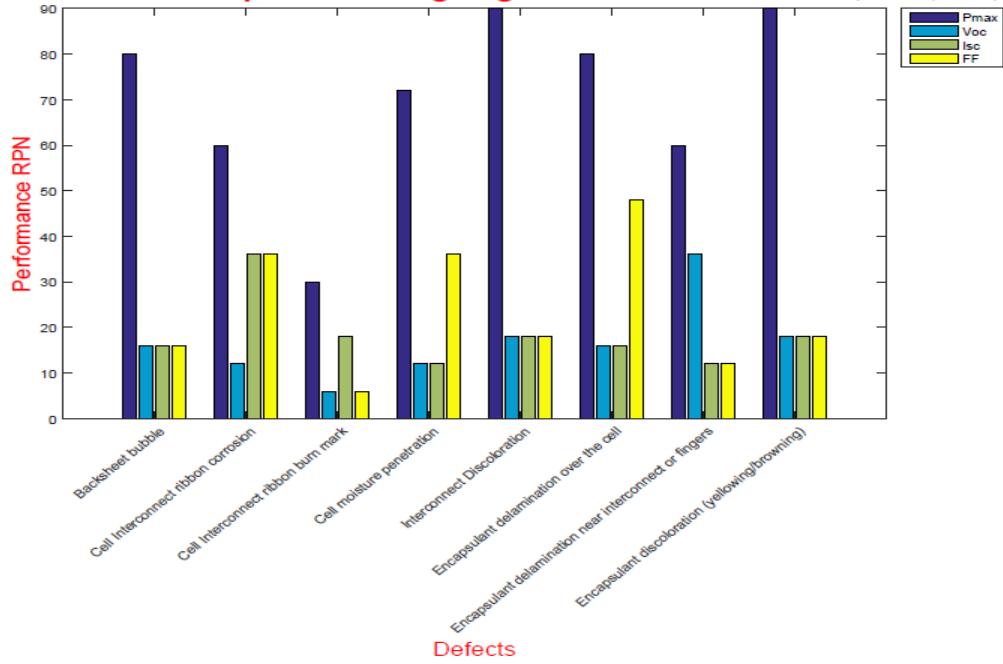


Global RPN using severity and occurrence

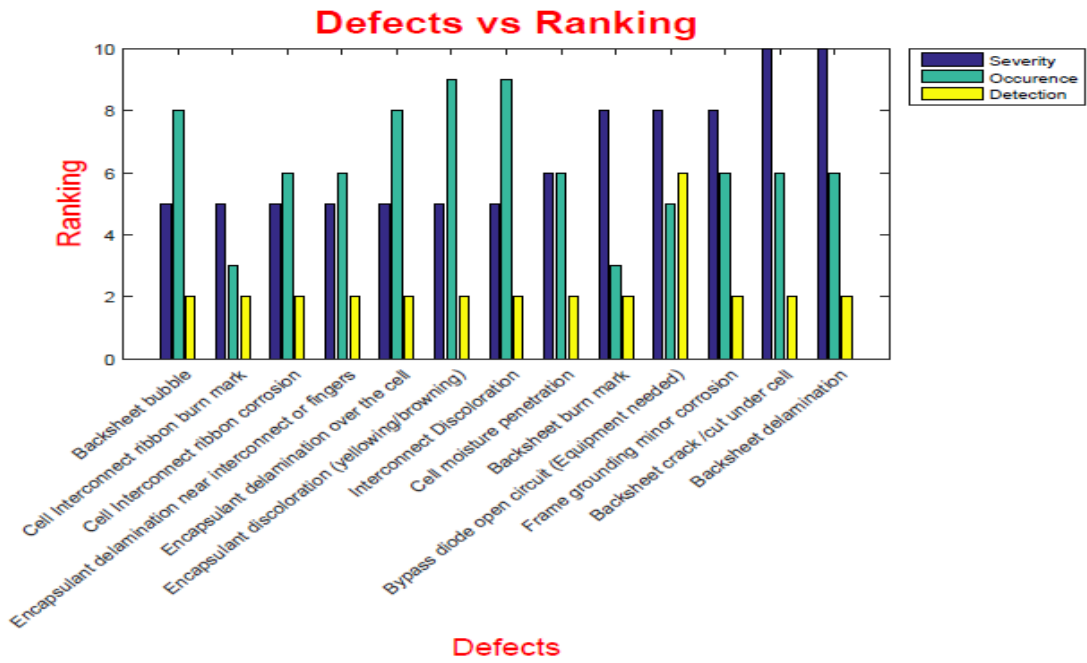


Comparison of performance RPN

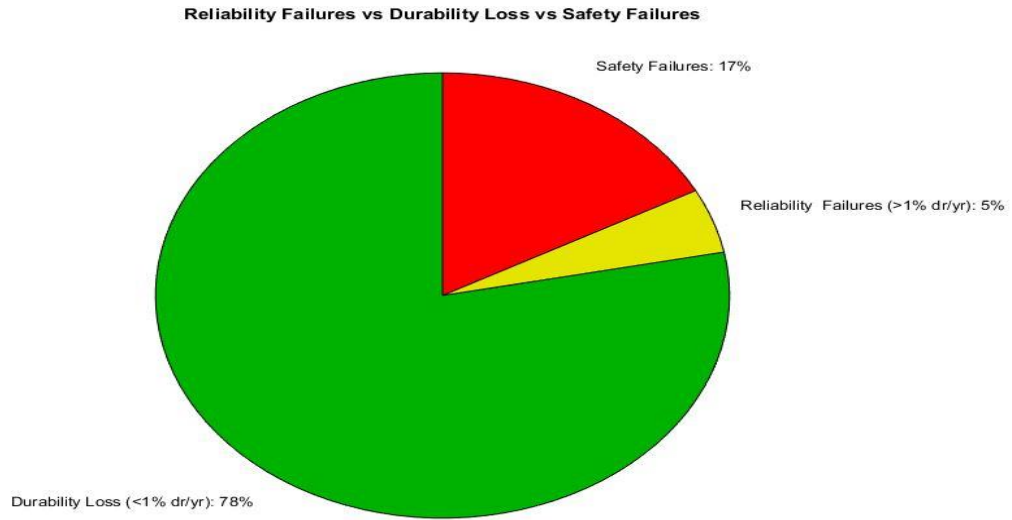
Performance RPN comparison using degradation rates of Pmax, Voc, Isc, FF



Defects Vs Ranking plot

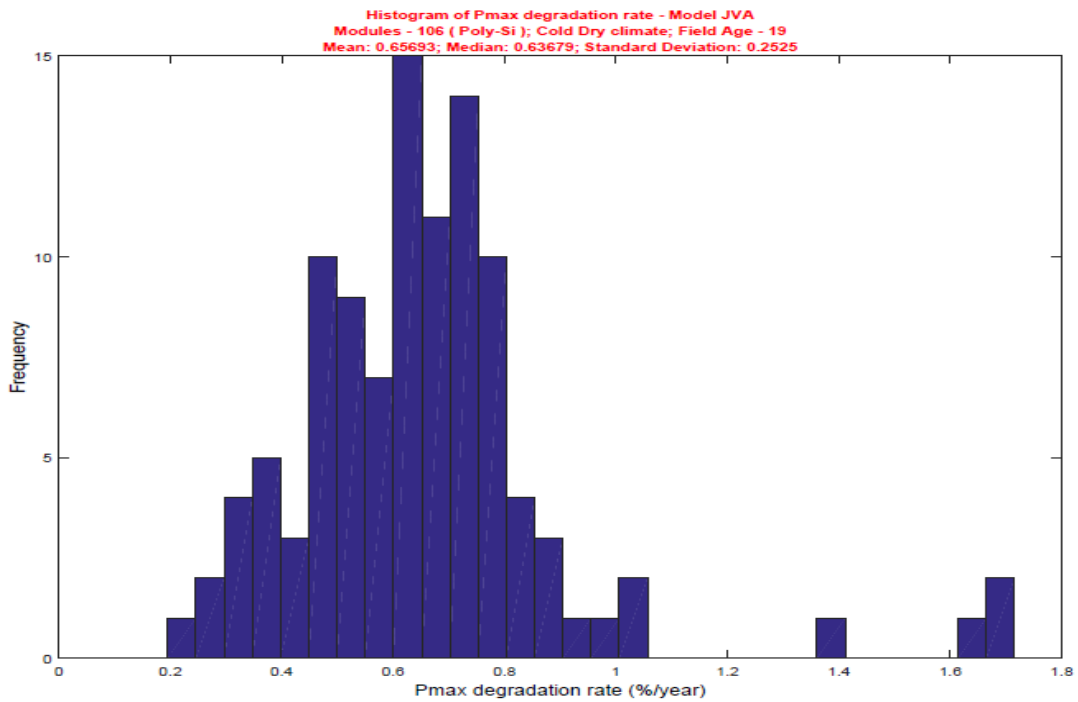


Pie chart

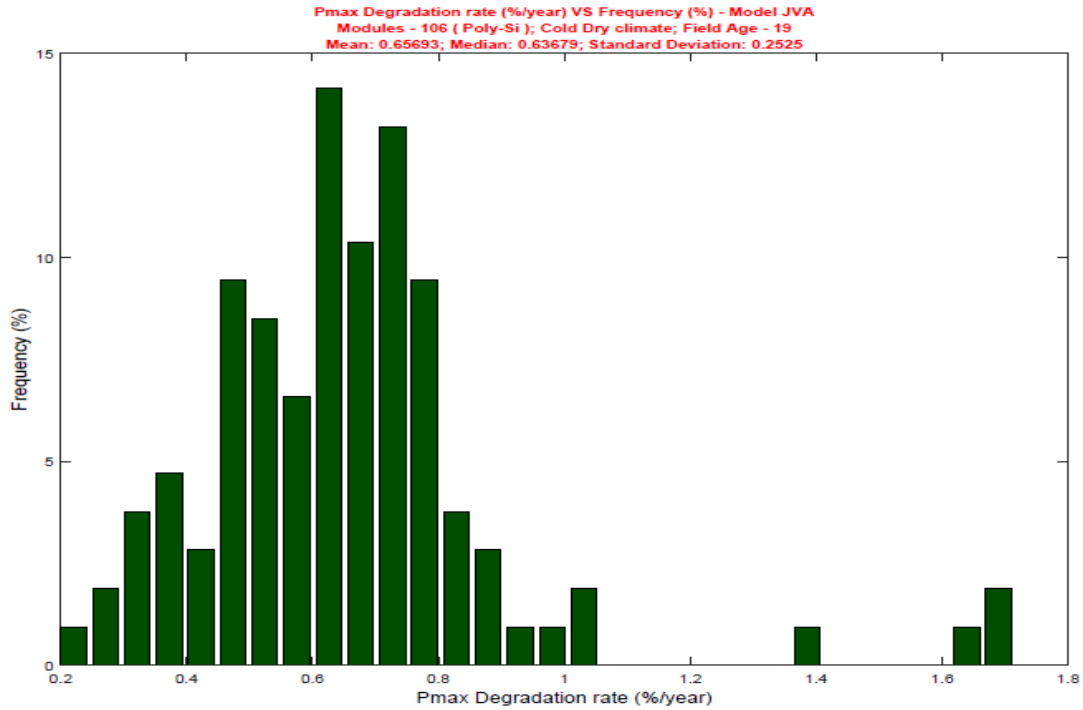


Correlation plots

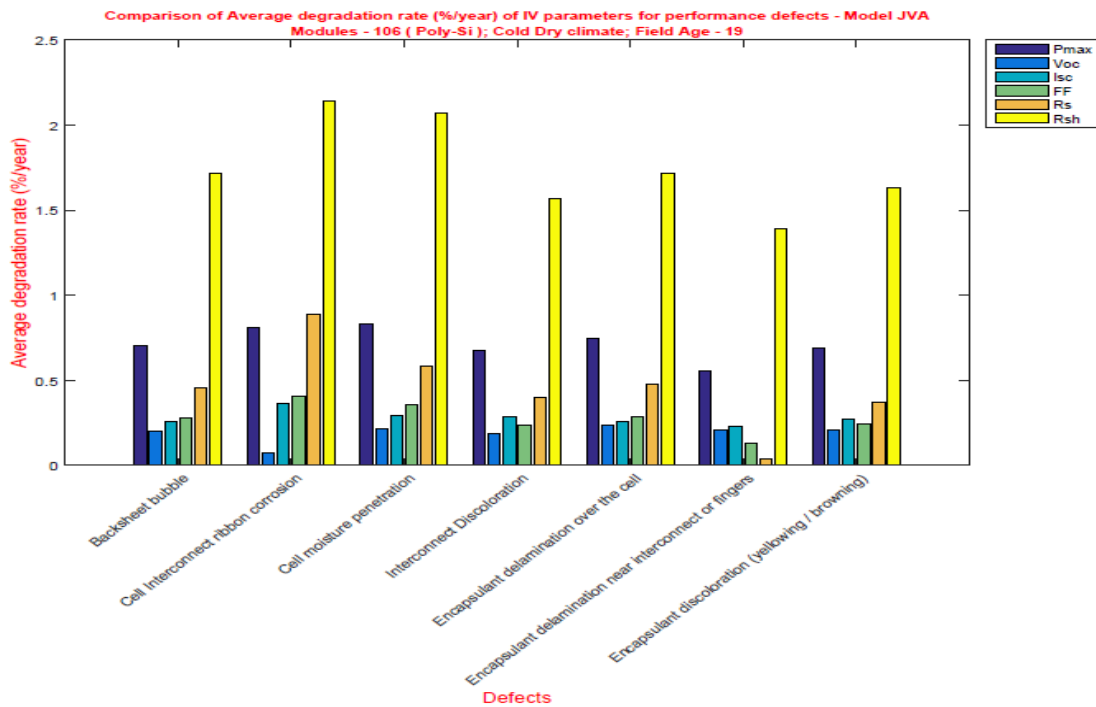
Histogram of Pmax degradation rate (%/year)



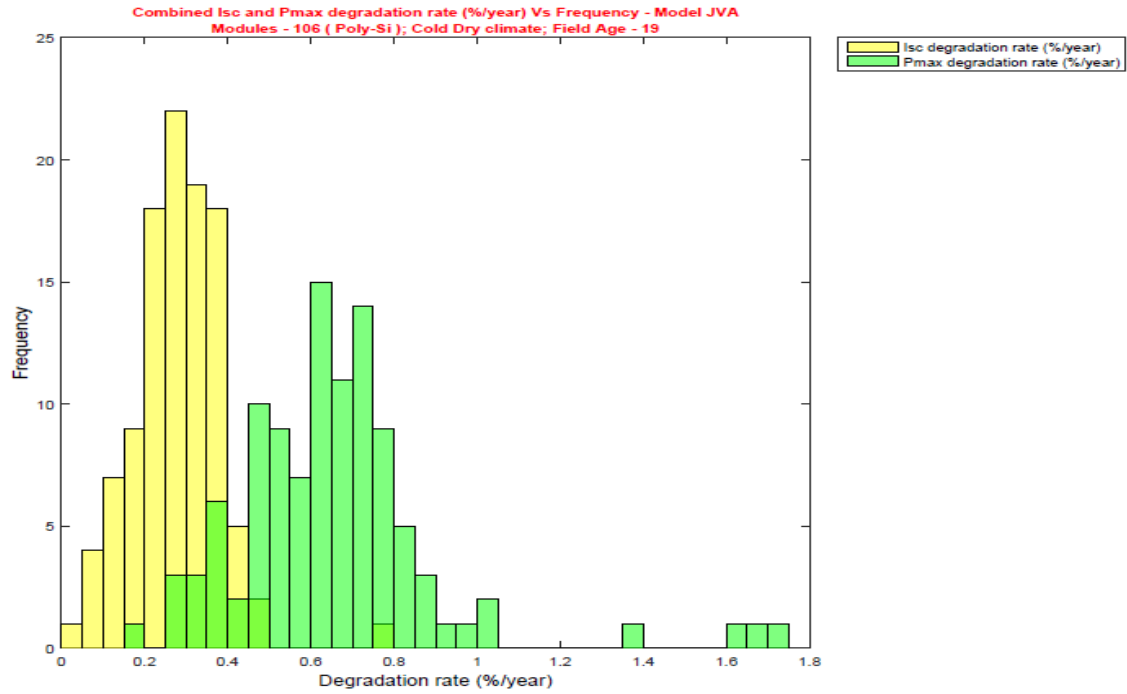
Histogram of Pmax degradation rate (%/year) Vs frequency (%)



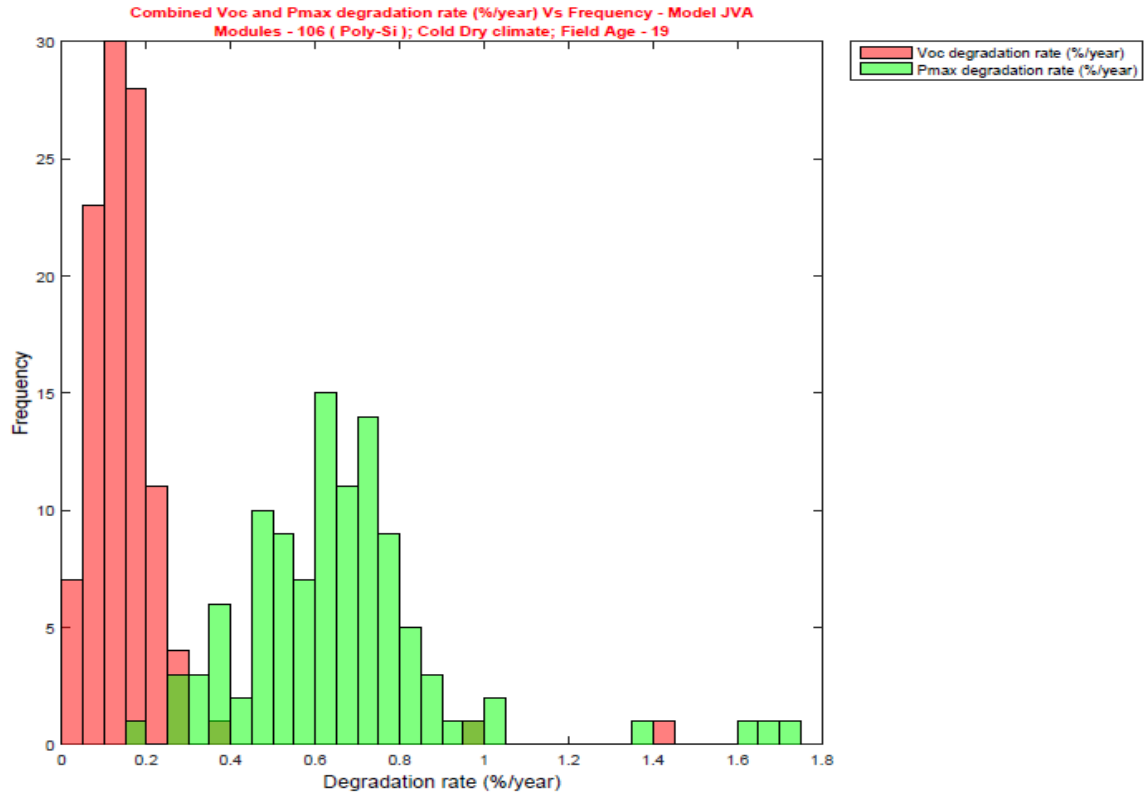
Comparison of average degradation rate (%/year) of IV parameters for performance defects



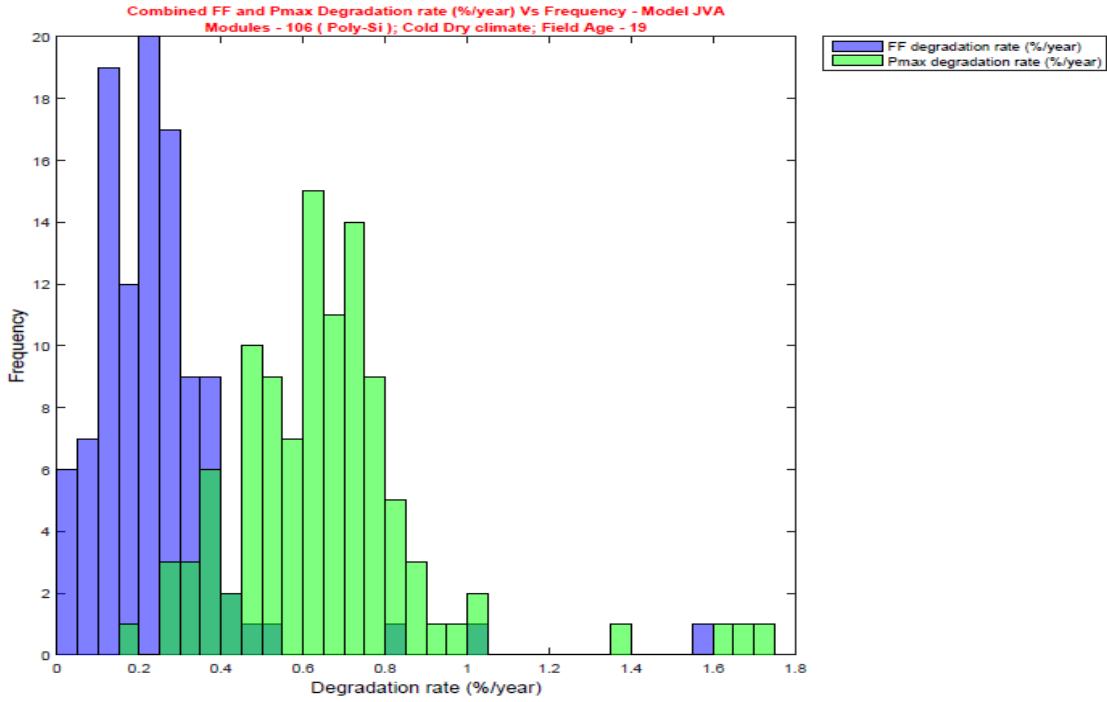
Combined Histogram of Isc and Pmax degradation rate (%/year)



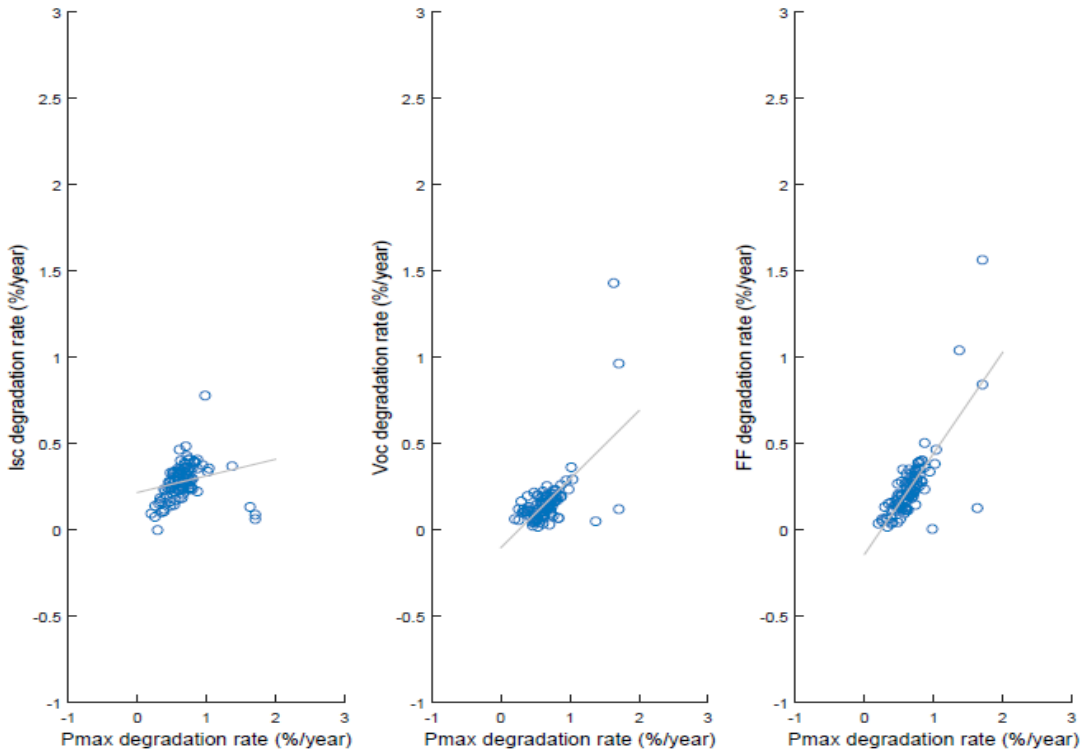
Combined histogram of Voc and Pmax degradation rate (%/year)



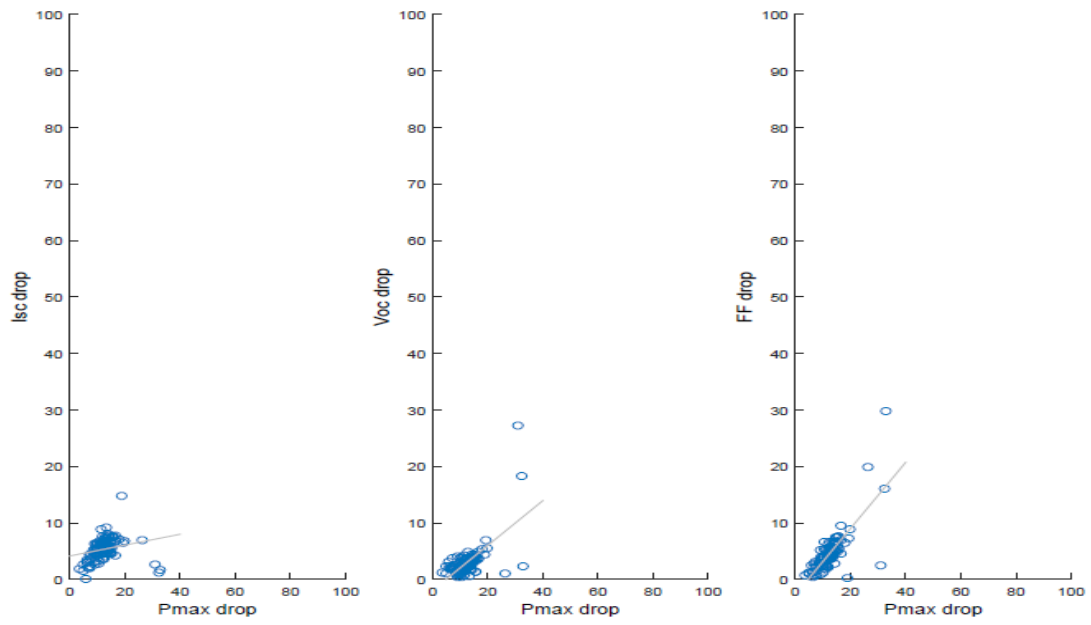
Combined histogram of FF and Pmax degradation rate (%/year)



Linear relation plot 1



Linear relation plot 2

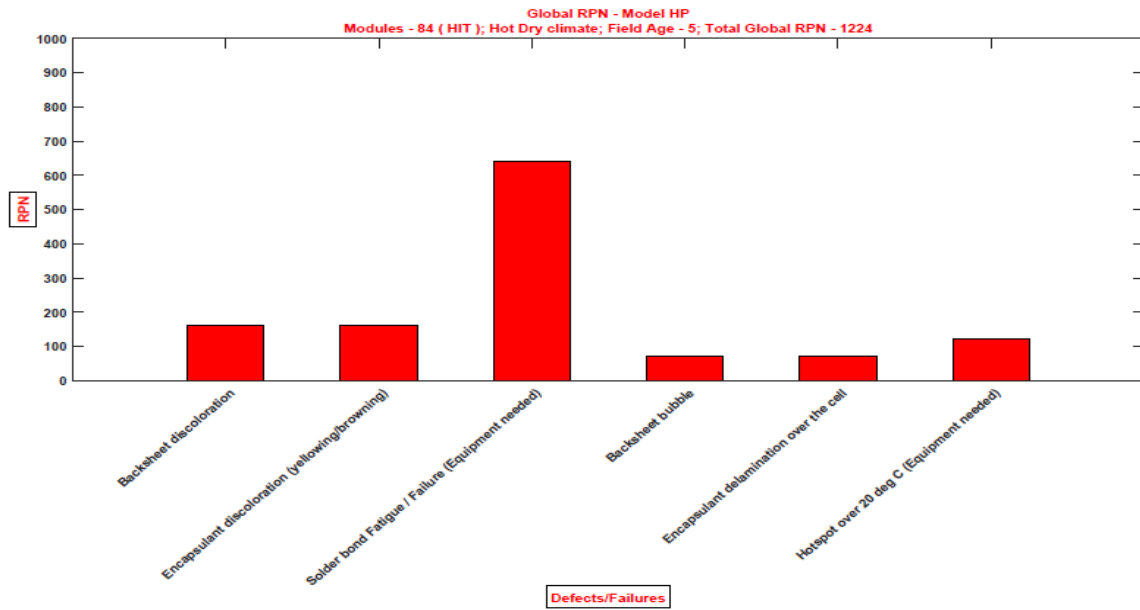


APPENDIX D

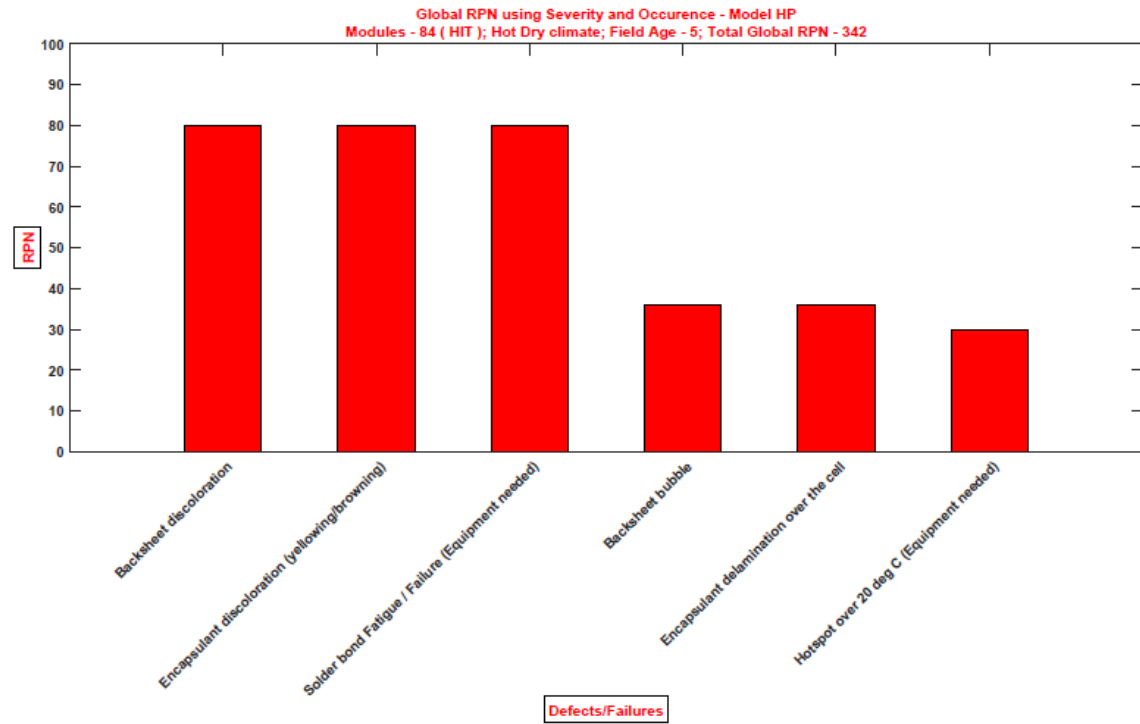
PLOTS FROM MODEL HP

RPN plots

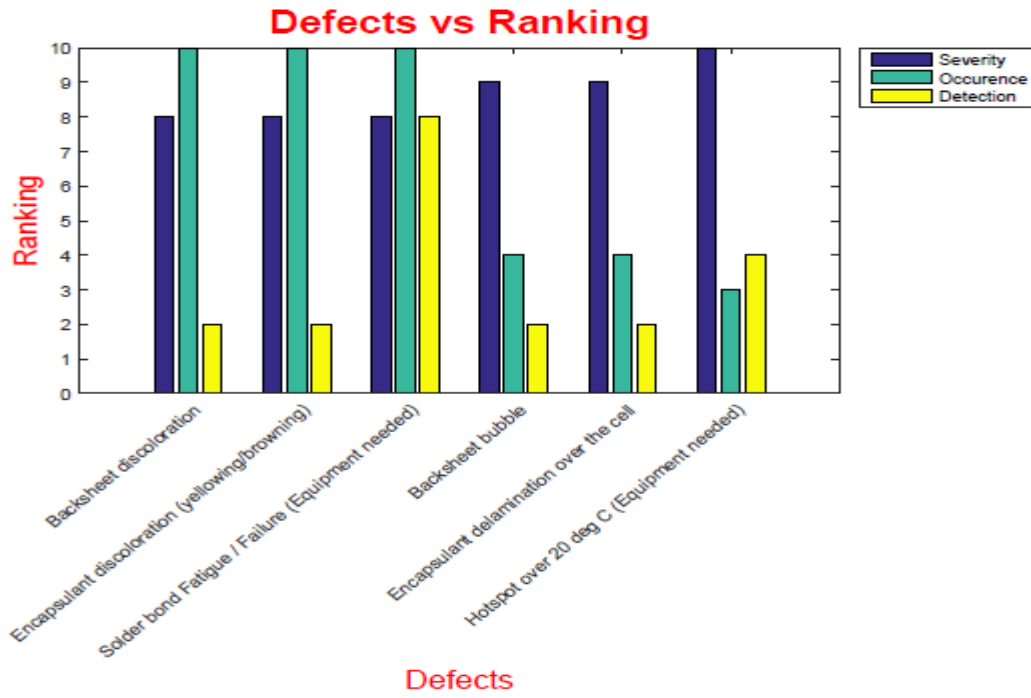
Global RPN plot



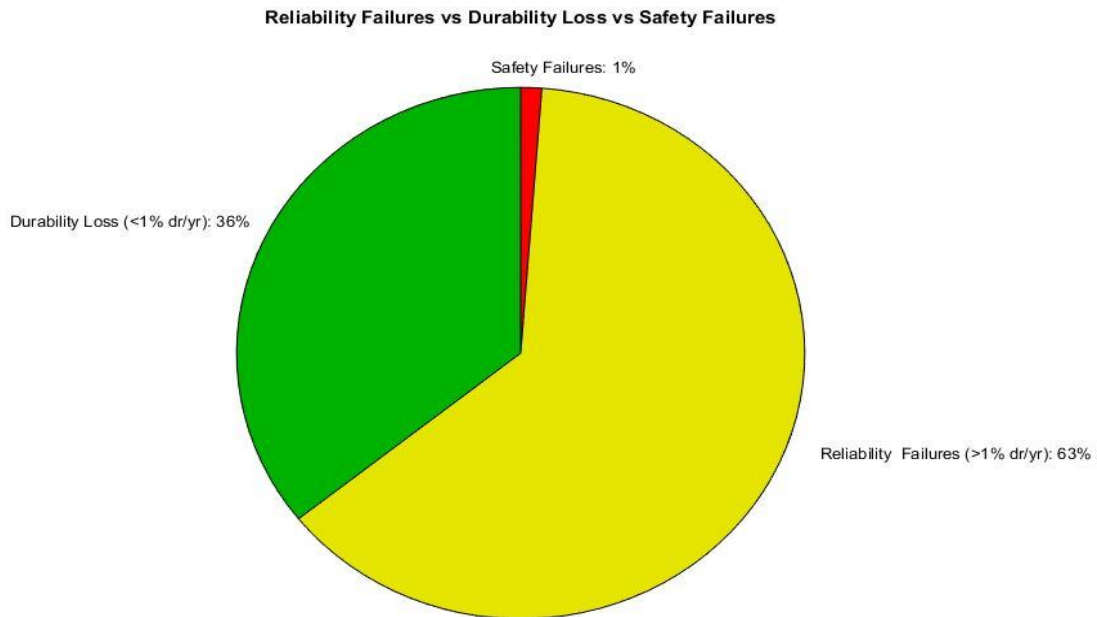
Global RPN using severity and occurrence



Defects Vs Ranking

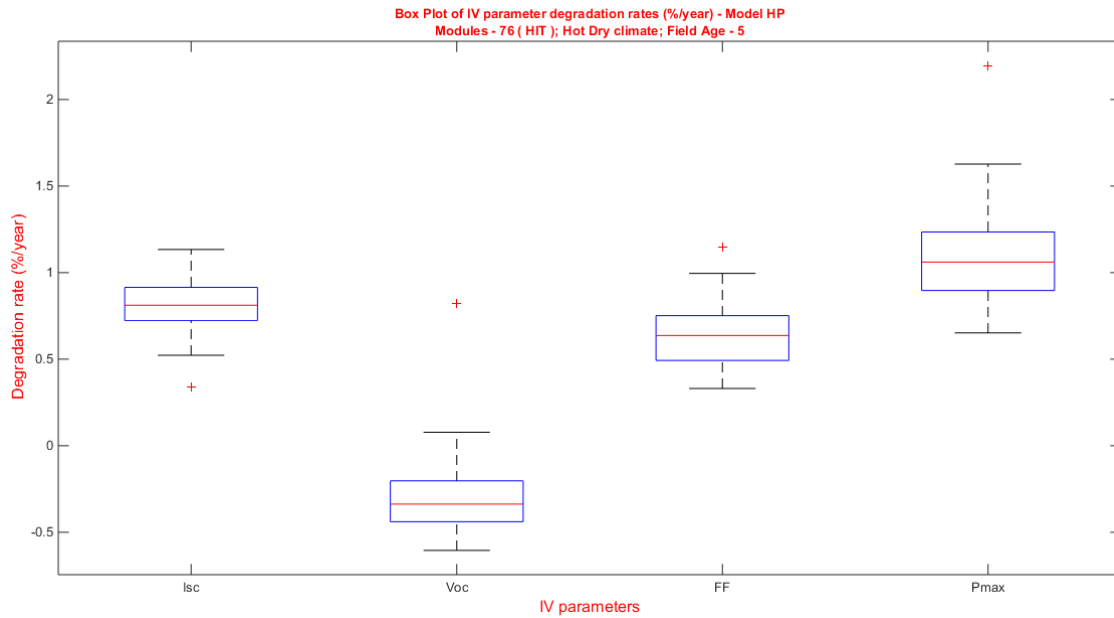


Pie Chart

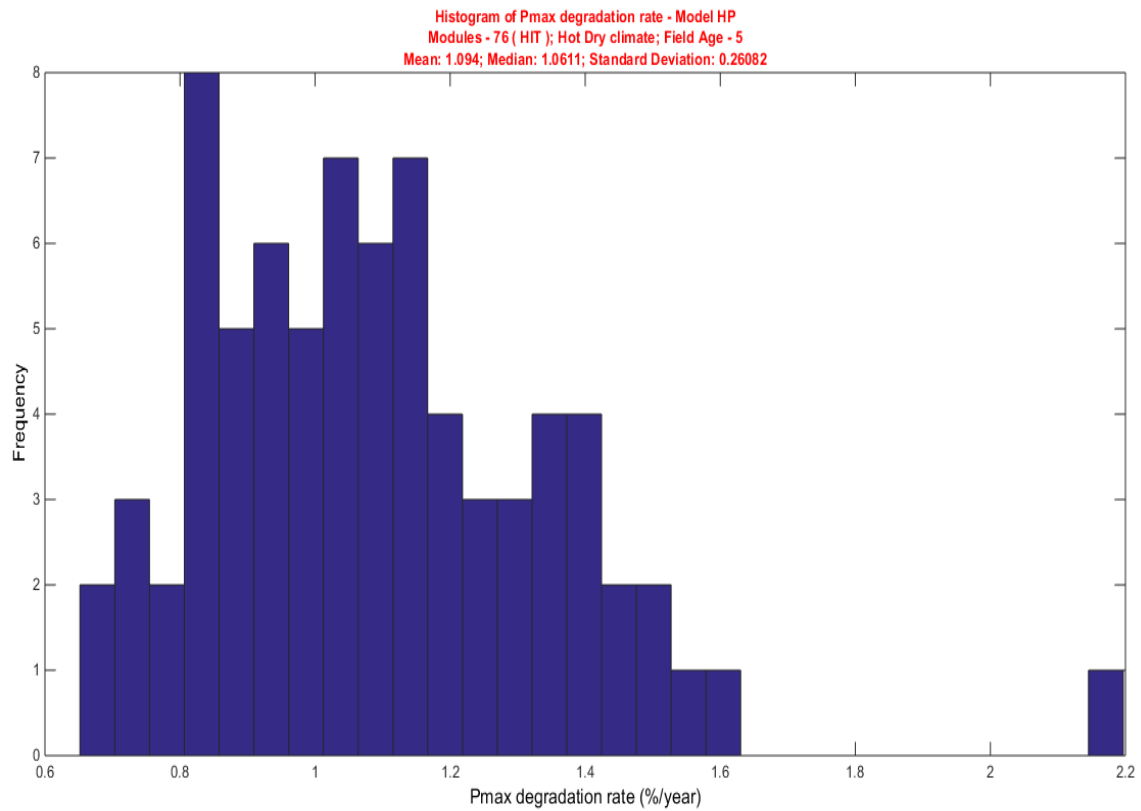


Correlation plots

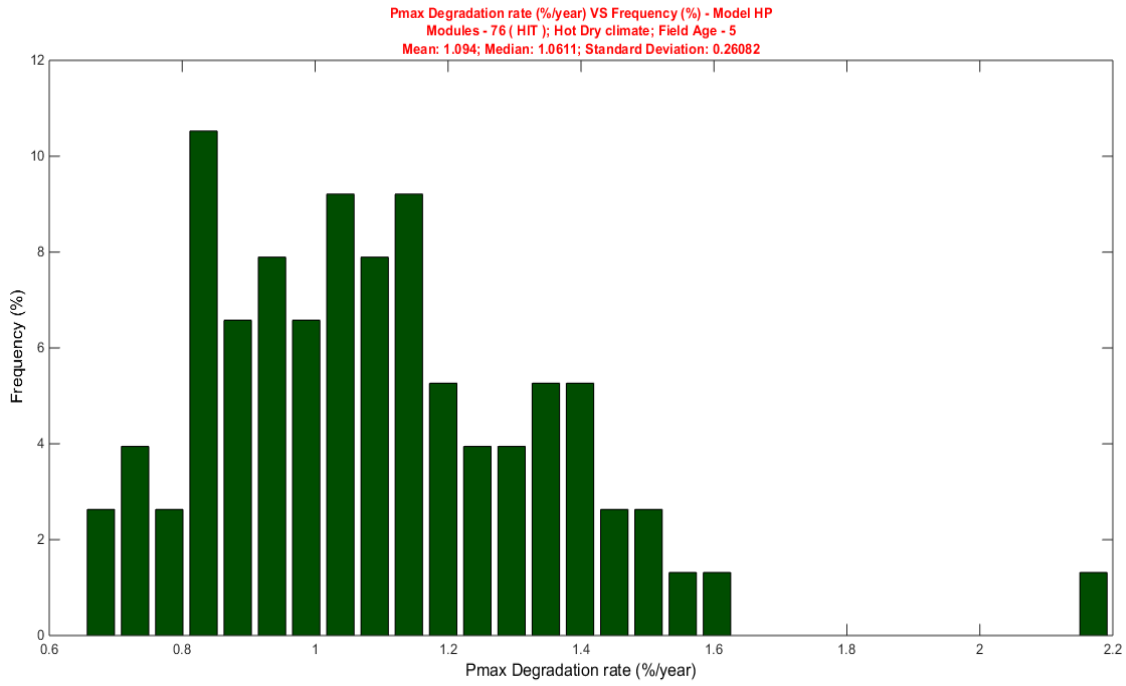
Box plot of IV parameter degradation rates (%/year)



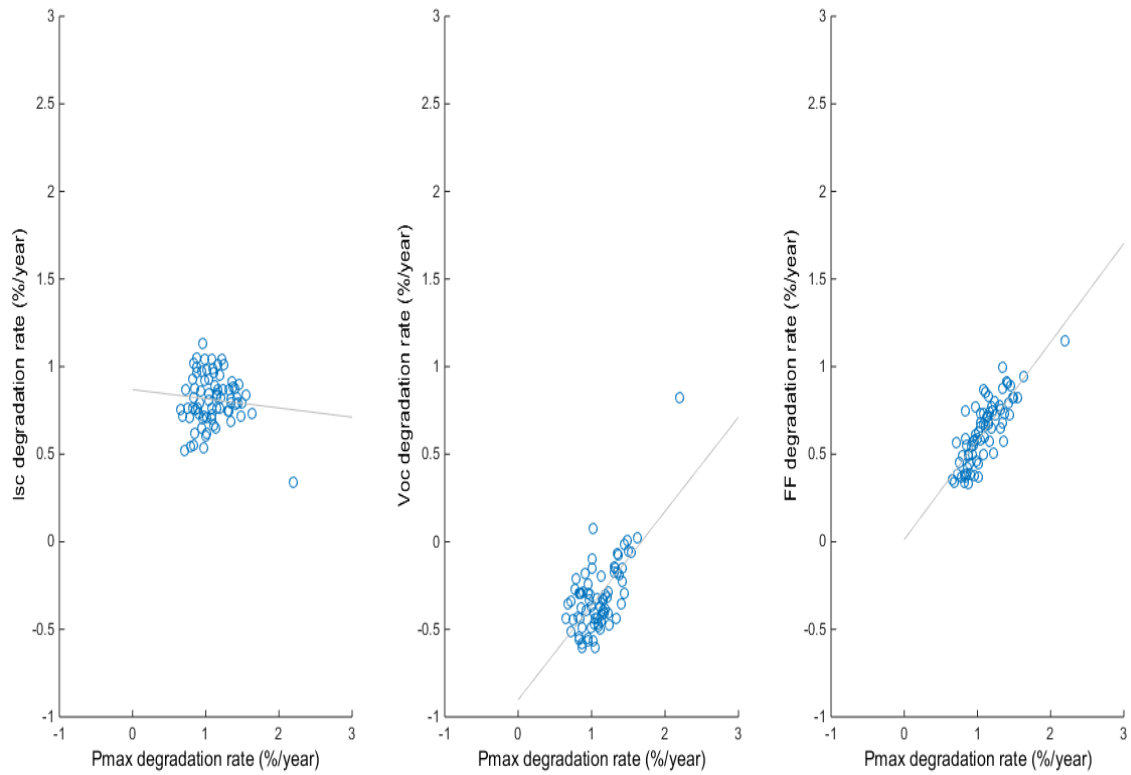
Histogram of Pmax degradation rate (%/year)



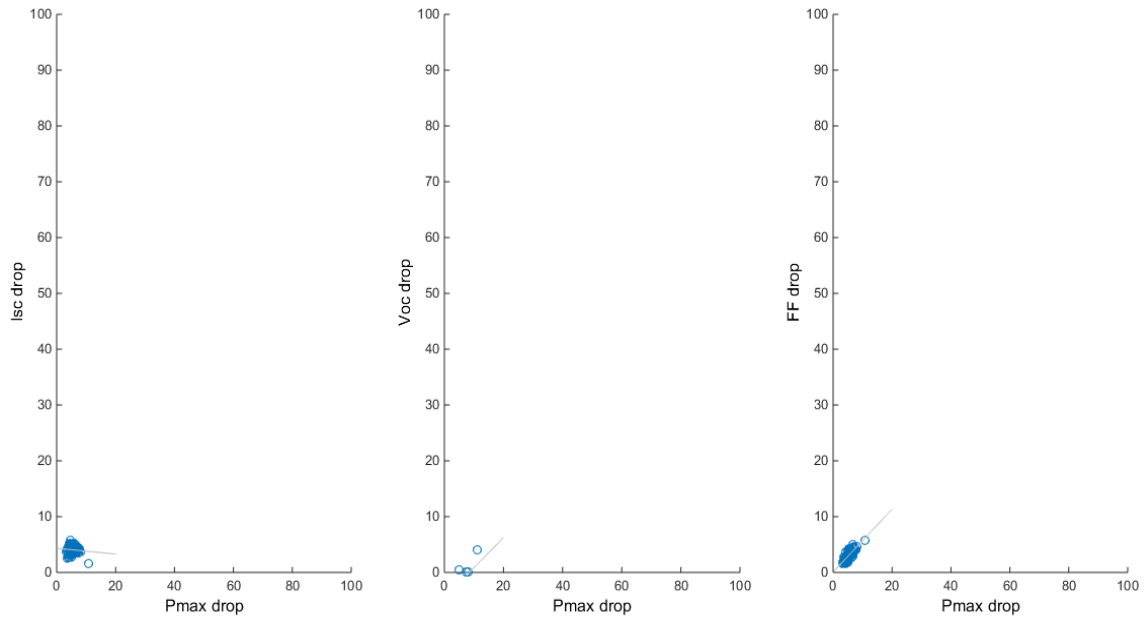
Histogram Pmax degradation rate (%/year) vs Frequency (%)



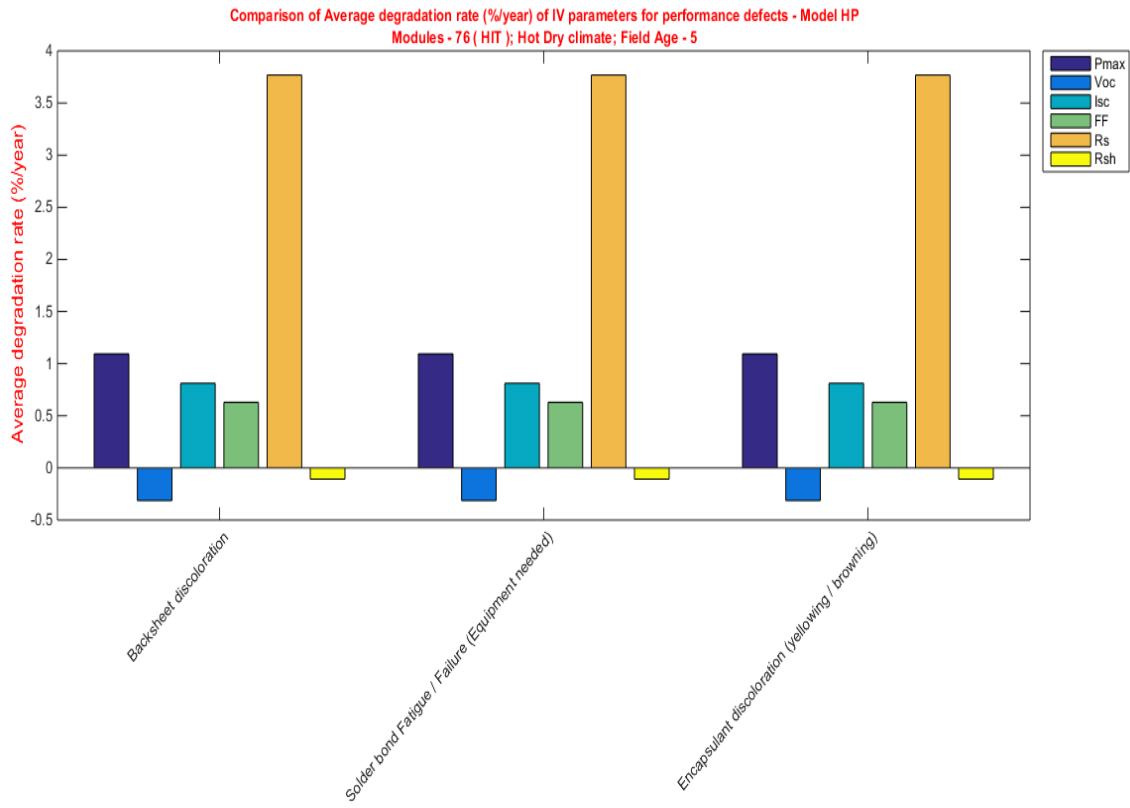
Linear relation plot 1



Linear relation plot 2

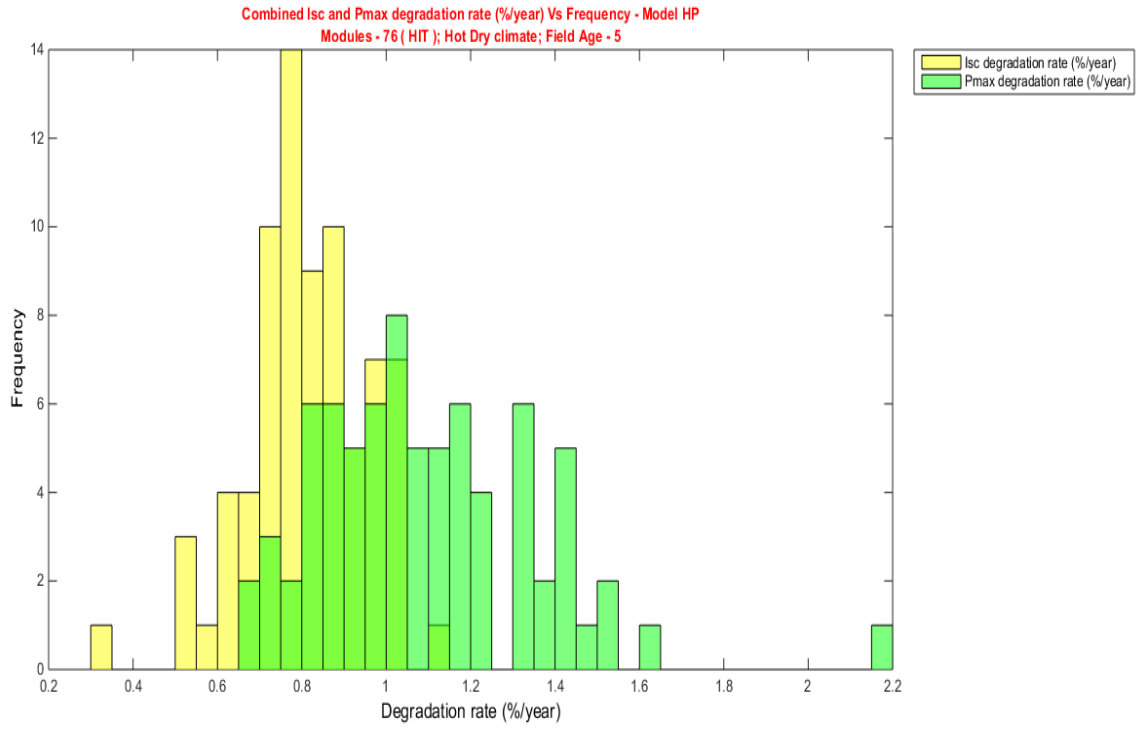


Comparison of average degradation rate (%/year) of IV parameters

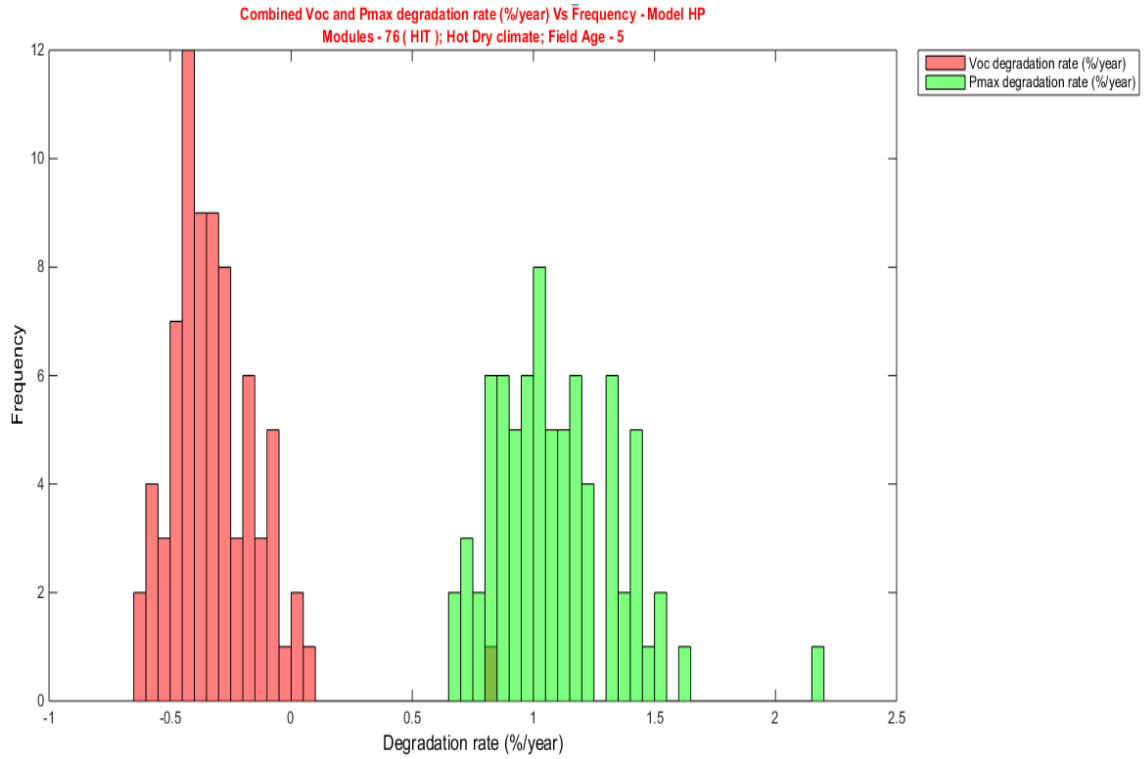


Defects

Combined histogram of Isc and Pmax degradation rate



Combined histogram of Voc and Pmax degradation rate



Combined histogram of FF and Pmax degradation rate (%/year)

