LIFETIME PERFORMANCE OF CRYSTALLINE SILICON PV MODULES

Ewan D. Dunlop
European Commission, Joint Research Centre, Institute for Environment and Sustainability, Renewable Energies Unit
TP 450, via E. Fermi 1, I-21020 Ispra (Va), Italy

ABSTRACT

A comparison of the original and weathered power output of several different silicon technologies, dating back to 1982 is presented and confronted together with examples of degradation and weathering effects. The basis of the analysis is the JRC Ispra outdoor test field where examples of diverse generations of PV technology have been subjected to long term climatic exposure. Some of the degradation may be attributed to photon effects while others are more related to encapsulation and delamination issues. The effect of performance degradation on the Energy Life performance is explored in order to quantify the impact of different degradation mechanisms on the energy generation. Results indicate the initial degradation is not the key issue for maximising energy output.

1. INTRODUCTION

The effects of degradation of Photovoltaic solar modules and arrays and their subsequent loss of energy performance can have a serious impact on their total energy generation potential. Various mechanisms have been discussed as the source of the degradation. One such source is the initial photon degradation related to a physical process in the solar cell itself [1], this effect is normally observed in the first hours of operation. Other effects are related to long term weathering and degradation of the module package resulting in a degradation of the module performance [2]. In order to understand the effect and relevance of each of these mechanisms on the total energy production of a PV module or array over its life time we require to identify the associated degradation rates for each of these processes.

With this knowledge of the degradation rates combined with the life expectancy of the module we can take the first steps in defining the total energy output per lifetime of a PV module or array. We express this total energy in this paper as the “Energy Life“ of the module; all degradation processes reduce this Energy Life. By establishing a figure of merit concept such as the Energy Life one may then begin to assess the relative importance of each of the degradation mechanisms as presented in this paper.

2. EXAMPLES OF INITIAL DEGREDATION

There have been many recent publications regarding the so-called photon degradation of mono crystalline silicon solar cells. However this is by no means a new concept as already as early as 1993 with the publication and implementation of the IEC standard for the qualification testing of PV modules [3] the observation of this process has been made. During an IEC test procedure there is the requirement to perform a so called outdoor exposure (OE) test of 60kWh solar irradiance in short circuit conditions. At the JRC ESTI laboratory over 60 modules types have been subjected to this test with the measurement of the module power before and after the exposure. Presentation of these observations was first made in 1995 for the module qualification testing sequence [2].

This OE test was specifically introduced in order to identify degradation mechanisms, which may escape the accelerated indoor testing methods. Indeed we can see that its inclusion is in fact well justified, if we consider that 60kWh.m-2 is a very low stress level for a module expected to last over 20 years (~20MWh.m^{-2} of solar irradiance).

Fig. 1 represents the summary of degradation levels observed in these 66 modules of different construction and cell configurations. Degradations observed range from no change to 6.3% degradation in P_{max}. In most case we have observed a correlation between the P_{max} degradation and the short circuit current degradation. This would suggest a series resistance change in the exposed modules consistent with other reports.

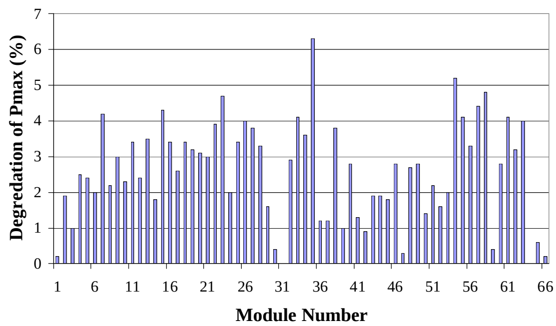

Fig. 1 Summary of the degradation in P_{max} after the Outdoor Exposure test for 66 module types tested at JRC Ispra.

The average degradation observed from Fig. 1, for the purposes of estimating energy life in Section 4 is 2.6% with deviation of ± 1.3%.

3. EXAMPLES OF CONTINUOUS DEGRADATION

As has been reported elsewhere detailed, analytical data of the progressive degradation of PV modules is not readily available [4]. One exception to this rule, which presents a detailed review of the long-term operation of a PV array and its associated loss mechanisms, is described in [5]. The crystalline silicon array in question uses Arco Solar ASI 16-2300 modules. The array was installed in March 1982, and a sample set of 18 modules were then measured at JRC in October 1982. The average deviation of the measured power from the declared power was -

3.9%. At this time we can not say for sure that all of this is due to photon degradation but considering the OE data presented in Section 2 it is possible to estimate 2.6% photon degradation and 1.3% deviation from declared power.

One can be confident that we are within the expected band concluded in section 2 of 2.6%± 1.3%. Since that time the repeated measurement of the modules has shown an average weighted degradation of 5.2%. Over the 19 years of operation this would correspond to a compound equivalent degradation of 0.27%per annum excluding the initial degradation due to Photon effects. If we include photon degradation as constant factor we would have degradation rate of 0.4% per annum. This is less than reported for other sources [4] but may be attributed to the high level of maintenance and replacement of components as indicated in [5].

The degradation rate for a PV array installed in 1991 [6] indicates a degradation of 4.39% in 11 years or 0.4% per annum. This degradation rate is inclusive of the initial photon degradation. The remarkable agreement between these two publications would indicate that in fact it is a consistent and reliable estimate of the continuous degradation effects. Also of note here is the fact that these were also Arco Solar modules but of type M-75.

The causes for degradation in continuous operation can be many. Some examples taken from the JRC outdoor test site (Fig. 2) are, severe discoloration, delamination, cracking of cover glass, splitting of back-sheets, wiring degradation and junction box failure Some examples are shown in Fig. 3 to 5.

Fig. 2 The JRC Outdoor Test field, running since 1982.

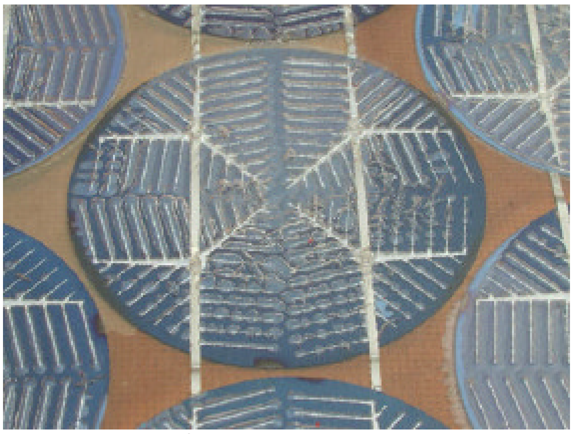

Fig. 3 Example of severe discoloration and delamination.

Fig. 4 Splitting delamination of the back-sheet, note in this case the moisture ingress appears still to be blocked by the encapsulent.

Fig. 5 Junction box degradation leading to corrosion of the electrical connectors.

Even although some of these defects appear catastrophic in most cases the result is only a reduction in power output (i.e. a degradation not total failure). In fact, as has been reported in [4] it is much more common to observe performance losses due to these effects rather than failures. This results in practice that the systems continue to operate but with considerably reduced power performance.

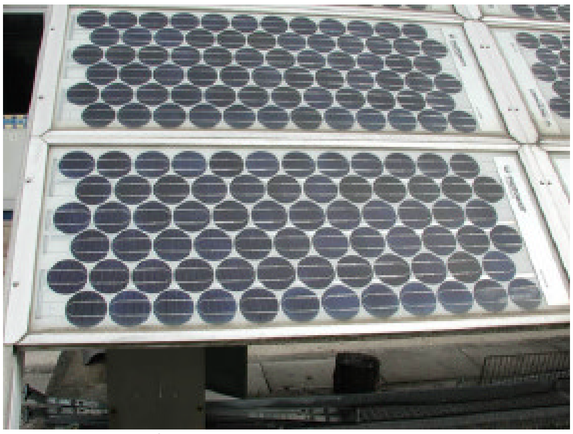

Fig. 6 A set of 19 year old PV modules exposed at the JRC site which show none of the visible signs of degradation illustrated in Fig. 3 through 5.

Presented here are specific defects to support the arguments of the paper and extract some measurable parameters of estimation of the Energy Life of a PV module. It should be by no means interpreted that all these defects are always present on any system in. In Fig. 6 we see the condition of another set of modules exposed on the same site also since 1984 which display none of the defects listed before

4. ESTIMATES OF PV MODULE ENERGY LIFE

The terminology "Energy Life" introduced here, is the estimation of that energy which one would expect to generate with a given module over its warranty operating life. This introduces the concept of no longer calculating capital cost per installed watt peak, but instead the cost of generating kWhs over the module or array lifetime.

Much of the discussion surrounding the performance of Photovoltaic solar modules relates to two issues at the present time, firstly the performance ratio (including peak power) definition and secondly the durability of the product (lifetime). From the indications which we have given in Sections 2 and 3, the estimated life time of these products can be confidently predicted to reach at least 20 years with and over all degradation of ~10% of initial installed power.

Concurrently, more and more emphasis is being placed on developing a Watt-Hour label or Energy Rating method to define the kWh per year expected energy generation [7]. If we combine these concepts we can arrive at what one may postulate as the energy generation for the module lifetime, or Energy Life of a PV module or array.

One may immediately raise the question "what has this to do with the weathering of silicon PV modules?" The answer is very simple we require fundamentally to know the mechanisms and characteristics of the degradation process in order to establish the Energy Life of a given module.

Of vital importance to this, is which of the degradation mechanisms we are examining here is the dominant factor in the Energy Life of a PV module. As has been demonstrated above initial degradation of ~2.6 % in initial power are typical for all silicon PV modules while the continuous degradation of the performance can typically reach 5.5% over the 20 year warranty life-time.

In Table I one may see the calculated the effects of the two degradation mechanisms described here (initial photon degradation and long term continuous degradation). For this purpose we have assumed the following criteria:

- P_{max} initial 100W
- Module life-time 20 years
- Solar Irradiance input 1095kWh per annum

The Energy Life of the module is thus the sum of annual production per year minus the degradation losses. In Table I a, the calculated Energy life of this "module" is given as a function of initial photon degradation (vertical) and continuous degradation (horizontal). A perfectly non-degrading 100W module would then have a 20-year Energy Life of 2.19MWh. Also calculated in Table I is the energy loss b. in kWh and the relative degradation c.

5. DISCUSSIONS

The losses introduced and quantified for both of these degradation process has been shown to be in the order of 0 to 3.9% for the initial degradation and 0.1% to 0.7% per annum for the continuous degradation. The effect on Energy Life can be seen in Table I to result in losses in the order of 5.2% for the typical values observed in Section 2 and 3 over the module lifetime. This is weighted slightly more to the continuous losses (2.8%) than to the photon degradation (2.5%).

Table I The estimated energy life of a 100Wp PV module over its 20 year life time a. as a function of the degradation mechanisms as expressed in kWh. Secondly b. the power losses due to the degradation expressed in kWh. Thirdly c. the % degradation loss in Module Energy Life.

a. Energy (kWh)	**Continuous Degradation(%)**			
Photon Degradation (%)	**0**	**0.1**	**0.3**	**0.5**
0.0	2190	2169	2128	2089
1.5	2157	2136	2096	2057
2.5	2135	2115	2075	2036
3.5	2113	2093	2054	2015

b. Losses	**(kWh)**			
0.0	0	20	61	100
1.5	38	53	93	132
2.5	55	74	114	153
3.5	33	96	136	174

c. Losses	**(%)**			
0.0	0	0.9	2.8	4.6
1.5	1.5	2.4	4.2	6.0
2.5	2.5	3.4	5.2	7.0
3.5	3.5	4.4	6.2	7.9

However if one considers reports of continuous degradation of up to 0.7% per annum [4] this would result alone in 8% degradation in the module energy life. All indications regarding the photon degradation are that, in the worst case, it will remain around the level of 2.8% ± 1.3% while the possibilities for addition continuous degradations are much higher.

Fig. 7 illustrates the progressive loss in Energy Life with increasing annual degradation rate. We would therefore conclude that the most important factor in maximising the PV module Energy Life is in fact the reduction of the continuous annual degradation process and not the initial photon degradation.

Considering the financial loss associated with a degradation of 5.2% (typical value) per 100W module this relates to Euro 64.20. This is over 10% of the initial capital cost of the module at present rates of Euro 6/W_p.

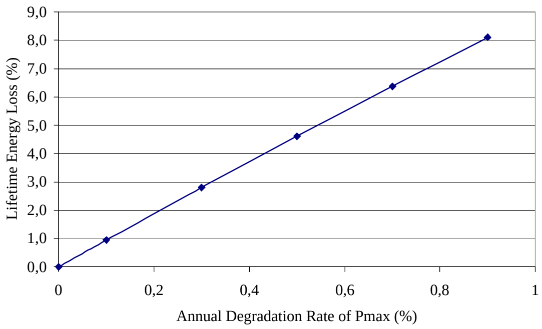

Fig. 7 The loss of Energy Life production as a function of annual degradation rates. Reports have placed this rate between 0.2% and 0.7% per annum [2, 4, 5, 6, 8]

6. CONCLUSIONS

The energy lifetime performance is dependent on several factors such as, the initial photon degradation, material ageing and degradation that can be provoked by many factors. For the life time operation of a PV module or array the effect of the initial degradation is undesirable but in terms of lost energy production is less significant than the effect of constant degradation over the 20-year lifetime.

Much of this is reflected already in manufactures declarations and warranties. The initial power declarations are normally with in the range of 5% whereas the lifetime warranty is normally closer to 20%. This has been shown to be a very pragmatic but realistic approach.

Considering the calculations made in End life energy generation these losses can amount to 8% of estimate energy yield for a degradation of as little as 0.7% per annum, compared to a typical loss due to photon degradation of 2.5%.

While the work on reducing the initial degradation effects is of vital importance and is also generating a considerable activity and interest the study and understanding of the long term degradation mechanisms and more to the point how to reduce these effects still requires additional effort.

7. ACKNOWLEDGEMENT

The author wishes to acknowledge the helpful contributions from Antonella Realini (LEEE-TISO), Tony Sample and Heinz Ossenbrink (JRC).

8. REFERENCES

[1] Knobloch J., Glunz S. W., Henniger V. Warta W. and Wettling W., *21% Efficient Solar Cells Processed from Czochralski Grown Silicon*, proc 13th EU PVSEC, Nice, France 1995, pp 9

[2] Bishop J. and Ossenbrink H., *Five years of module qualification testing*, proc. 13th EU PVSEC Nice, France 1995, pp2104

[3] *Crystalline Silicon Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval* CEI/IEC 61215, IEC Geneva, Switzerland, 1993

[4] Quintana M. A., King D., McMahon T.J. and Osterwald C. R., *Commonly Observed Degradation in Field-Aged Photovoltaic Modules*, proc. 29th IEEE PVSEC, New Orleans, USA, 2002, pp 1436.

[5] Realini A., Bura E., Cereghetti N., Chianese D., Rezzonico S., Sample T. and Ossenbrink H., *Study of a 20 year old PV Plant (MTBF Project)*, proc. 17th EUPVSEC, Munich, Germany 2001, pp 447

[6] Reis A. M., Coleman N.T., Marshall M.W., Lehman P.A. and Chamberlin C.E., *Comparison of PV Module Performance before and After 11-years of field Exposure*, proc. 29th IEEE PVSEC, New Orleans, USA, 2002, pp 1432

[7] Anderson D., Bishop J. and Dunlop E.D., *Energy Rating of Photovoltaic Modules*, proc. 16th EUPVSEC, Glasgow, UK, 2000, pp 2087

[8] Sample T. and Ossenbrink H., *The results of 12 years of Module Qualification Testing to IEC61215*, to be published in proc. WCON3, Osaka, Japan 2003.