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Research Article

Performance Testing (consistency, breakdown rate) of Crystalline PV Modules and its Energy Yield Comparison with other types in Composite Climate

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Abstract

Photovoltaic Modules are designed to meet the reliability and safety requirements of national and international test standards. Qualification testing is a short duration (typically, 60-90 days) accerated testing protocol, and it may be considered as a minimum requirement to undertake consistency testing. The goal of qualification testing is to identify the initial short term consistency issues in the field, while the qualification testing/certification is primarily driven by marketplace requirements. This paper examines the recent consistency and failure rates of crystalline PV modules of different manufacturers over a period of one year conducted at Photovoltaic Testing Facility Lab, Solar Energy Centre, located in Gurgaon Region of Haryana (India) and its comparison with reliability studies of other PV technologies. This paper further reports the low irradiance behavior of PV modules kept under outdoor measurements resulting in significant differences within a given technology and effecting the final energy yield of different PV module types.

Keywords: *Polycrystalline, Photovoltaic Module, Performances energy yield.*

1. Introduction

The assessment of PV module performance is typically based on the nominal output power that is commonly related to standard test conditions (STC).

In general, PV manufacturers provide information about the electrical characteristics of modules at STC. Specifically, such information includes the open circuit voltage (V_{oc}), short circuit current (I_{sc}), MPP voltage (V_{mpp}), current (I_{mpp}), power (P_{mpp}), efficiency (η) and temperature coefficients.

The testing activity and methodologies of photovoltaic modules is a problematic field of applied research. It is due to climatic reasons because photovoltaic modules performances and lifetime duration is directly affected by climatic operative conditions. Different standards can apply to photovoltaic modules performances but they often presents an intrinsic limit related to specific nature of prescribed tests and difficulties in comparison of results.

The exigency of a well defined testing model which can produce comparable data and can help to increase the excellence of industrial production and can help final users in their commercial choices, regarding PV modules is an important argument and field of research, both for industry and for academia, because it can be a field for enhanced cooperation to define better testing methodologies.

The Present Standardization Scenario

In particular two standards are used for flat plate PV module performance characterization. They are both developed by IEC TC 82 WG2:

IEC61215: Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval.

IEC61646: Thin – film terrestrial photovoltaic (PV) modules – design qualification and type approval.

2. Purpose of the Test Conducted

The object of this test sequence is to determine the electrical and thermal characteristics of the module and to show, as far as possible within reasonable constraints of cost and time, that the module is capable of withstanding prolonged exposure in climates described in the scope. The actual lifetime expectancy of modules so qualified will depend on their design, their environment and the conditions under which they are operated. (Akhmad, K *et al* (1997).

The results of various qualification testing conducted at TUV PTL are presented in this paper. (IEC 61215), (IEC 61646).

Module Reliability: Qualification testing is a set of well defined accelerated stress tests - irradiation, environmental, mechanical and electrical – with strict pass fail criteria based on functionality/performance, safety/insulation and visual requirements.(IEC 60904-1).The qualification testing does not, as anticipated, identify all the possible lifetime/ reliability issues that

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would be encountered in the field; however it does identify the major/catastrophic design quality issues that would initially occur in the field. The type, extent, limits and sequence of the accelerated stress tests of the qualification standards have been stipulated with two goals in mind: one, accelerate the same failure mechanisms as observed in the field but without introducing other unknown failures that do not occur in the actual field; and two, induce these failure mechanisms in a reasonably short period of time (60-90 days) to reduce testing time and cost. As an ISO 17025 accredited laboratory, TUV Rheinland PTL has tested more than 5,000 photovoltaic modules from nearly 20 different countries and issued several hundred qualification certificates.

Fig.1a Solar Energy Centre (SEC), located in Gurgaon Region of Haryana (India)

Fig. 1b Solar Energy Centre (SEC) (outdoor test bed) located in Gurgaon Region of Haryana (India)

In India, one of the center of excellence for solar is Solar Energy Centre (SEC), located in Gurgaon Region of Haryana (India).It is the technical division of Ministry of New and Renewable Energy (MNRE), New Delhi, India. Major activities include research, project development, technical validation, testing and standardization for both solar thermal and solar photovoltaic products. It is a reference centre for all solar energy related activities. SEC serves as an effective interface between the government and institutions, industry and user organizations for development, promotion and widespread utilization of solar energy in the country.

Pass Criteria (IEC 61215 Qualification Testing)

A module design shall be judged to have passed the qualification tests and therefore to be IEC type approved, if each test sample meets all the following criteria:

- The degradation of maximum output power does not exceed the prescribed limit after each test nor 8% after each test sequence.
- No sample has exhibited any open circuit during the tests.
- There is no visual evidence of a major defect.
- The insulation requirements are met after the tests.
- The wet leakage current test requirements are met at the beginning and the end of each sequence and after the damp heat test.
- Specific requirements of the individual tests are met.

Pass Criteria (IEC 61646 Qualification Testing)

After completion of all test sequences, the following pass criteria have to be fulfilled:

- Final STC output power after stabilization (e.g., light soaking) at least 90% of the minimum rated power: $(0.9 \times (P_{manufacturer} - \text{tolerance})$
- Minimum requirements for the electric insulation (dry and wet)fulfilled:
  - $R_{iso} > 40\ M\Omega\ /A\ [m^2]$ (A = module area)
- No major visual defects detected.

Various results have been previously presented by TUV PTL, where the failure rates obtained in the qualification testing of flat plate modules have been discussed over 13 years as per IEC61215 and IEC1646 standards of both crystalline silicon and thin film modules for three consecutive multi year periods: 1997-2005, 2005-2007, 2007-2009. A detailed analysis of the failure rates in the qualification testing is presented elsewhere. (Tamizh Mani, G *et al* (2010)

In the present study, different specimens of PV module of different companies are analyzed by solar energy centre researchers and the failure rates obtained in the qualification testing has been discussed in detail as (per IEC61215).

(M- Module No)

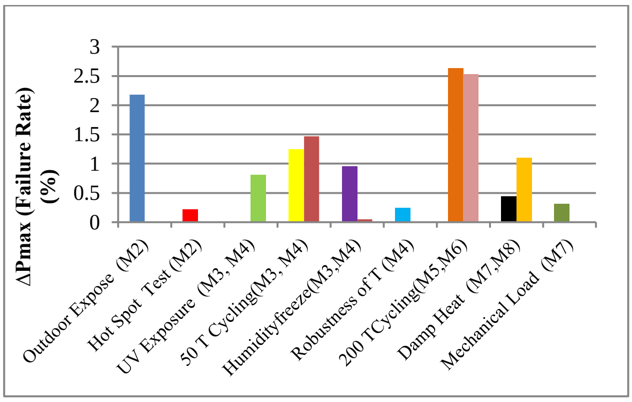

Fig.2 Failure rate comparison of *Tata BP Solar* modules (Mono C-Si) for 2011-2012

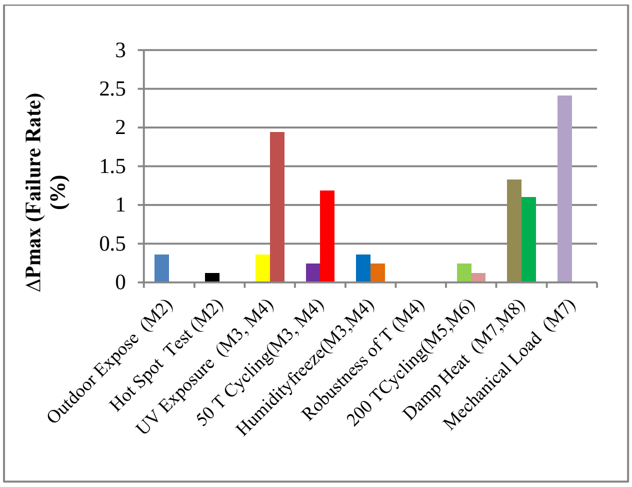

Fig.3 Failure rate comparison of *2N solar* modules (Multi C-Si) for 2011-2012

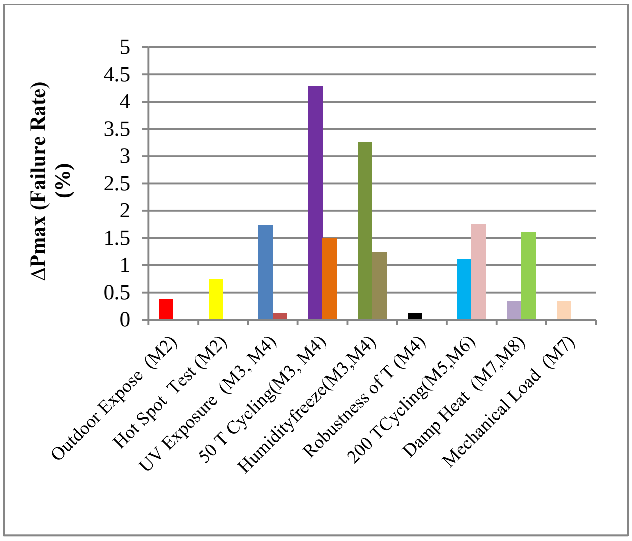

Fig.4 Failure rate comparison of *Arion Solar* modules (Multi C-Si) for 2011-2012

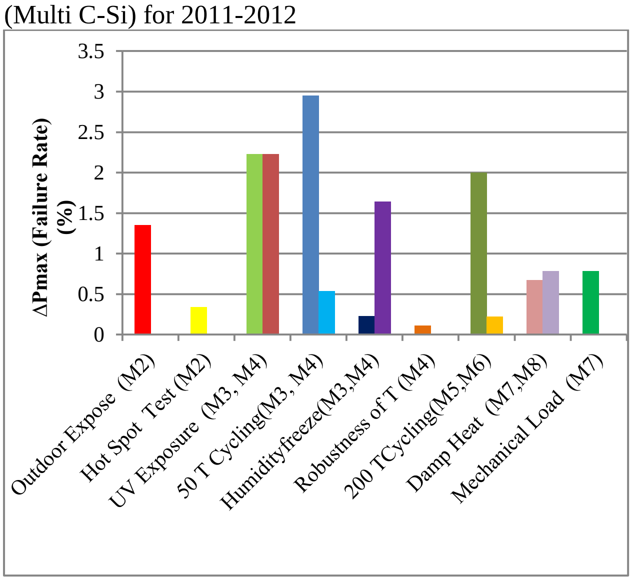

Fig.5 Failure rate comparison of *HBL Ltd* modules (Multi C-Si) for 2011-2012

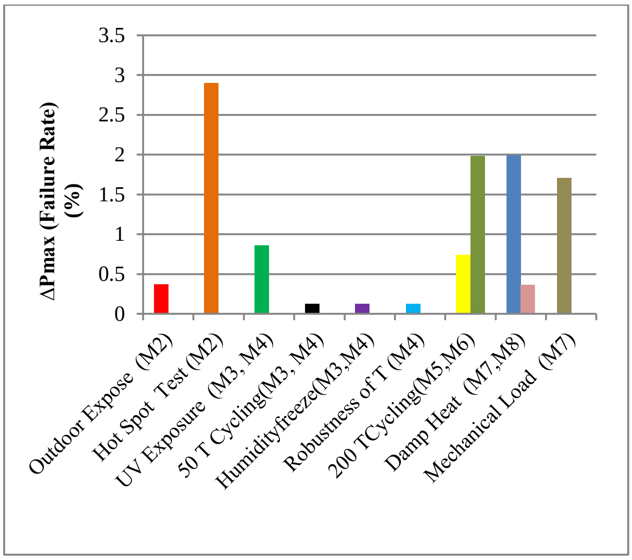

Fig.6 Failure rate comparison of *Waaree* modules (Multi C-Si) for 2011-2012

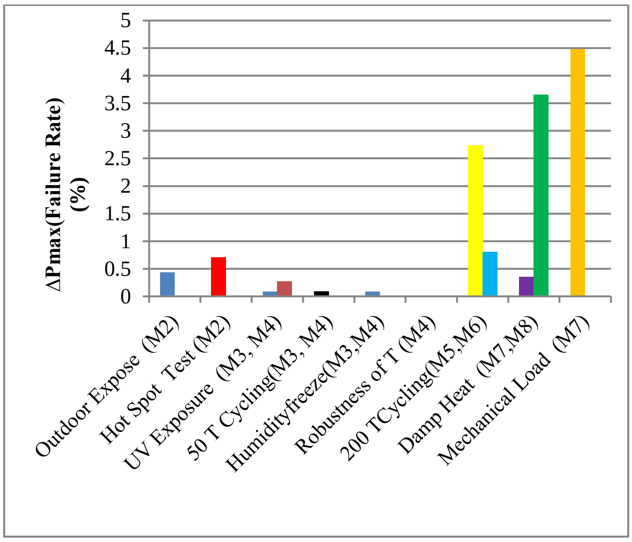

Fig.7 Failure rate comparison of *Reil* modules (Mono C-Si) for 2011-2012

In the year 2011-2012 period, many C-Si modules both multi and mono were tested of various companies for the qualification certification.

For the outdoor exposure test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Outdoor Exposure test	2.18	0.357	0.37	1.35	0.37	0.438

For the Hot Spot Endurance Test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N

Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Hot spot Endurance Test	0.22	0.119	0.749	0.34	2.9	0.70

For the Ultra violet exposure test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Ultra Violet Exposure Test	0.01	0.358	1.73	2.23	0.86	0.089

For the 50 thermal cycling test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
50thermal Cycling Test	1.249	0.238	4.29	2.95	0.124	0.089

For the Humidity Freeze test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Humidity Freeze test	0.95	0.358	3.26	0.225	0.124	0.089

For the Robustness of termination test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Robustness of Termination	0.24	0	0.125	0.11	0.125	0

For the 200 thermal cycling test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
200 Thermal Cycling Test	2.63	0.241	1.11	2	0.739	2.74

For the Damp heat test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Damp Heat Test	0.44	1.325	0.33	0.672	1.99	0.351

For the Mechanical Load Test, change in the P_{max} values for the manufacturers named as Tata BP Solar, 2N Solar Limited, Arion Solar, HBL Limited, Waaree and Reil are as follows

	Tata BP Solar	2N Solar Ltd	Arion Solar	HBL Ltd	Waaree	Reil
Mechanical Load Test	0.309	2.41	0.332	0.78	1.707	4.47

Comparison with reliability studies of other PV technologies

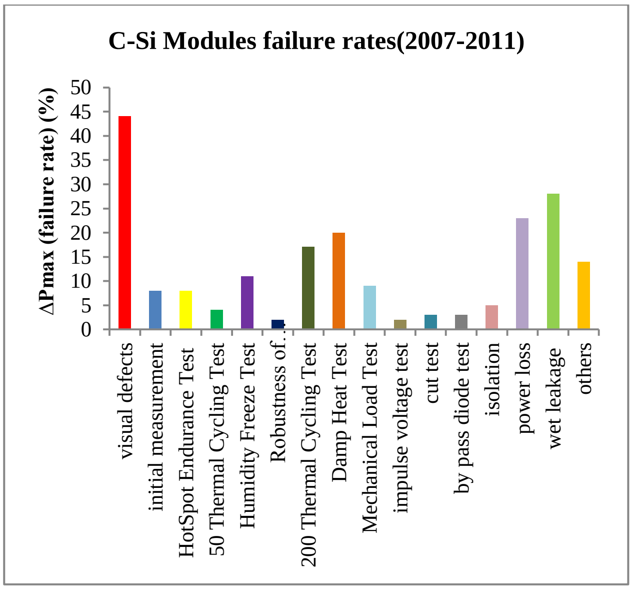

Fig.8 Failure rate comparison of crystalline silicon modules from 2007-2011 conducted at TUV Rheinland PTLs solar module testing facility in Arizona

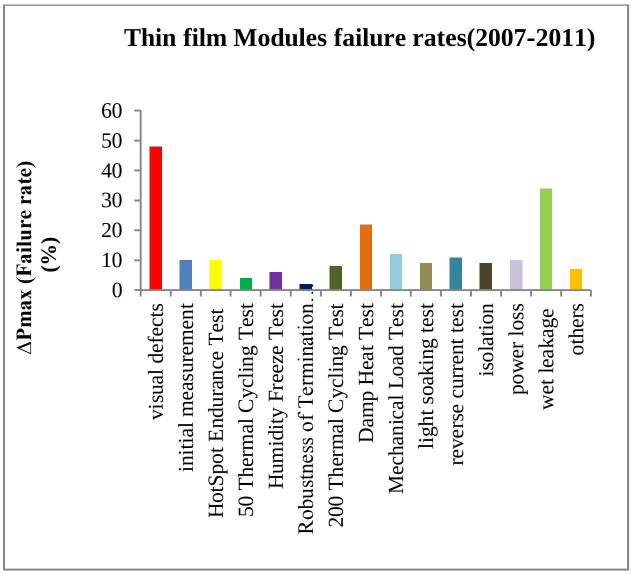

Fig.9 Failure rate comparison of thin film modules from 2007-2011 conducted at TUV Rheinland PTLs solar module testing facility in Arizona

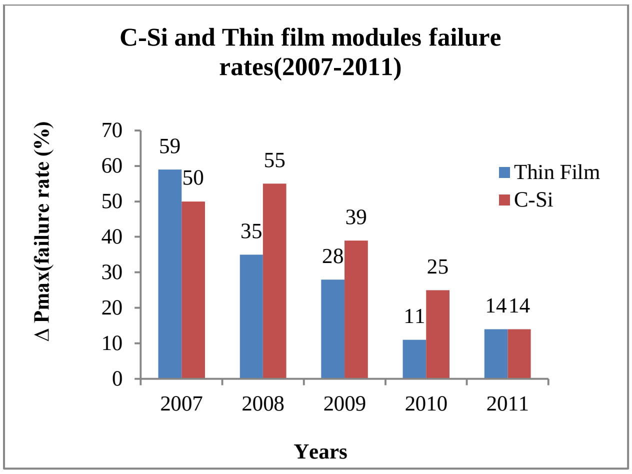

Fig.10 Failure rate comparison of thin film modules and crystalline silicon modules from 2007-2011 conducted at TUV Rheinland PTLs solar module testing facility in Arizona

The comparative failure analysis conducted at **TUV Rheinland PTLs solar module testing facility in Arizona** showed that the fraction of new manufacturers in 2007-2009 period was about 39% but encouragingly, the failure rates for most of the major stress tests have dramatically decreased for the 2007-2009 period compared to the previous period of 2005-2007.

3. Seasonal Weather conditions in Gurgaon (Composite Climate), India

To evaluate technology specific effects when measuring the energy yield, the seasonal changes of the weather conditions and the technology-specific characteristics must be known for the region of the particular test site (Biicher, K (1997).

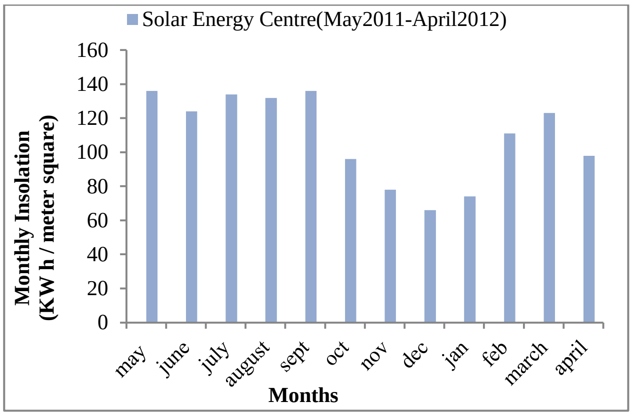

Fig.11 The analysis of the one-year weather data with the given distribution of solar insolation for Gurgaon, India (Composite Climate)

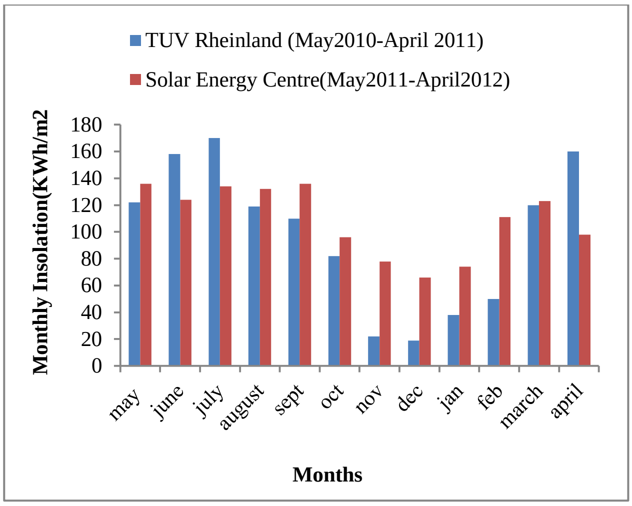

Fig.12 Distribution of monthly in-plane insolation at the outdoor test site in Solar Energy Centre, Gurgaon, India compared with the monthly in-plane insolation at the outdoor test site in Arizona

The data recorded at the test site in Arizona reveal that the three winter months with a cumulative annual insolation of 2.2% (Nov), 1.6% (Dec) and 2.9% (Jan) played a minor role in the given energy yield analysis. The significant insolation occurred in the three summer months: The total insolation for June, July and August was 38.6%, while the following seven months, from September to March, had a total insolation of 37.5%. Moreover, exceptional insolation levels for the spring of 2011 were recorded in March and April. The total cumulative insolation for the entire year was 1183 kWh/m^2.

While on the other hand the data recorded at the test site in Solar Energy Centre reveal that the three winter months with a cumulative annual insolation of 5.9% (Nov), 5.04% (Dec) and 5.6% (Jan) played a minor role in the given energy yield analysis. The significant insolation occurred in the three summer months: The total insolation for June, July and August was 29.8%, while the following seven months, from September to March, had a total insolation of 52.2%. Moreover, exceptional insolation levels for the spring of 2012 were recorded in March and April. The total cumulative insolation for the entire year was 1308 kWh/m^2.

Besides the annual available solar insolation energy, the distribution of solar spectrum varies significantly in the course of a single day and over the entire year due to changes in the air mass and in the composition of the atmosphere. (Schweiger, M *et al* (2011).Since each module technology has a different spectral response, this variation influences the energy yield of the modules.

4. Influence of light spectrum in different technologies

The IEC 60904-1 standard establish the general method for measurement of photovoltaic current-voltage characteristics and besides this, the IEC 60904-3 standard establish the spectral distribution of the light that should be used when a measurement of the electrical characteristics of a PV module is made. It is known as 1.5AM and the actual spectral distribution of the sunlight should be measured in any electrical test of a module under sunlight exposition.

Sometimes it is not possible and it is very difficult to assure 1.5AM spectral distribution both indoors and outdoors. (Cannon, T *et al* (1993). Nevertheless using sunlight the spectral distribution is not as stable as indoors therefore into a solar simulator the repeatability of the measurement is easier to achieve (Minemoto, T *et al* (2007). In this case the problem is reduced to take periodically a measurement of the light spectrum inside the simulator.

Each technology has a different spectral response (Fig.13). As the measurement of the electrical characteristics must be translated to STC, a spectral correction must be applied (Gottschalg, R *et al* (2005). It usually means that the obtained current has to be multiplied by a spectral factor that depends on the spectral response of the technology under analysis and the spectral distribution of the light

It is also possible to use a calibrated cell of the same technology and type of the PV module under analysis for the control of the light of the simulator. In this case the problem is that changing this cell often could imply a risk in the repeatability of the measurements of the solar simulator. For this reason a spectral correction for each technology is preferred.

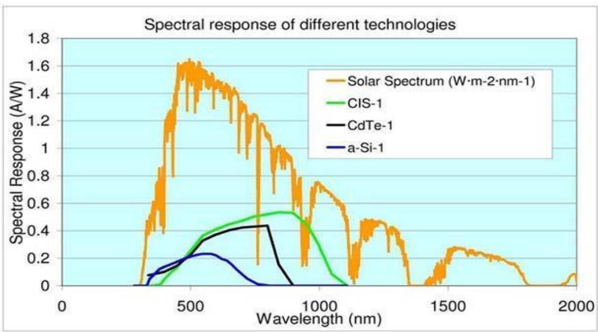

Fig.13 Typical spectral response of different thin film technologies and AM 1.5 spectral distribution

As clear from the above figure the a-Si modules (blue curve) has its spectral response in the narrow band of about 300nm-800nm. CdTe (black) and CIS (green) show similar curves with SR values from 350-1000nm. These results obtained by the Rural Engineering Department, Electrotechnical Section, EUITA Agricola, UPM, Madrid, Spain were similar to the results obtained by the TUV Rheinland (Arizona).

As to study the spectral response of different specimens, previously TUV Rheinland had configured a unique measurement station to determine the spectral response on a module basis, where the system allows non destructive measurement of single and multi junction modules in a wavelength range between 300nm to 1200nm and in wavelength intervals of 1nm. As expected, the results showed significant differences between the different single - junction and multi junction PV module technologies. The SR curve of a CIGS module falls into the same range as those of C-Si modules (350nm-1200nm), but for some CIGS modules, the SR data attains values higher than 1200nm. Due to this situation, the classification of IEC 60904-9 (up to 1100nm) may be insufficient for some module flasher combinations). (Schweiger, M *et al* (2011).

5. Temperature Dependence

Besides the non stability of module performance, spectral response, in order to explain the significant differences in the performance of different PV module types we must take clear look at characteristics like temperature dependence (Carlson D.E, *et al* (2000). Laboratory and Outdoor measurements have shown substantial differences in the temperature and low irradiance behavior of the different technologies.

Temperature Coefficients as well as the average module temperature vary. The temperature dependence has been discussed in previous studies. (Jahn, U *et al* (2010), (Jahn, U *et al* (2011), (Schweiger, M *et al* (2011). The results showed that difference of γ (T_c of P_{max}) within one technology are rather higher, in hot summer months with relatively high average module temperatures, low values of γ have been observed.

In the present study measurement of temperature coefficients has been done of two different technologies of different module manufacturers

Tata BP Solar (Mono C-Si)

Temperature coefficient for current	0.002 A/^{o}C
Temperature coefficient for voltage	-0.036 V/^{o}C
Temperature coefficient for power	-0.278 W/^{o}C

2N Solar Limited (Multi C-Si)

Temperature coefficient for current	0.046 A/^{o}C
Temperature coefficient for voltage	-0.264 V/^{o}C
Temperature coefficient for power	-0.346 W/^{o}C

Arion Solar (Multi C-Si)

Temperature coefficient for current	0.002 A/°C
Temperature coefficient for voltage	-0.075 V/°C
Temperature coefficient for power	-0.364 W/°C

HBL Limited (Multi C-Si)

Temperature coefficient for current	0.0014 A/°C
Temperature coefficient for voltage	-0.023 V/°C
Temperature coefficient for power	-0.179 W/°C

Waaree (Multi C-Si)

Temperature coefficient for current	0.0014 A/°C
Temperature coefficient for voltage	-0.058 V/°C
Temperature coefficient for power	-0.3298 W/°C

Reil (Mono C-Si)

Temperature coefficient for current	0.047 A/°C
Temperature coefficient for voltage	-0.334 V/°C
Temperature coefficient for power	0.476 W/°C

6. Low Irradiance Behavior

Indoor measurements of the low irradiance behavior also resulted in large differences for the several specimens (Jahn, U *et al* (2010). These measurements could be reproduced in an almost similar constellation at outdoor conditions. The best way to analyze the low irradiance behavior without effects like spectral shifts or angle dependence is self reference method which uses the PV module itself as the irradiance detector, like the temperature behavior, the low irradiance behavior showed significant differences within a given specimen of given technology.

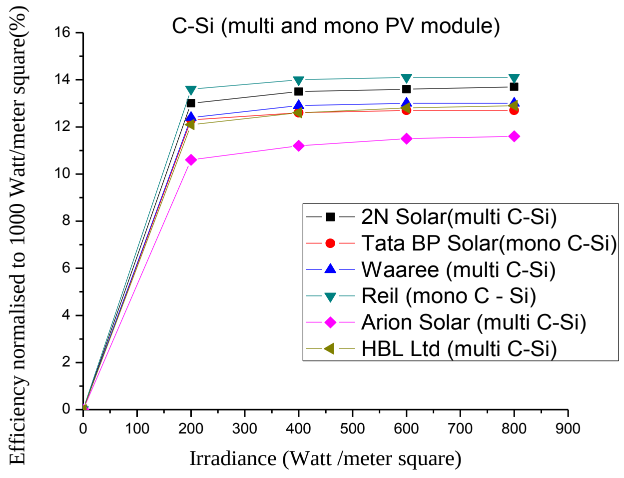

Fig.14 Low irradiance behavior of different multi crystalline PV modules, using self reference method

These performance differences of certain multi c-Si modules clearly influence the energy yield for different irradiance levels. (Cereghetti, N *et al*(2003) Some of the modules show a good performance generating significantly more electrical energy from its total yield at low irradiance (< 400 W/m^2) while some of the modules do not produce more energy with optimal low irradiance as shown in the following figure

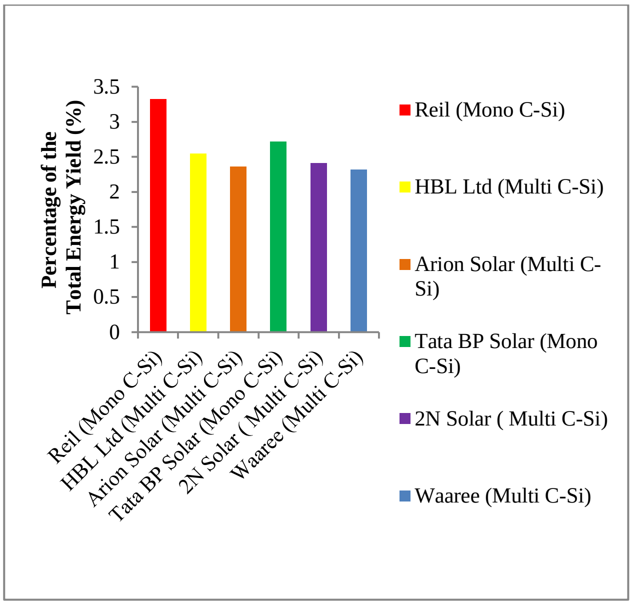

Fig.15 Comparison of the energy yield generation of six modules of different manufacturers *at optimal low irradiation (< 400 Watt/ meter square)*

7. Results of the outdoor measurements and technology specific characteristics

Specific Energy Yield and Ranking

To compare the energy yield of different specimens with different nominal power values, it is necessary to normalize the measured energy yield [Wh] with the nominal output power at STC [Wp]. It is known that P_{max} influences the specific energy yield [Wh/Wp] in an extremely negative way (Zinber, B., (2010). Factors such as history and conditioning of the modules prior to measuring play an important role for multi C-Si modules, as do good measurement conditions (solar spectrum, module temperature, irradiance, etc).

The P_{max} measurements of this study were performed outdoors and the ranking of energy yield measurements of two different technologies performed at Solar Energy Centre (SEC), located in Gurgaon Region of Haryana (India), was studied in the period of 01.05.2011-30.04.2012.

The annual energy yields analyzed from the data of one year P_m values shows a difference of 16.48 % between the lowest and highest energy yield values of different manufacturers of two different technologies of crystalline PV modules as compared to thin films (11.8%)(Schweiger, M *et al*(2011).

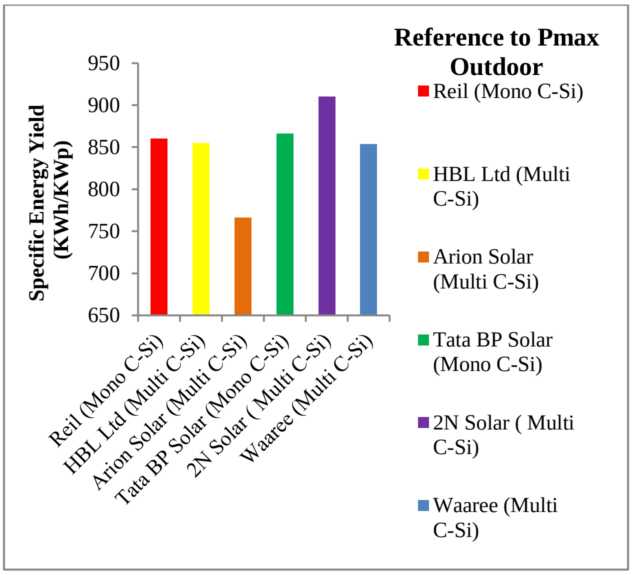

Fig.16 Ranking of energy yield measurements of 6 modules of different manufacturers of two different technologies performed at Solar Energy Centre, Gurgaon, India in the period 01.05.2011 - 30.04.2012

Applying the outdoor P_{max} value for normalizing the energy yield was identified as the best method because of short-time instability effects and spectral mismatch effects in measurements with the indoor flasher. Uncertainty in the P_{max} value is one of the errors and must be included and considered when interpreting the results.

Total Energy Production

The most important result is the energy yield of each PV technology. In the one year span from 2011-2012, different crystalline module types were studied and total energy production were found out as shown in the figure below

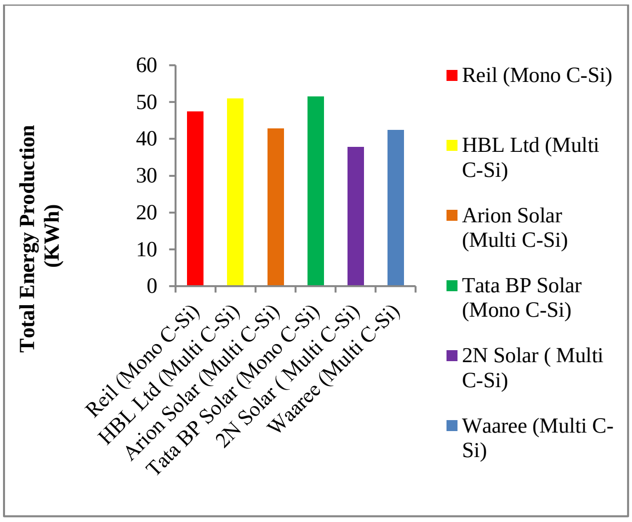

Fig.17 Comparison of the total energy production of six modules of different manufacturers of two different technologies performed at Solar Energy Centre, Gurgaon, India in the period 01.05.2011 - 30.04.2012

The total energy production analyzed from the data of one year values shows a difference of 23.52 % between the lowest and highest energy production values.

Conclusions

The comparative failure analysis of different multi-crystalline PV modules of different manufacturers over a period of one year was conducted at Photovoltaic Testing Facility Lab, Solar Energy Centre, located in Gurgaon Region of Haryana (India).

The results obtained for different crystalline PV modules both mono and multi of manufacturers named as Reil and Tata BP Solar, as well as HBL Ltd, Arion Solar, 2N Solar and Waaree respectively have been studied. The inferences drawn are as follows

- PV modules are complex products and are subject to fabrication and material – related tolerances:
- Degradation processes and long term reliability is complex and may not be uniform for modules of the same construction and type
- For laboratory tests also variations in test conditions need to be considered.
- IEC test levels are normally not sufficient to find out weaknesses in the module construction. For C-Si modules enhanced degradation will appear beyond 2000hours test duration for Damp Heat Test and beyond 400 cycles for thermal cycling test. (Carlson, T *et al* (2006),
- Failure rates of IEC qualification testing tend to decrease over the past years due to advanced / advancing technologies and improved quality control (for C-Si and also thin films). (Cousins, PJ *et al* 2010).
- Most test failures are due to problems in module processing and quality control issues.

With respect to low irradiance behavior, the mono C-Si module of Reil showed the highest value of efficiency as well as percentage of total energy yield, while on the other hand, mono C-Si module of Tata BP Solar showed lower value. At low irradiance, the multi C-Si module of 2N Solar showed the best performance, while Waaree (multi C-Si) and HBL Ltd (multi C-Si) showed average performances and Arion solar (multi C-Si) tested specimen left some room for improvement.

The analysis of the single year high precision outdoor data of six crystalline PV modules of different manufacturers of two different technologies yielded the following conclusions

The significant factors influencing the specific energy yield and total energy production of PV modules of crystalline module types is low irradiance, temperature dependence, spectral matching with the solar spectrum and its changes in the course of a day as well as year for a given climate respectively.

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Ministry of New and Renewable Energy, 19th Milestone, Gwalpahari, Gurgaon- Faridabad Road, 122001, Haryana, India.

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