LONG TERM PERFORMANCE OF PV MODULES – RESULTS FROM SWEDISH CASE STUDIES

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ABSTRACT:
PV-modules based on crystalline silicon are often purchased with a warranty of 25 years. The modules that are tested and approved according to the IEC 61215 standard are considered to have an expected lifetime of 20-30 years. Although the tests are designed to simulate the stresses that modules are exposed to in real operation, it is not until analyses are made of modules that have been in operation for many years that definite statements about module lifetime can be made. Today more and more systems are approaching these long lifetimes and thereby providing us with true examples of module lifetime.

A number of studies of the long-term performance of commercially available PV modules can be found in the literature today. However, experiences from PV module performance in the Nordic climate are few.

The purpose of this study is to analyse how modules that have been in operation for 20-25 years have been affected during this time. The sample modules for the study come from early PV installations in Sweden. The results show that, with the exception of one module, the 70 tested modules have maintained their performance. The conclusion is that a 25-year technical lifetime of modules based on crystalline silicon cells is realistic in the Swedish climate. For PV-modules with improved encapsulation technology this value may even be conservative.

Keywords: PV Module, Performance, Crystalline, Field testing, Nordic climate

1 INTRODUCTION

1.1 Measuring long term performance of PV

After the first energy crisis in the mid 1970's, PV was expected to play an important role in the future energy system. Massive PV research and development projects were launched in various places worldwide. It was soon recognized that, together with cost 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 the PV module types turned out to have severe problems with reliability caused by the used encapsulation method and harsh environments. Delamination, cracked cells, broken interconnects, discoloured resin, hail storm damage and other problems occurred at field testing. At the same time laboratory testing methods were developed. At Jet Propulsion Laboratory in California a test sequence was used that includes several accelerated lifetime tests, mechanical strength and electrical isolation measurements. It was called the "JPL Acceptance test". It was adopted by other countries and is now after many revisions an international standard (IEC 61215), since 1993.

In the beginning of the 1980's 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.

A purchased PV-module today is normally accompanied by a warranty of 25 years. The warranty is based on a type approval (IEC 61215) [1], which is a procedure involving a number of accelerated lifetime tests, based on the JPL acceptance test. In order to convince the market that a 25 year 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.

1.2 Background

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 of 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.

The oldest grid connected PV system in Sweden that is still in operation was built in 1984 at Huvudsta in Stockholm. The system consists of 48 polycrystalline Kyocera modules that are mounted on the façade of the attic on top of a multi dwelling residential building. A picture of the system can be seen in figure 2 below.

Figure 2: A picture of the 2,1 kWp system at Huvudsta, taken in October 2006.

The production has been monitored through all these years and the system is still working just fine. An investigation of the performance of the Huvudsta modules has been carried out in order to complement the results of the Bullerö study.

1.3 Objective

The objective of this paper is to present the results of the two field tests described in chapter 1.2. In addition, the paper includes the analysis results of the first field test of long term PV-performance in Sweden, which was carried out in year 2000, following the dismantling of the Sandkullen PV-installation. Sandkullen had been operating since 1979.

The paper thus presents a collective result of the long term performance field tests carried out in Sweden up to today.

2 METHOD

The method for studying the 25 year old modules is based on comparisons of IV-curves from early measurements and recent ones.

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 outer factors:

- Irradiance [G_I]
- Spectrum of the light
- Module temperature [T_m]
- Angle of incident light

In order 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/m²
- Reference spectrum = AM 1.5, Global
- Reference module temperature [T_{STC}] = 25°C
- Light perpendicular to module surface

In field testing, these conditions are practically impossible to achieve exactly. The results need to be compensated 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.

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/m² [2].

Deviations in module temperature are compensated linearly according to a ratio [α] given by the module 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:

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

Measurements in natural sunlight are made under non specified spectral conditions (if they are not recorded at the time of the measurement). According to IEC 60904 1-10 all spectral distributions occurring at GI >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 Measurement equipment

The instrument for recording IV-curves was a STELLA Photovoltaic Array Field Tester [6]. It is a portable array tester and it uses a discharged capacitor that functions as ‘load resistor’ and to measure current and voltage 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 when measuring the modules from the Bullerö system. The measurements at the Huvudsta system were not made for each separate module, only for the four different strings in the system and the system as a whole. Therefore another plug-in, 350V/15A was used for these measurements.

A reference cell was used for measuring irradiance and a PT100 temperature sensor was connected to the reference cell for measuring cell temperature. The reference cell is a Siemens cell with a structure similar to the modules. It consists of nine cells, where the centre cell is the actual reference cell and the rest are dummies. The PT100 sensor is glued to the backside of the cell. The PT100 sensor does not return a temperature directly. It gives a resistance value that has to be converted into °C. The datasheet of the PT100 [7] gives that each ohm over 100 W corresponds to approximately 2,56 °C over zero degrees. The picture below shows the reference cell.

Figure 3: The Siemens reference cell that was used for measuring irradiance and cell temperature.

2.3 The modules

The modules from the Bullerö system are produced by ARCO-Solar and the following information has been retrieved from the datasheet of the modules [7].

Table I: Data of the Bullerö modules.

Producer: ARCO	Module type: ASI 16-200
Cell type: C-SI	Effective cell area: 0.26 m²
Cells per module: 33	$P_M = 33\ W_P$
$I_{SC} = 2.5$ A	$V_{OC} = 20$ V
Decrease in P_M per ° C of temperature increase: 0.53 %	

The following information has been retrieved from the datasheet of the Kyocera modules [3] from the system at Huvudsta.

Table II: Data of the Huvudsta modules.

Producer: Kyocera	Module type: PSA 100 H-361H
Cell type: P-SI	Effective cell area: 0.36 m²
Cells per module: 36	$P_M = 44\ W_P$
$I_{SC} = 2.67$ A	$V_{OC} = 16{,}5$ V
Decrease in P_M per °C of temperature increase: 0.51 %	

2.4 Measuring arrangement

When the dismantled modules from the Bullerö system 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 Bullerö modules was quite simple. Two wooden pallets nailed together and placed at 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 stable temperature. The picture below shows the measuring arrangement.

Figure 4: The arrangement for measuring the Bullerö modules.

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° (AM 1.5 can be assumed). The registered irradiance differed between 889 and 942 W/m² with a mean value of 925 W/m².

The measurements at the Huvudsta system were carried out on the 19th of June 2007 between 12.20 and 12.30. The inclination of the sun was thus 50 – 52 °, corresponding to AM 1,24 approximately. The registered irradiance varied from 789 to 810 W/m^2 with a mean value of 800 W/m^2. Registered irradiance during the measurement of IV-characteristics for the whole plant was 809 W/m^2.

Since this system is in operation it was not convenient to make measurements of each single module. However from the string box it was easy to measure IV-curves for the four different strings and of the whole system. The reference cell was held in the same plane as the modules, with care taken not to shade any of the modules that were being measured.

Before the measurements the modules were lightly cleaned in order to remove bird droppings and dust.

Figure 5: Measuring irradiance at the Huvudsta system.

3 MEASUREMENT RESULTS

This chapter summarizes the data collected from the two different measurements. The calculations of the results follow the theory in chapter 2, however with one exception. In the early IV measurements of these two systems the reference temperature of 28° was used. This is therefore also used as reference temperature for the new IV-curve in order to be able to make a fair comparison.

3.1 Measurements

The table below summarizes the data from the measurements of the Bullerö modules. P_0 is compensated according to equation (1) in chapter 2.1.

Table III: Results from measurements of the Bullerö modules.

Module number	G_I [W/m²]	T_m [°C]	I_{SC} [A]	V_{OC} [V]	P_M [W]	P_0 [W]
250652	918,3	40,0	2,16	18,3	26,3	30,5
250555	942,8	44,9	2,28	17,8	24,0	27,8
250453	933,7	45,4	2,28	17,5	26,1	30,5
250428	942,8	45,1	2,26	17,7	26,8	31,0
250576	942,2	45,1	2,26	17,6	25,0	29,2
250459	936,0	46,9	2,26	17,4	25,4	29,9
250595	936,0	46,9	2,25	17,4	25,4	29,9
250685	910,8	46,9	2,18	17,6	25,1	30,3
250566	902,0	46,9	2,18	17,4	25,4	31,1
250420	902,6	47,4	2,16	17,5	25,8	31,5
250522	924,8	47,2	2,16	17,4	25,5	30,6
250468	934,6	48,5	2,25	17,7	26,8	31,8
250545	938,9	48,5	2,12	17,7	16,3	19,3
250523	928,8	49,0	2,23	17,6	25,9	30,7
250899	931,7	46,7	2,22	17,5	26,1	31,0
250450	928,1	47,9	2,21	17,4	24,9	29,7
248850	925,5	47,9	2,28	17,4	25,7	30,7
250563	919,3	47,7	2,19	17,6	25,4	30,3
250574	917,0	45,6	2,21	17,6	25,1	30,0
250578	924,8	45,9	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.

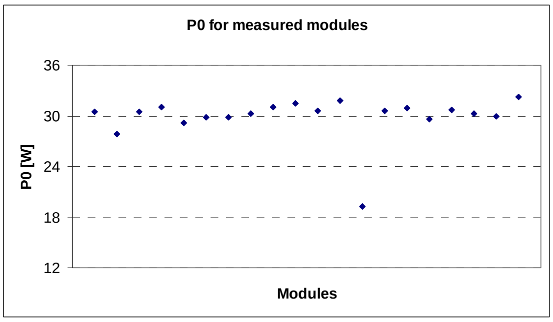


Figure 6: Measured power of the Bullerö modules.

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

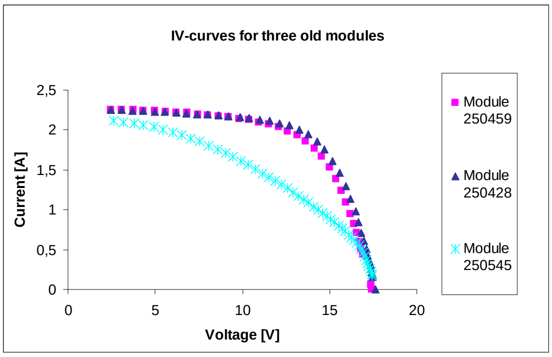


Figure 7: IV-curves for three of the measured modules from Bullerö.

Data from the measurements of the Huvudsta systems is summarized in table 2 below. P_0 is compensated according to equation (1) in chapter 2.1.

Table IV: Results from measurements of the Huvudsta modules.

String	G_I [W/m²]	T_m [°C]	U_{MP} [V]	I_{MP} [A]	I_{SC} [A]	V_{OC} [V]	P_M [W]	P_0 [W]
A	789	53	190	1,92	2,21	229	365	529
B	789	53	179	2,04	2,21	228	365	529
C	790	53	179	2,01	2,20	227	360	521
D	793	53	161	2,02	2,23	208	326	470
All	809	53	177	8,1	9,06	230	1430	2020

The first three strings showed similar values, but the fourth string (D) has a significantly lower open circuit voltage. The difference corresponds to approximately the voltage of one module. The figure below shows the IV curves of the four strings, notice the lower voltage of string D.

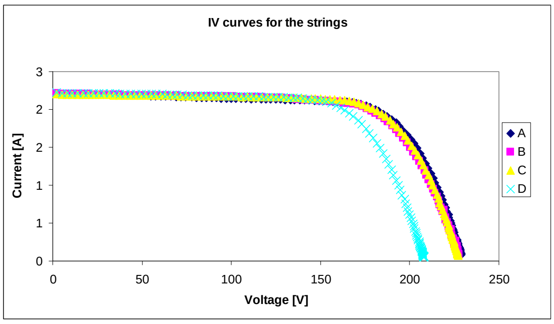
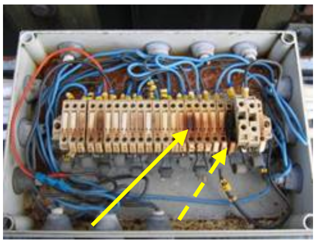


Figure 8: IV curves for the four strings of the Huvudsta system.

An inspection of the array junction box revealed a short circuited module. The modules within a string are connected in series in a junction box where also the by-pass diodes are located. The boxes of the four strings are placed outdoors for pedagogic reasons and are hence exposed to outdoor variation in humidity. One of the junction boxes has experienced a breakthrough in the electrical isolation, most likely caused by high DC-voltages in combination with moisture that has penetrated the box. The result is a shorted module. See figure 9.

Since this loss of power is not related to module degradation the IV-curve of the system as a whole was compensated for this.

Figure 9: Short circuit of a module in one of the junction boxes. The phenomenon occurred once before (and was repaired), see dotted line.



The compensation is made by assuming that string D would have displayed the same values as the mean of string A, B and C, if all modules had been connected properly. The difference between the sum of string A, B, C and ABC-mean and A, B, C, D is then added to the IV curve of the whole system. The result can be seen in the graph below.

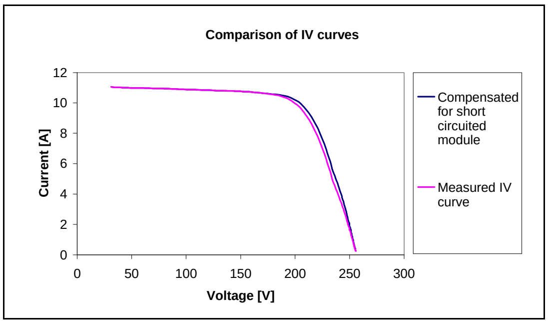


Figure 10: Difference between measured IV curve and IV curve compensated for one short circuited module.

The new data for the compensated IV curve are listed in the table below.

Table V: Data for IV measurement of the Huvudsta system compensated for one short circuited module.

G_I [W/m²]	T_m [°C]	U_{MP} [V]	I_{MP} [A]	I_{SC} [A]	V_{OC} [V]	P_M [W]	P_0 [W]
809	53	177	8,28	9,06	230	1465	2070

3.2 Visual inspection

After 23 years of operation the modules at Huvudsta show no visual signs of defects. The modules look virtually "as good as new".

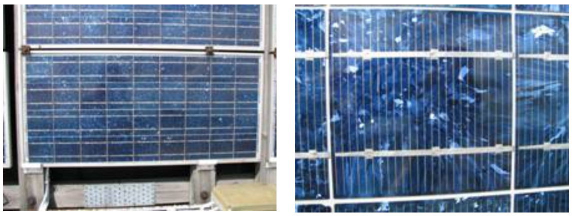


Figure 11: The Kyocera modules in the Huvudsta system looks perfectly good after 23 years, no defects could be detected by a visual inspection.

The modules from Bullerö have a few visibly detectable defects. But in general the modules show very little trace of outer degradation. A few modules have got some stains in the front glass. But these defects did not result in any significant changes in measured performance that could separate these from the other modules. The pictures below show the modules with the stains in the glass.

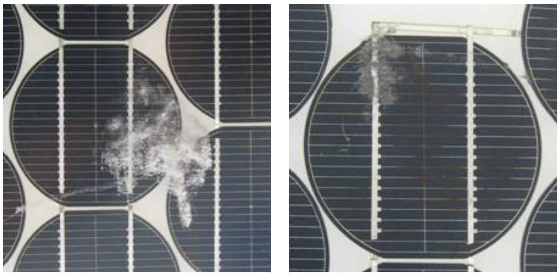


Figure 12: Stains in front glass.

From the 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 particularly many discoloured cells could be noticed. The two pictures below show one typically unaffected cell and one cell displaying the bronze discolouration.

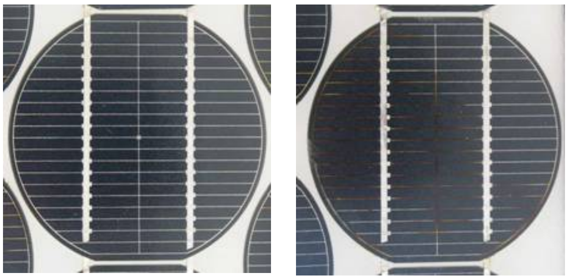


Figure 13: To the left: A typically unaffected cell. To the right: A cell with discoloured grid pattern.

Only one cell shows a clear degradation of the performance. In this case part of the cell has clearly degraded and turned into a yellowish colour. This cell is found in the single module that showed a significantly 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.

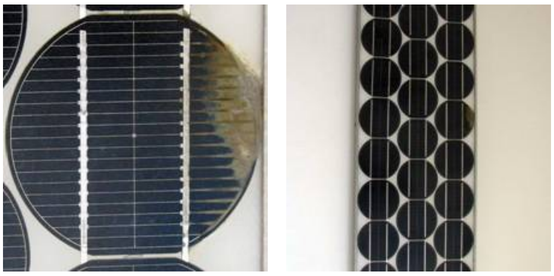


Figure 14: To the left: The cell with a clearly visible degradation. To the right: The module where the degraded cell is fitted

3 ANALYSIS

In order to draw a conclusion as to how the performance of the modules has been affected by their 21-25 years of outdoor service, the obtained measurements need to be compared to performance data from the start of operation.

4.1 Årsta and Huvudsta

The datasheet for the ASI 16-2000 module gives a value of the peak power of 33 W. For the PSA 100H-361H module 44 W is stated. These values can be used for comparison. However values from measurements carried out in 1985 are chosen, even though they are associated with some errors, because they stem from measurements made on the actual modules installed.

In 1985 a study was carried out to measure the performance of the modules after the installation in Årsta and Huvudsta respectively [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.

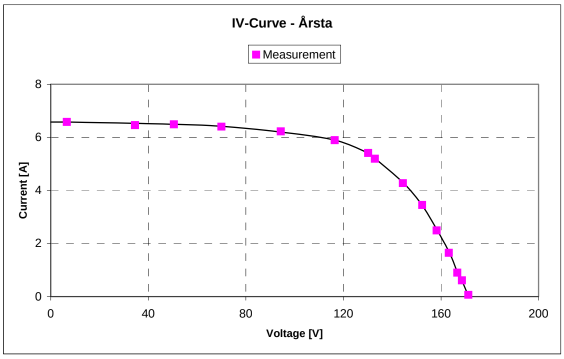


Figure 15: IV-Curve from measurement of the Årsta installation, measured in July 1985 at G_I = 868 W/m² and T_A = 56 °C.

A mean value of the power of the modules of the Årsta plant can be calculated from this, knowing that the modules were connected ten modules in series 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/m² and T_m = 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 29.9 W. This corresponds to decrease of 3.8 %. If the module with significantly 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/m² and T_m= 28 °C.

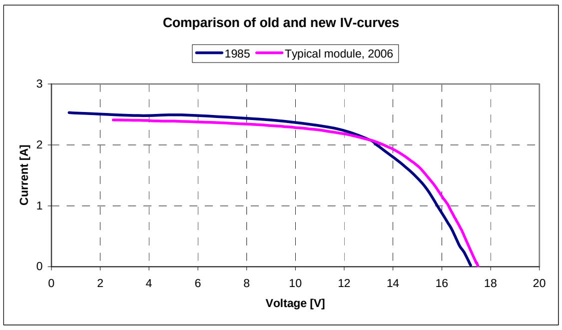


Figure 16: Comparison of IV-curves from the 1985 measurement and from a typical module from the 2006 measurement. Both IV-curves are compensated to G_{STC}=1000 W/m² and T_m= 28 °C.

The peak power from the new measurement of the Huvudsta plant is 2020 W. This corresponds to a decrease of 4,4 %. If the peak power is compensated for the identified short-circuited module the remaining decrease is 2.0 %. The figure below illustrates the difference between the IV-curves from the 1985 measurement and the 2007 measurement. The IV-curves are compensated to G_{STC}=1000 W/m² and T_m= 28 °C.

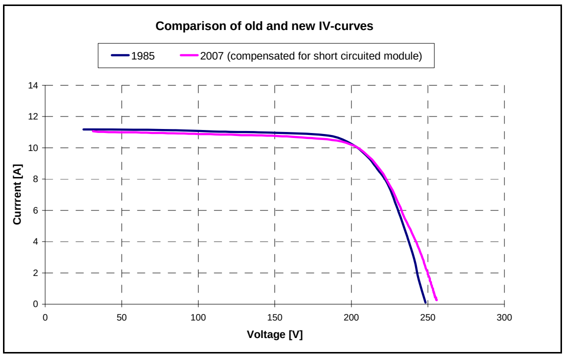


Figure 17: Comparison of IV-curves from the 1985 and 2007 measurements. Both IV-curves are compensated to G_{STC}=1000 W/m² and T_m= 28 °C.

4.1.1 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 %.

A certain error is also introduced by the translation from measured data to STC. This error is less than 4 % [9].

This results in a total error of +/- 7 %.

When comparing typical module performance in the present study of the Bullerö modules 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 %.

4.2 Sandkullen

In 1979 the first PV-installation in Sweden was taken into operation at Sandkullen in Stockholm. The modules tested consisted of polycrystalline silicon cells encapsulated by means of five different methods which were representative at the time. In 1991 control measurements showed significant performance degradation for four of the five module types (efficiency reductions of 15 – 45 %). The fifth module type, of the brand Philips, used a method encapsuling the cells between two glass sheets. Up until 1991 no performance degradation was recorded for this module type.

This type of encapsulation method is used today in the manufacturing of semi-transparent PV-modules.

Before the dismantling of the Sandkullen experimental plant new performance measurements were carried out. The degradations already noticed in 1991 had continued. The Philips modules however presented a peak power value (compensated to STC conditions) higher than the initial value by 2 %, clearly showing that any degradation was within the accuracy of the used measuring methods. Table VI presents the module type and data from the initial measurements.

Table VI: 1979 peak power measurements.

Module type	Peak power in 1979 [Watts]		Module material, in the following order: Front/Encapsulant/ Back. Frame
	Natural sunlight	Solar simulator	
Philips BPX47A	194	193	Glass/PVB/glass. Aluminium frame

5 CONCLUSION

The module performance of three early PV-installations, based on module types that are still used today, has been tested after 21 – 25 years of outdoor exposure in the Swedish climate. The results show very well working modules with no proven performance degradation.

The Sandkullen experimental plant was taken into operation in 1979 and dismantled in 2000. The plant included Philips modules with an encapsulation method that is still used in semi-transparent modules today. After 21 years of operation the modules showed no signs of performance degradation, neither visually nor regarding peak power.

The Bullerö modules, originally part of the Årsta plant built in 1981, were tested in 2006. Twenty modules were tested and an average peak power reduction of 4 % was found. The degradation is within the accuracy of the used method and a general degradation of the modules cannot be concluded.

One of the 20 Bullerö modules (IV-curve in figure 7 and Photo in figure 14) showed a distinct degradation. Visual inspection of this module revealed one cell partly discoloured and surrounded by small bubbles in the encapsulating resin. The cell has most likely been exposed to a "hot-spot". The IV-characteristic is typical for a module with one defect cell with decreased series resistance and partly shunted. This module stands for nearly 2 % of the degradation mentioned above.

The visual inspection generally showed 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 17.

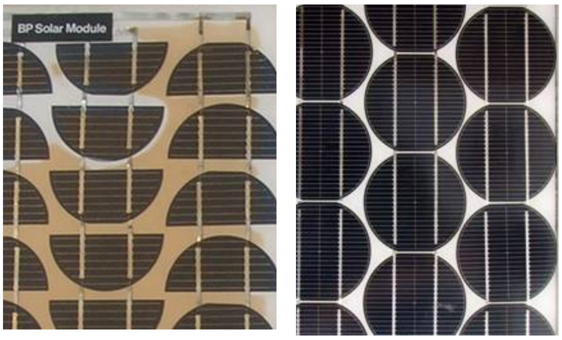


Figure 18: To the left: BP-modules tested at JRC Ispra for more than 15 years. To the right: A typical part of one of the tested Bullerö modules.

The modules of the Huvudsta plant were tested in 2007, having been in continuous operation since 1984. Visual inspection revealed no signs of module degradation. One module was found to be short circuited in the junction box, which has an exposed design. Compensated for the short-circuited module, the array shows a 2 % reduction in peak power compared to initial measurements. Again, the degradation is within the accuracy of the used method and a general degradation of the modules cannot be concluded.

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