Performance of old PV modules

Measurement of 25 years old crystalline silicone modules

Elforsk rapport 06:71

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Preface

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Summary

PV-modules based on crystalline silicon are often purchased with a warranty of 25 years. It is of a general interest to verify if such a warranty is realistic in the Swedish climate. When the stand-alone installation at Bullerö in the archipelago of Stockholm was dismantled an opportunity to measure performance of modules that had been in operation for 25 years showed up.

The modules were transferred to Energibanken's test site north of Stockholm.

All modules were measured in natural sunlight, close to "Standard Test Conditions, STC". The measurements were carried out on the 30th of August in clear weather. The measured electric parameters were compensated with standardized methods in order to account for the slight deviation from STC. Nineteen of the twenty modules obtained average peak power values which were less than 2.0 % lower than data obtained in the beginning of the modules' operation. Furthermore, this apparent degradation falls within the accuracy of the utilized measurement technique.

One of the 20 modules shows a degradation of roughly 50 %. Visual inspection of this module reveals one cell with a suspicious appearance. The cell is partly discoloured and surrounded by small bubbles in the encapsulating resin. The cell has most likely been exposed to a so called "hot-spot" phenomenon. The IV-characteristic is typical for a module with one defect cell, partly shunted and with a decreased series resistance..

The appearance of cells in the other modules shows generally only a few defects such as corroded contact grids and bubbles in the encapsulating resin. Long-term testing of modules in countries with higher ambient temperatures very often results in a pronounced "yellowing" of the encapsulating resin. No cracked cells were observed and only one case of minor delamination.

The conclusion is that a 25-year technical lifetime of modules based on crystalline silicon cells is realistic in the Swedish climate. This figure may even be somewhat conservative today when the encapsulation of the PV modules has been improved.

Sammanfattning

Solcellsmoduler säljs ofta med en garanti på 25 år. Det finns ett allmänt intresse att veta om denna garanti är realistisk i det svenska klimatet. När solcellsanläggningen på Bullerö i Stockholms skärgård monterades ned erbjöds ett utmärkt tillfälle att verifiera prestanda hos moduler baserade på kristallint kisel som varit i drift i 25 år.

Modulerna demonterades av en rivningsfirma och transporterades till Energibankens lokaler strax norr om Stockholm.

Modulerna mättes i naturligt solljus under förhållanden som var mycket nära de krav som ställs vid mätning av solcellers prestanda (Standard Test Conditions, STC). Mätningen utfördes den 30 augusti i klart väder i Stockholm. Mätresultaten kompenserades med standardiserade metoder till STC-förhållanden. Nitton av tjugo moduler hade en uppmätt prestanda som låg mindre än 2.0 % under den jämförande mätningen från 1985. Denna skenbara försämring ligger inom felgränserna för mätmetoden.

Den tjugonde modulen uppvisade en nära 50 procentig försämring. Denna försämring kan härledas till en synligt defekt cell. Cellen har troligen varit utsatt för en s.k. ”hot-spot” någon gång under driften.

Inspektion av övriga moduler visade påfallande få visuella defekter utöver den ovan nämnda. Ingen gulning av inkapslingsmaterialet kunde skönjas. Gulningen är annars ett vanligt förekommande problem hos moduler som är i drift i varmare klimat än det svenska. Några celler hade stråk av korroderad metallisering. Detta är troligen endast ett kosmetiskt problem. Inga spräckta celler och endast ett fall av begränsad delaminering kunde hittas.

Slutsatsen är att 25 års teknisk livslängd för solcellsmoduler baserade på kristallint kisel är fullt rimlig och kanske till och med i underkant i det svenska klimatet, särskilt med tanke på att dagens moduler har ännu bättre inkapslingsmaterial.

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1 Introduction

A purchased PV-module today is often accompanied with a warranty of 25 years. The warranty is based on a type approval (IEC 61215) [1], which is a procedure with a number of accelerated lifetime tests. In order to convince the market that a 25 years warranty is realistic, it is important to support the type approval data with data from field-testing. For the Swedish market, it is desirable to use data from field-testing in the Swedish climate. When the Bullerö stand-alone PV plant was dismantled, an opportunity to check performance of modules that have been exposed to outdoor conditions for over 25 year showed up.

After the first energy crisis in the mid 1970’s, PV was expected to play an important role in the future energy system. Massive research and development on PV related projects were launched in various places worldwide. It was soon recognized that, together with costs reductions, the reliability of PV modules was a key issue. In this early period a number of different cell encapsulation methods were tested. Many of them turned out to have severe problem with reliability caused by the used encapsulation method and harsh environments. Delamination, cracked cells, broken interconnects, discoloured resin, hail storm damage among other problem occurred at field-testing. At the same time laboratory testing methods were developed. At Jet Propulsion Laboratory in California a test sequence that includes several accelerated lifetime tests, mechanical strength and electrical isolation measurements was used. It was called “JPL Acceptance test”. It was adopted by other countries and is now after many revisions an international standard (IEC 61215).

In the beginning of 1980 it was generally accepted that a module type that had passed the JPL acceptance test was expected to have a lifetime of up to 10 years. Most of the previously mentioned and often encountered problems had disappeared as a result of improved encapsulation techniques. Warranties were written according to this.

The first Swedish PV demonstration system was built in 1981. It was mounted on the façade of a building in Årsta south of Stockholm. After 6 years of operation the system was dismantled. In 1988, the modules were re-erected as a part of a stand-alone system in the National Park Bullerö in the archipelago of Stockholm (pictures of both the installation at Årsta and Bullerö can be seen in figure 1 below). The system served as the energy source for the visitors and the park guard, who lived on the island all year round. In May 2006, the modules were dismantled once again, since the island had become fully electrified thanks to a cable from the mainland.

The modules appeared relatively unaffected after 25 years at outdoor conditions. Production data from the operation of the Bullerö plant did not indicate any loss of peak efficiency. It was decided that it was of great interest to thoroughly investigate the present performance of the modules.

Figure 1. To the left: Sweden’s first PV demonstration project in Årsta, Stockholm. To the right: The stand-alone PV system on Bullerö, based on the modules from Årsta.

2 Method

The method for studying the 25 years old modules is based on comparisons of early and recent measurements of IV-curves and peak power.

2.1 Theory

The IV-curve is the most important characteristic of the performance of a photovoltaic system. As the name implies, it represents the current as a function of the voltage. There are a number of important values that can be retrieved from the IV-curve:

- The short circuit current (I_{SC}). The current when the voltage over the photovoltaic cell, module, array or system equals zero.
- The open circuit voltage (V_{OC}). The voltage reaches its maximum point when the current equals zero.
- The maximum power point (P_M). The power has its maximum where the product of the current and the voltage has its maximum.
- The fill factor (FF) is calculated as $FF = P_M / (V_{OC} * I_{SC})$

The output from a PV cell is dependent on a couple of external factors:

- Irradiance [G_I]
- Spectrum of the light
- Cell temperature [T_A]
- Angle of incident light

To be able to compare PV cells and modules, standard values have been chosen for these parameters. The P_M value obtained under these conditions is called the peak power [P_0]. The values for the parameters when measuring peak power are [2]:

- Reference irradiance [G_{STC}] = 1000 W/m^2
- Reference spectrum[1] = AM 1.5, Global
- Reference cell temperature[1] [T_{STC}] = 25^{o}C
- Light perpendicular to module surface

These conditions are in practise impossible to exactly achieve. Therefore it is necessary to compensate the results for any discrepancy from the above-mentioned values in order to be able to compare them with other measurements. In this work, a reference cell was used to register both the irradiance and the cell temperature during the measurements.

[1] In 1981 the reference spectral distribution was AM 1.0 and the reference temperature was 28^{o}C [3].

Deviations in irradiance are compensated linearly by multiplying the measured power with 1000/measured irradiance, as long as the irradiance is in the range 700 to 1000 W/m^2 [2].

Deviation in cell temperature is compensated linearly according to a ratio [α] given by the datasheet. This is valid as long as the cell temperature is in the range 25 to 60°C [2].

The equation for calculating the peak power then becomes:

$P_0 = P_M * G_{STC}/G_I * (1+(T_A-T_{STC})* \alpha)$

Measurement in natural sunlight is done under non specified spectral conditions (if it is not recorded at the time of the measurement). According to IEC 60904 1-10 all spectral distributions occurring at G_I >700 W/m2 comply with a Class A solar simulator. From King et.al. [4] it is concluded that the spectral error when measuring crystalline silicon devices is +/- 2 % when the air mass value ranges from 1,0 to 2,5. If the measurements are made in natural sunlight during midday a Swedish summer day and recorded with a reference cell it can be assumed that no compensation for spectral deviations has to be made.

2.2 Equipment

The instrument for recording IV-curves was a STELLA Photovoltaic Field Array Tester [5]. It is a portable array tester and it uses a discharged capacitor that functions as ‘load resistor’. Current and voltage are measured during the process of charging the capacitor.

To cover a wide span of different voltage- and current-measuring ranges the power components have been designed as interchangeable plug-ins. The 30V/4A plug-in was used throughout the whole experiment.

A Siemens reference module that was assumed to be stable was used for measuring irradiance and cell temperature (Figure 2). It consists of nine cells, where the centre cell is the actual reference cell. The surrounding dummies are there to eliminate edge effects on the reference cell. A Pt100 temperature sensor is glued to the backside of the centre cell. The Pt100 sensor returns a resistance value that has to be converted to a temperature value. From a datasheet of the Pt100 [6] it can be read that each Ω over 100 Ω corresponds to approximately 2,56 °C over zero degrees

Figure 2. The Siemens reference cell that was used for measuring irradiance and cell temperature.

2.3 The modules, ASI 16-2000

The following information has been retrieved from the datasheet of the modules [7].

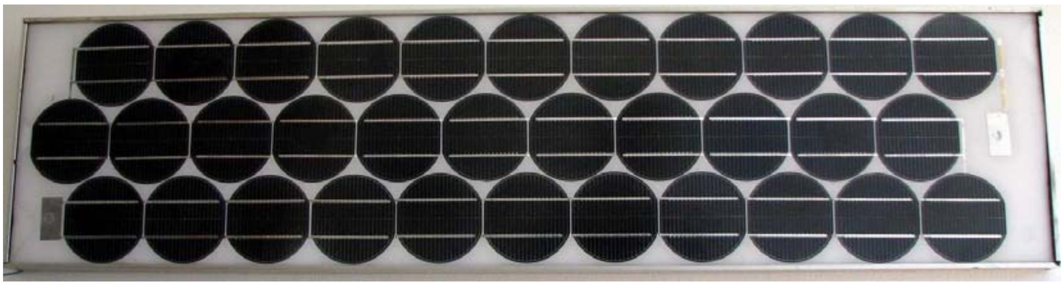

Figure 3. The ASI 16-2000 module.

Producer: ARCO

Module type: ASI 16-2000

Cell type: C-SI

Effective cell area: 0.26 m^2

Cells per module: 33

P_M = 33 W_P

I_{SC} = 2.5 A

V_{OC} = 20 V

Decrease in P_M per degree of temperature increase: 0.53 %

2.4 Measuring arrangement

When the modules arrived they were stripped from remaining metal fittings and the front surface was wiped lightly with a wet cloth to remove dust.

The arrangement for measuring the modules was quite simple. Two wooden pallets nailed together with a suitable angle (approx. 50°) were used as stand for the modules and the reference cell. The inclination is necessary in order to give perpendicular irradiance on the modules. The stand was too small for all modules to fit. The modules that were waiting to be measured were distributed on the ground without any shading. This was a way to ensure that the modules reached a steady temperature. The picture below shows the measuring arrangement.

Figure 4. The arrangement for measuring the modules.

3 Results

The measurements were carried out in Stockholm between 13:27 and 14:29 on the 30th of August. This means that the inclination of the sun was approximately 40^o (AM 1.5 can be assumed). The registered irradiance differed between 889 and 942 W/m^2 with a mean value of 925 W/m^2.

3.1 Measurements

The table below summarizes the data from the measurements. P_0 is compensated according to the equation in chapter 2.1.

Tabel 1. Results from measurements.

Module number	G_I [W/m^2]	T_A [^{o}C]	I_{SC} [A]	V_{OC} [V]	P_M [W]	P_0 [W]
250652	918,3	40,00	2,16	18,3	26,3	30,5
250555	942,8	44,87	2,23	17,8	24,0	27,8
250453	933,7	45,38	2,28	17,5	26,1	30,5
250428	942,8	45,13	2,26	17,7	26,8	31,0
250576	942,2	45,13	2,26	17,6	25,0	29,2
250459	936,0	46,92	2,26	17,4	25,4	29,9
250595	936,0	46,92	2,25	17,4	25,4	29,9
250685	910,8	46,92	2,18	17,6	25,1	30,3
250566	902,0	46,92	2,18	17,4	25,4	31,1
250420	902,6	47,44	2,16	17,5	25,8	31,5
250522	924,8	47,18	2,16	17,4	25,5	30,6
250468	934,6	48,46	2,25	17,7	26,8	31,8
250545	938,9	48,46	2,12	17,7	16,3	19,3
250523	928,8	48,97	2,23	17,6	25,9	30,7
250899	931,7	46,67	2,22	17,5	26,1	31,0
250450	928,1	47,95	2,21	17,4	24,9	29,7
248850	925,5	47,95	2,28	17,4	25,7	30,7
250563	919,3	47,69	2,19	17,6	25,4	30,3
250574	917,0	45,64	2,21	17,6	25,1	30,0
250578	924,8	45,90	2,26	17,9	27,4	32,2

The mean value of the measured power from all modules is 29.9 W. The figure below shows nicely how only one module diverges from the others. The rest is gathered around the 30 W line.

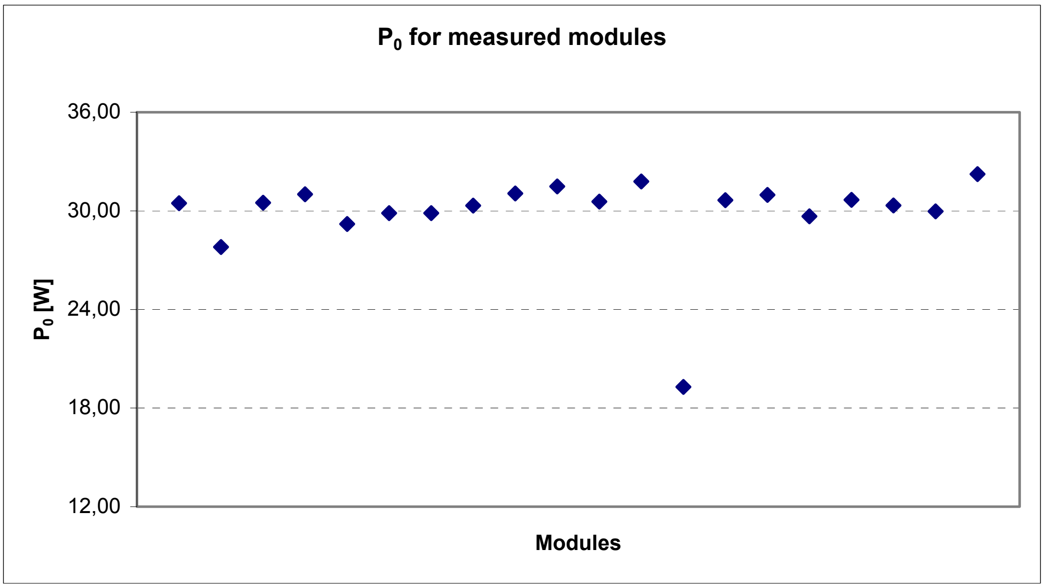

Figure 5. Power from the measured modules.

Most of the modules showed similar IV-curves, with the module with significant lower power (modules number 250545) as the obvious exception. The figure below shows a graph with IV-curves from three different modules, including module 250545.

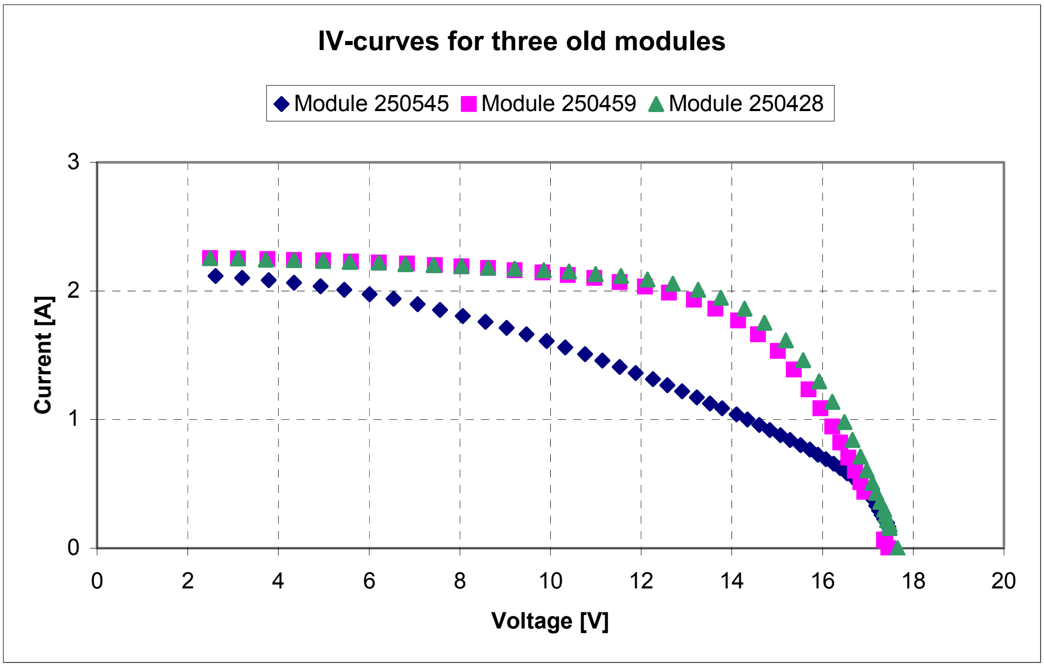

Figure 6. IV-curves for three of the measured modules. The two upper curves are examples of typical IV-curves and the lower is the IV-curve for the module with significant lower power.

3.2 Visual inspection

In general the modules showed very little trace of outer degradation. A few modules had some stains in the front glass. But these defects did not result in any significant changes that could separate these from the other modules. The pictures below shows some visible defects.

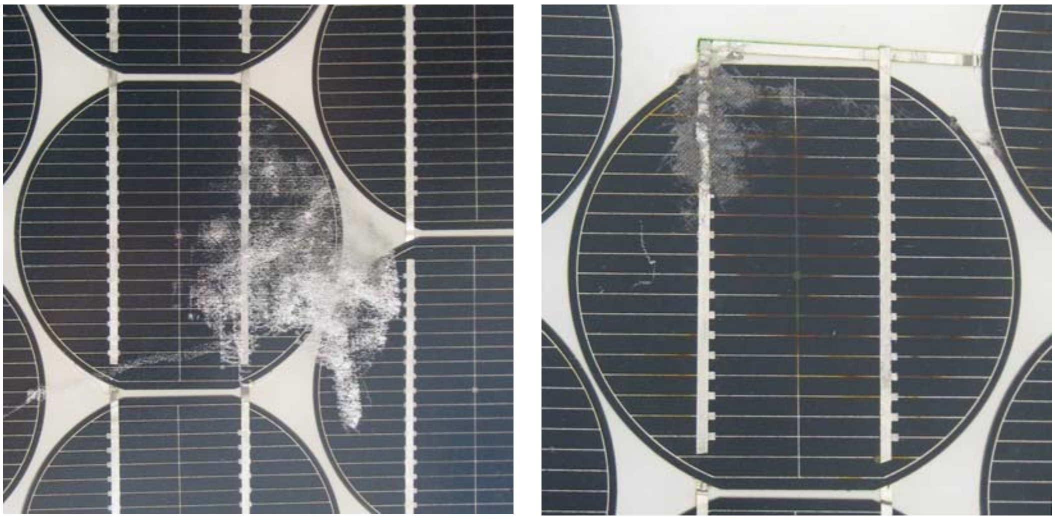

Figure 7. To the left: Stains in front glass. To the right: Delaminated area on one cell in module 250555, which most likely causes the observed decrease in fill factor.

From a visual inspection of the cells in the modules it is clear that many cells seem to be unaffected. But many cells also show a grid pattern that has been discoloured into a bronze tint. However, no significant difference for modules with particular many discoloured cells could be noticed. The two pictures below show one typically unaffected cell and one cell displaying the bronze discolouration.

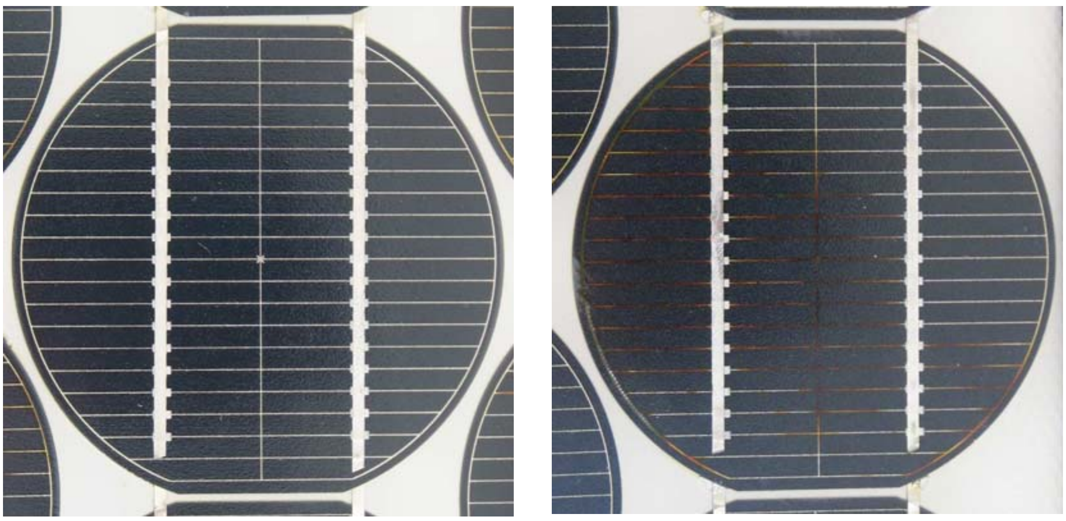

Figure 8. To the left: A typically unaffected cell. To the right: A cell with discoloured grid pattern.

Only one cell shows a clear degradation. In this case part of the cell has clearly degraded and turned into a yellowish colour. This cell is located in the single module that showed a significant lower power than the rest of the modules. This indicates that the degradation of this cell is the reason behind the power decline of this module. The pictures below show the degraded cell and the module where it is fitted.

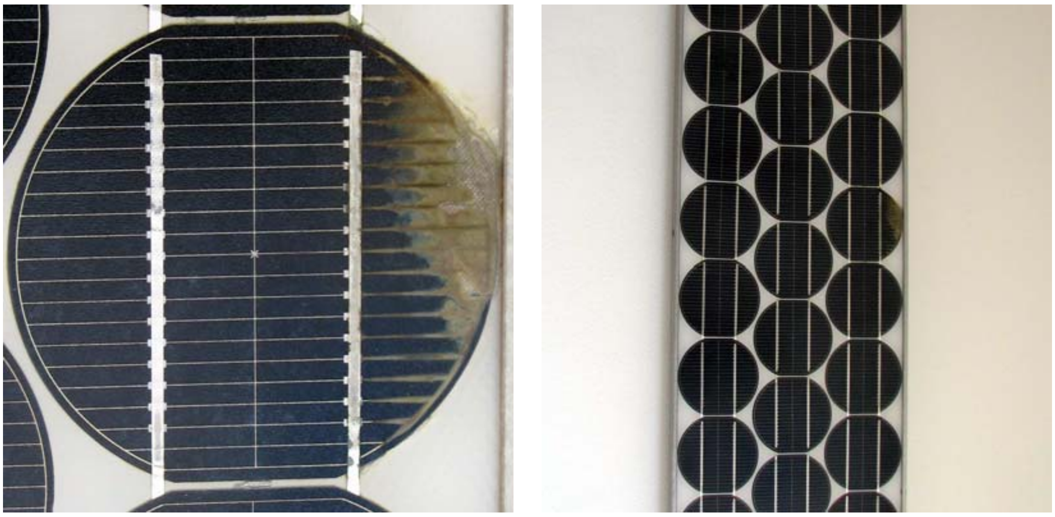

Figure 9. To the left: The cell with a clearly visible degradation. To the right: The module where the degraded cell is fitted

4 Analysis

To draw conclusion on how these modules performance have been affected by their 25 years of outdoor service it is necessary to compare the obtained measurements with measurements that were made when the modules were new.

The datasheet for the ASI 16-2000 module gives a value of the peak power of 33 W. This value can also be used for the comparison. However the value from the measurement in 1985 is chosen, even though it is associated with some errors, because it is measured on these particular modules.

4.1 Comparison with initial data

In 1985 a study was carried out to measure the performance of these modules after the installation in Årsta [3]. The modules were not measured separately, but an IV-curve for the whole string was obtained. The figure below shows the result of the measurement in Årsta.

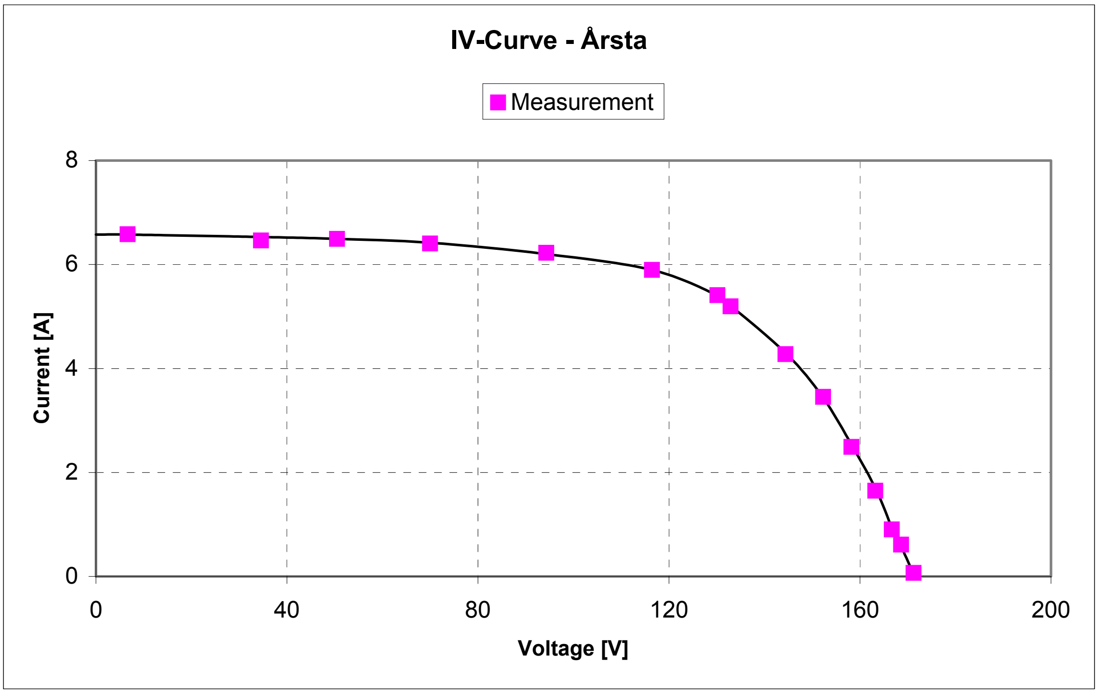

Figure 10. IV-Curve from measurement of the Årsta installation, measured in July 1985 at G_I = 868 W/m^2 and T_A = 56 °C.

A mean value of the power of the modules can be calculated from this, knowing that the modules were connected ten modules in serial in three parallel strings.

$P_M \approx 130.2/10 * 5.41/3 = 23.47$ W.

This number is compensated in the same way as the newly measured values in order to compare the values. The conditions for the 1985 measurements were: G_I = 868 W/m^2 and T_A = 56 °C. This gives

P_0 = 23.47 * (1000/868) * (1+((56-28) * 0.0053)) = 31.05 W_P

The mean value of the peak power from the new measurement of all the modules is 29.88 W. This corresponds to decrease of 3.8 %. If the module with significant lower power is excluded the decrease is only 2.0 %. The figure below illustrates the difference between the IV-curve from the 1985 measurement and a typical module from the 2006 measurement. The IV-curves are compensated to G_{STC}=1000 W/m^2 and T_A=28 °C.

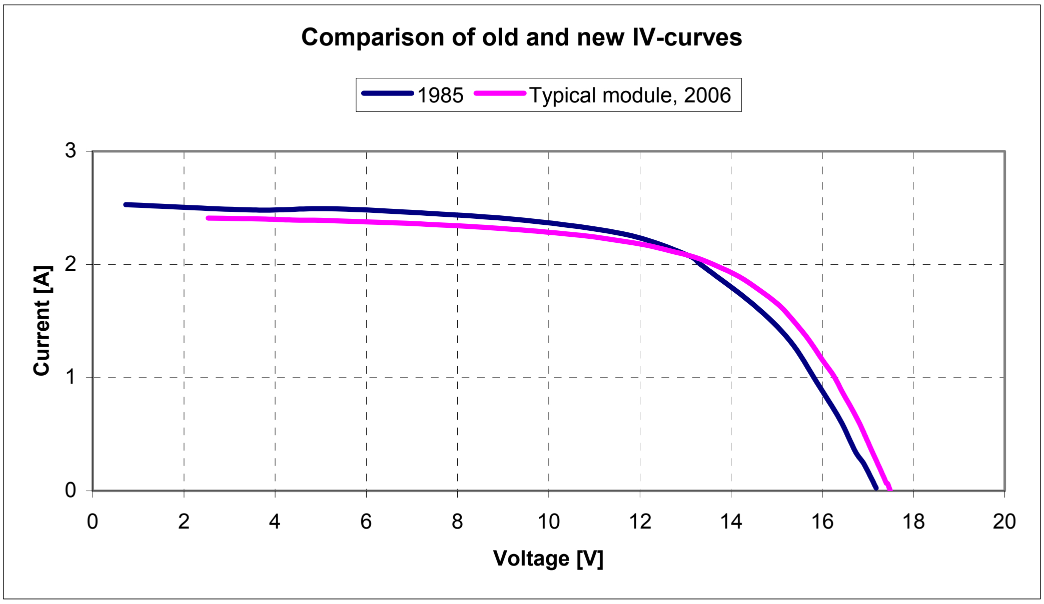

Figure 11. Comparison of IV-curves from the 1985 measurement and from a typical module from the 2006 measurement. Both IV-curves are compensated to G_{STC}=1000 W/m^2 and T_A=28 °C.

4.2 Discussion and error sources

Three types of errors in the measurements are expected to occur:

1. Irradiance. The used reference cell is calibrated +/- 1 % at STC conditions. Spectral variations are estimated to add another +/- 1 %.
2. Temperature. The cell temperature is estimated from a measurement of a Pt-100 sensor glued to the reference cell in the reference module. A special temperature study was done and the result indicates an error in P_0 caused by an error in the temperature measurement of +/- 2 %. The size of this error is confirmed by the change in Voc caused by increased temperature.
3. A general error arising from electrical measurements is estimated to be less than 1 %.

This results in a total error of +/- 5% which is used in the following discussions.

When comparing typical module performance in the present study with the average module performance from the 1985 measurement another error is introduced. This error is caused by mismatch between individual modules when they are connected in series and parallel. This mismatch will distort the resulting IV-curve and leads to a slightly lower value of the fill factor for the connected modules compared to the individual modules. The size of this error was estimated by using a mismatch tool, which is a part of the PV-sizing software "PVsyst". As input to this tool the standard deviation in Isc and Voc obtained in the measurement were used. The result shows that the mismatch error is less than 0,5 %.

5 Conclusion

Twenty modules which were manufactured and installed in 1981 have been measured after 25 years of outdoor exposure in the Swedish climate. The results are compared with old measurements.

The modules have an average peak power of 3,8 % lower than the average value measured in 1985. Earlier measurements, 1981, of the individual modules have been lost. The 3,8 % degradation is within the accuracy of the used method and a general degradation of the modules cannot be concluded.

One of the 20 modules (IV-curve in Figure 6 and Photo in Figure 9) shows a distinct degradation. Visual inspection of this module reveals one cell with a suspect appearance. The cell is partly discoloured and surrounded with small bubbles in the encapsulating resin. The cell has most likely been exposed to a so called "hot-spot"[2]. The IV-characteristic is typical for a module with one defect cell with decreased series resistance and partly shunted. This module adds 1,8 % to the 3,8 % degradation mentioned above.

The appearance of cells under visual inspection shows generally a low rate of defects such as corroded contact grids and bubbles in the encapsulant. Long term testing of modules in countries with higher ambient temperatures very often results in pronounced "yellowing" of the encapsulant [8]. A typical example of this is shown in Figure 12.

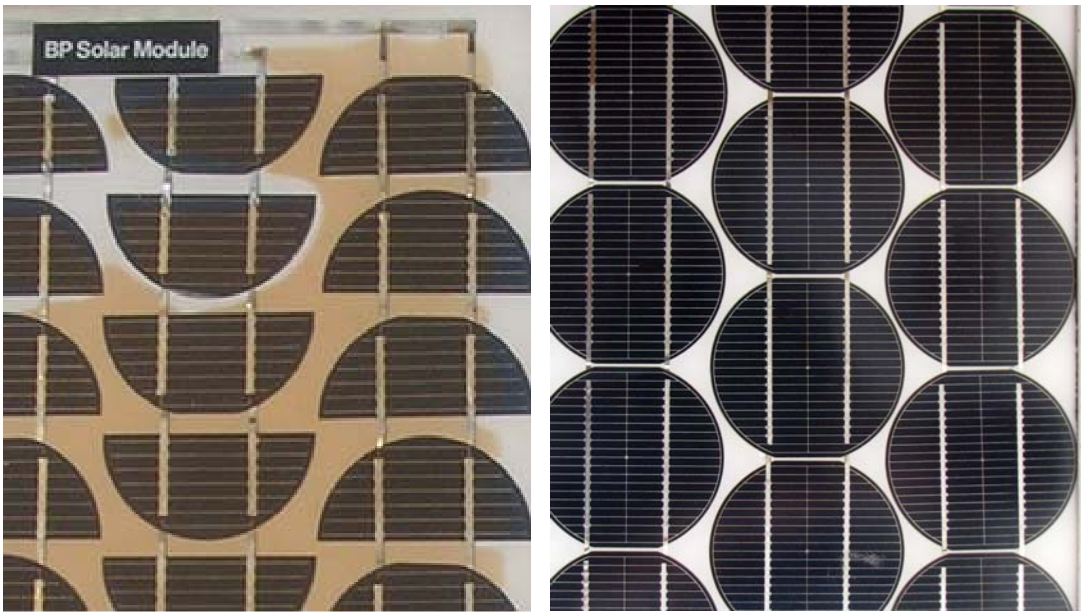

Figure 12. To the left: BP-modules tested at JRC Ispra for more than 15 years. To the right: A typical part of one of the tested modules.

[2] A hot-spot occur when a slightly shaded cell forces the module into short circuit through the bypass-diode. The shaded cell will then act as the load for the other cells in the module.

6 References

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