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Analysis of Degradation and Annealing Effects of Amorphous Silicon Photovoltaic Modules

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Contents

Abstract

The interest in investigating the characteristics of annealing and degradation processes comes from the encouraging results obtained with a PV plant integrated into a flat roof [Pol07]. Outcomes of this project show that, compared to crystalline silicon, the better thermal behaviour and the annealing processes of amorphous silicon compensated for a significant part of the losses due to the nearly horizontal installation. This outcome suggests that for Building Integrated Photovoltaic (BIPV) applications amorphous silicon modules are more suitable than crystalline silicon ones.

In fact, the effect of annealing and degradation processes (Staebler-Wronski effect) on a-Si performance is in competition with the seasonal variations of the sun spectrum. This project aims to investigate in depth how real operating performances of a-Si depend on the Staebler-Wronski effect (SW), and to compare this dependence with the dependence on seasonal sun spectrum variations.

The study is divided into four main topics:

- monitoring the PV plant;
- detailed analysis of the SW effect on triple junction a-Si modules;
- comparison between the SW effects on three different a-Si based technologies;
- comparison between the influence of the SW effect and of seasonal sun spectrum variations on single junction a-Si power modules.

The main outcomes of the work are summarised below.

PV-plant performances proved to be rather constant during the 2004-2010 period, despite the fact that some significant maintenance work was carried out. The a-Si power dependence on annealing temperature and duration was mapped; the findings show that an annealing of about 12h at 90°C is the best compromise between defect recovery and amount of energy required for the process. Reversibility of the annealing and degradation processes was studied: consecutive degradation-recovery cycles show that for an annealing temperature of 120°C the power degradation is not totally reversible. Degradation processes performed on different a-Si technologies show that light soaking spectrum could have an influence on the degradation.

Comparison between sun spectrum variation and the SW effect performed on a-Si (sj) module shows that, during the year, power value varies about 15% due to sun spectrum and about 8% due to the SW effect.

1 Introduction

The cost reduction of the energy produced by means of solar modules is a key factor for the success of photovoltaics as a worldwide energy source. However, in order to meet grid-parity, PV plant installation costs would have to drop around 1€/W, which, for thin-film PV technologies (especially a-Si, CIGS and CdTe), would mean module production costs of around 0.5-0.6€/W [Fth09]. In particular, a-Si technology shows interesting features, especially from the point of view of PV building integration (BIPV). Due to a better thermal coefficient (in comparison with other technologies) and its typical defect recovery at high temperature, a-Si modules do not need to be back ventilated in order to maintain high performances. Therefore, a-Si PV modules can be fully integrated into flat roofs or façades, also reducing installation costs. Moreover, it is possible to deposit a-Si on different types of substrates, making it possible to obtain semitransparent and/or flexible modules that are very interesting for BIPV applications.

In this context it is therefore very interesting to acquire knowledge about light and thermal induced effects on a-Si modules under real operating conditions. The study focuses on the characterization of the annealing process, in terms of temperature and heating duration. Particular attention was dedicated to the reversibility of the annealing-degradation process, by analysing outdoor data of the CPT plant (continuously monitored since 2003) and by conducting subsequent annealing-degradation tests on our indoor and outdoor facilities.

The work is structured as follows:

- monitoring of the "CPT Solar" plant. A 15kW a-Si PV plant that is thermally insulated and integrated into a flat roof;
- analysis of the annealing and degradation effects on triple junction amorphous silicon modules (Uni-Solar), the same modules as on the CPT Solar plant;
- comparison of the annealing and degradation process on three different a-Si based technologies: single junction, double junction and triple junction;
- comparison between the influence on the amorphous silicon seasonal behaviour of the annealing-degradation process and sun spectrum variations.

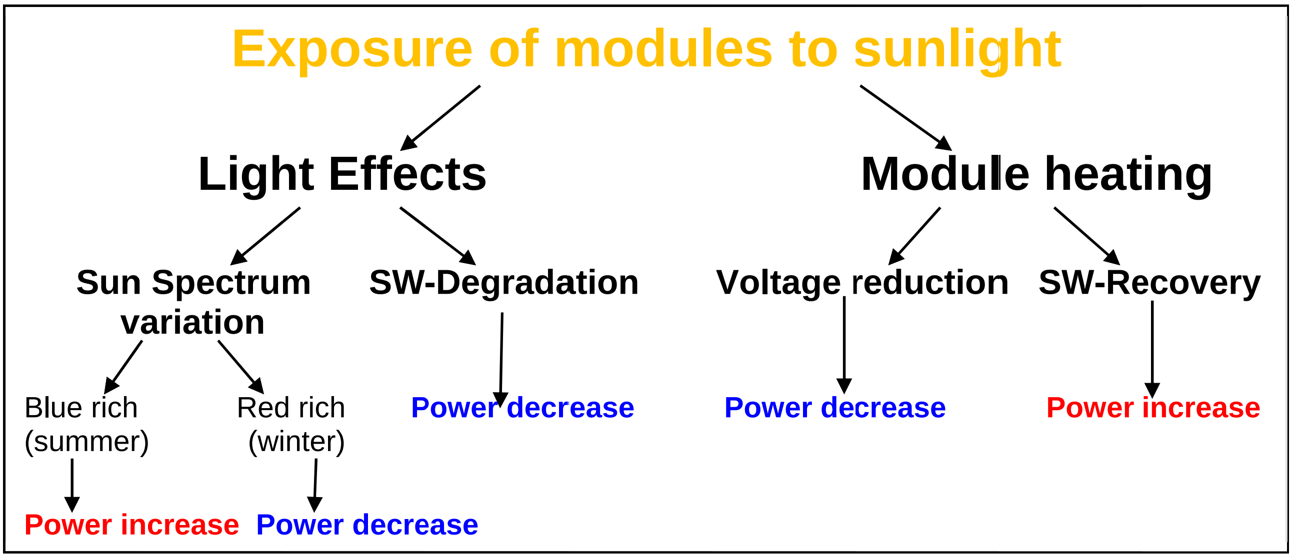

Figure 1. *Competitive effects affecting the performance of a-Si modules exposed to the sunlight.*

2 Annealing, degradation and spectral effect on a-Si modules

In 1977 Staebler and Wronski showed that in a-Si devices exposed to the light are created defects that strongly decrease photoconductivity and hence performances [Sta77]. It is generally accepted to divide these defects into two different types: fast and slow [Yan93]. The terms "fast" and "slow" refer to the ease with which the degradation can be recovered. Fast defect are characterized by low activation energy (<0.3eV) and by the fact that a temperature around 40°C is enough to anneal them. The activation energy of slow defects is higher (>0.9eV), hence to reach noticeable annealing rates a temperature higher than 80°C is necessary. It was already shown that at a temperature of about 150°C, the defects are completely recovered [Sta77].

Under real operating conditions the modules are exposed to the sunlight but, at the same time, the working temperature goes up to 80°C for thermal isolated modules installed in Lugano (46°N, 8°E). Therefore, depending on irradiation and on temperature a different amount of defects is created or annealed in the a-Si modules.

At ISAAC the topic began to be investigated 20 years ago when the an a-Si plant was installed and monitored on the roof of the institute. Figure 2 shows the behaviour of two a-Si plant monitored by ISAAC: a single junction and a triple junction plant. The general trend of the efficiency is to decrease. The intensity of the decrease is high in the first months and afterwards it becomes smaller and smaller. Within this general trend is clearly noticeable a variation that has a shorter period (a year) and a swinging tendency.

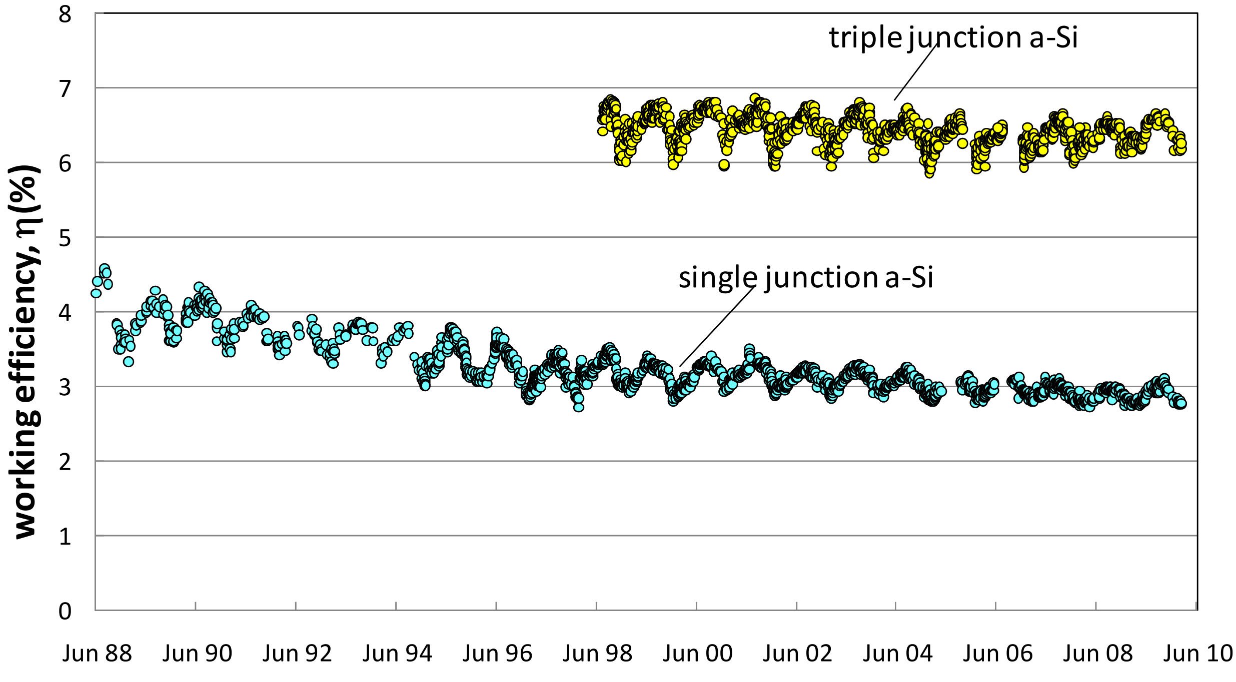

***Figure 2**. Long term behaviour of a single junction (black dots) and a triple junction (yellow dots) a-Si open rack plants.*

The long term trend seems to be mainly due to the slow defects created by the exposition to the sunlight. Since, for this plant, the highest module temperature never exceeds 65°C these defects are never annealed, and their amount increases during the years. As a matter of facts, the degradation intensity decreases with the time. This effect is in agreement with the assumption that the degradation process is self-limiting [Cue99]. The total amplitude of this degradation phenomenon represents almost the 30% of the plant efficiency (that is alot, but we are dealing with an a-Si technology that is 20 years old!).

The seasonal behaviour is likely due to the subsequent formation and annealing of the soft defects. In winter the working temperature is low hence, most of the defects are not annealed and the efficiency decreases. In summer the working temperature is higher and sufficient to anneal most of the fast defects, increasing the efficiency. The relative amplitude of the phenomenon is pretty constant: about 15% of the actual efficiency.

Finally, since the Staebler-Wronski effect (SWE) is a bulk effect [Zho86], it is important to consider that the intensity of these phenomenon depends on the thickness of the a-Si layers. In particular, for multi-junction modules the effect is smaller than for single junction modules as already reported in literature [Kro97].

So far we attributed the cause of the seasonal behaviour only to the degradation and recovery effect, but actually some authors [Got04] consider the variation in incident spectrum as major contribution to these seasonal performance variations. Indeed, in literature, significant debates occurred over the last few years regarding the influences of thermal annealing versus solar spectrum on the performance of a-Si photovoltaic systems [Kin00, Nak03, Gru09]. Some have argued that seasonal patterns observed in system performance are due to elevated summer temperature causing thermal annealing, and others contended that relatively higher performance in summer are due to more favorable (blue rich) solar spectrum. The seasonal behaviour is most likely due to a combination of both the phenomena but since their effects on a-Si performance is somehow superimposed since both lead to a power increase in summer and a decrease in winter, some authors attribute this behavior to only one of the two phenomena. This interpretation could be due to geographical reasons because the amplitude of the effects mainly depends on location temperature and latitude (sun’s height in the sky affects the light spectrum), therefore depending on the place where the investigation is performed one of the two effects prevails on the other.

3 Tools and methods

3.1 Monitoring of the CPT-Solar plant

The 15.36kWp power plant (named CPT Solar) was connected to the grid in December 2003. It covers a flat roof surface of about 900m^2 and consists of 12 strings each with 5 Uni-Solar modules (60 modules in total). The 12 strings are connected to three SMA SB5000TL inverters, each with three independent MPPT capable inputs. Four strings in a 2+1+1 configuration are connected to each inverter.

Figure 3 gives a schematic representation of the CPT plant.

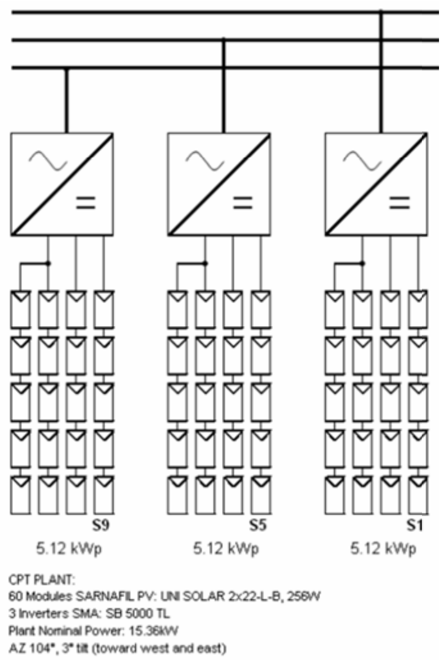

Figure 3. *Schematic representation of the CPT plant. Strings No. 1, 5, 9 are the reference strings for the plant.*

The building itself is oriented 14° south but the series are oriented east - west with an almost horizontal inclination of +/- 3°.

In addition to the inverters, a separate monitoring data acquisition system is used. Precision shunts, isolated signal converters and transmitters are used respectively for DC current and voltage. Data monitoring and acquisition is done by means of two Agilent Data Loggers. The main parameters - electrical, meteorological and thermal - are recorded each minute from 5am to 10pm. In order to monitor module temperature, before lamination, PT100 temperature sensors were fixed under 4 PV modules mounted on different parts of the plant. Further temperature sensors were placed underneath the various waterproofing layers.

The current and voltage accuracies of the monitoring data acquisition system were calculated, accounting for the accuracies of the different components of the latter: current accuracy is 1.2% whereas voltage accuracy is 0.7%. Accordingly, the expected uncertainties of the data analysis in terms of DC should not exceed 1.4%.

Figure 4 shows a recent view of the solar plant.

Figure 4. *General view of the CPT plant (July 2010).*

3.2 Annealing and degradation process on Uni-Solar modules

In order to better understand the behaviour of the CPT Solar plant, a detailed analysis aimed at defining the Staebler-Wronski effects was conducted on Uni-Solar modules of the same type (but of a different size) of plant modules. The Uni-Solar modules in this study are triple junction amorphous silicon modules (a-Si:H/a-SiGe:H/a-SiGe:H), each 31Wp, glued and seamed onto aluminium decks. This mounting system was provided by ISCOM.

In 1977 Staebler and Wronski reported for the first time a "*reversible photoelectric effect for a-Si […] long exposure to light decreases the photoconductivity […]. Annealing above 150°C reverses the process."* [Sta77].

This phenomenon, known as 'Staebler-Wronski effect', is essentially the creation of new defects induced by the light in the amorphous atomic structure. It is thermally reversible above 150°C but a partial recovery of the defects may be noticed for temperature higher than 40°C. In particular, the amount of recovered defects depends on the temperature level [Luc07]. In order to investigate this dependence in detail, we performed two different tests in an air-heating oven. By varying heating duration and temperature, we discovered how these two parameters affect the recovered level. This dependence is interesting from the point of view of applications, because through the knowledge of operating temperature distribution, it is possible to estimate the recovery intensity. In order to characterize annealing and degradation processes, module power was measured indoors by means of a pulsed solar simulator class A/A/A. No spectral response measurement of the devices was performed, nor any mismatch factor (MMF) correction for spectral mismatches to the AM1.5 reference spectrum applied to the IV curve measurement. Conversely, measurement conditions as close as possible to AM1.5 are achieved by carefully selecting proper spectrallymatched filtered reference cells (i.e. reference cells with spectral sensitivities close to those of the PV technology being tested).

Light soaking was executed both indoors and outdoors with the facilities shown in *Figure 5***.** Indoor light soaking was conducted by means of a steady state simulator equipped with 12 HQI lamps (class C/C/B). During the light soaking process, module temperature and electrical parameters were monitored by a PT100 sensor and a Maximum Power Point Tracker (MPPT).

The annealing process was executed both indoors and outdoors by means of the facilities shown in *Figure 6*. Indoor annealing was conducted in an air heating oven and the module temperature was monitored by 3 PT100s mounted on the rear of the module in order to verify temperature uniformity. Outdoor annealing was performed on the outdoor stand by electric foil heaters mounted on the rear of the modules.

Figure 5. *Light soaking facilities for PV modules.* ***Left:*** *Steady-state sun simulator.* ***Right:*** *outdoor stand for sunlight exposure.*

Figure 6. *Annealing facilities for PV modules.* ***Left:*** *Outdoor facility for annealing (by means of electric foil heaters) and degradation of the modules.* ***Right:*** *air heating oven supplied by SUPSI-IMC Institute.*

3.3 Investigation of the Stabler-Wronski effect on three different a-Si based technologies

The comparison aims to highlight the different performances of three a-Si based technologies in terms of the rapidity and intensity of the SW phenomenon.

Three different a-Si based technologies based are involved:

1. <u>Single Junction</u> (a-Si). Flexible modules on metallic substrate from VHF-TECHNOLOGIES, with a nominal power of 27 Wp;

2. Double Junction (a-Si/µc-Si). Known as 'micromorph' modules on glass substrate from PRAMAC (around 130Wp);
3. Triple Junction (a-Si:H/a-SiGe:H/a-SiGe:H). Flexible modules on metallic substrate from UNI-SOLAR (31Wp).

The comparison between these modules was performed by using indoor tools (air heating oven and steady state simulator). No outdoor comparison was performed.

3.4 Spectrum variation and Staebler-Wronski effect on a-Si

The seasonal behaviour of a-Si modules is well known [Nik08] but there is still no evidence indicating whether this behaviour depends on the seasonal spectrum variation or on the Staebler-Wronski effect. Considering the narrow a-Si Spectral Response (SR) of a-Si (see *Figure 7*), some authors show that seasonal behaviour depends on the variation of the sun spectrum [Got04]; others relate the particular a-Si performance to cell working temperature distribution: the higher the temperature, the more effective the recovery of defects [Cue99]. A combination of both effects is possible.

As seen in *Figure 6*, the spectral response of a-Si modules lies between 300 and 750nm, so the range is much narrower than that of c-Si and therefore more influenced by the variation of the light spectrum distribution. The air path of the light depends on the height of the sun in the sky, so the red component of the sun spectrum increases in winter, while in summer the blue component increases. The effect on a-Si modules is that in summer a greater portion of spectrum is available for electron-pairs generation, leading to higher power for an equal irradiation value.

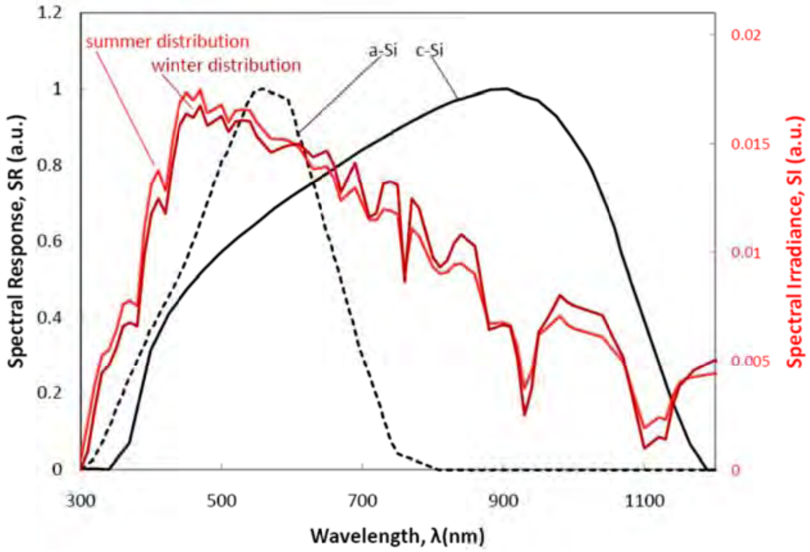

***Figure 7.** Spectral Response of standard c-Si and a-Si (sj) modules compared with two typical summer and winter sun spectra in Lugano (simulated and normalized to 1kWh/m^2).*

From the aspect of the Staebler-Wronski effect, a higher summer temperature leads to a more efficient defects recovery process, increasing a-Si module power. A lower winter temperature leads to a less efficient defects recovery process, producing a decrease in the module power.

Since the two different phenomena produce a similar effect on a-Si module power (summer: increase; winter: decrease), it is not easy to distinguish which makes the greatest impact. In order to distinguish between them, two different a-Si modules and two different IV-measurement systems were used in this study, as shown in *Table I*. The modules used are two a-Si single junction (60Wp from Kaneka) chosen in order to avoid any current matching problems between sub-cells series. One was stored indoors in the dark and at a constant temperature (around 25°C) while the other was exposed outdoors on a 45° tilted rack. The power of the indoor module is presumed to be constant throughout the year while the power of the outdoor module is presumed to vary because of the Staebler-Wronksi effect.

Figure 8. *Suntracker system for outdoor IV-curve measurement. Irradiation data are collected by means of a pyranometer and a c-Si reference cell. A temperature sensor (PT100), attached to the back of the module, is used to monitor module temperature*

In order to indicate the spectrum dependence, two different IV-curve measurement systems were used: an indoor pulsed solar simulator (class A/A/A) and an outdoor IV- measurement system on a suntracker. The two modules were measured at regular intervals with both systems. By measuring the modules outdoors, it was possible to define the a-Si dependence on the sun spectrum. Combining the measurements of the two modules with the two IV-curve measurement systems (see *Table I*) would make it possible to distinguish the relative importance of the phenomena.

Table I. *Combinations of measurement systems and modules used to distinguish the impact of the two phenomena investigated in this study: Staebler-Wronski effect and seasonal spectral variations.*

Module / Measure	**stored indoors**	**exposed outdoors**
indoor	No effects	SW effect
outdoor	Sun spectrum variation	SW effect + Sun spectrum variation

4 Results and discussion

All the results presented in this study refer to a Southern Alpine climate (46°N latitude) and are not necessarily transferable to other climatic conditions.

4.1 Monitoring of CPT Solar plant

The plant underwent various maintenance work during its operating period. Despite these changes, the plant performance ratio seems to have been constant and high (annual average of around 85%) over the period considered, as shown in *Figure 9*. In particular, it is still possible to identify the main features discussed in the first Final Report of the project [Chi07]:

- Winter decrease: optical losses due to light reflections on horizontal modules and low SW-defects recovery;
- Spring to summer increase: efficient SW-defects recovery due to higher module working temperature.

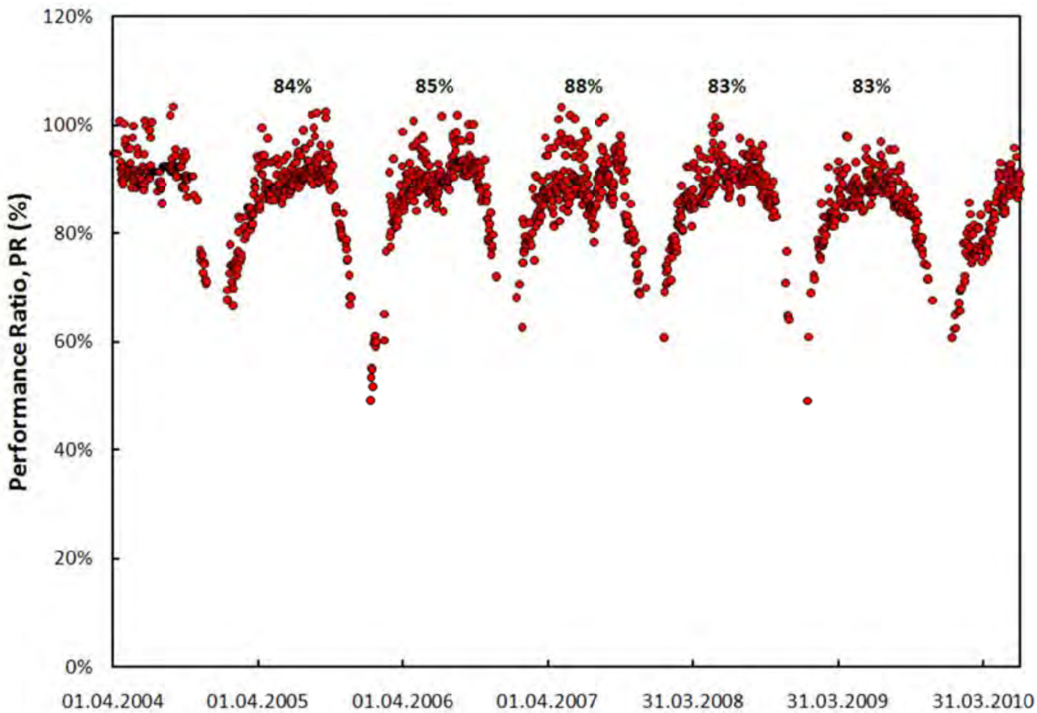

Figure 9. *Performance Ratio of string 1 of the CPT Solar plant. Numbers represent the annual average PR value. Period: April 2004-July 2010*

Thermal insulation of the plant makes it possible to enhance the module working temperature, producing a more effective defects recovery of the amorphous atomic structure of a-Si. This makes a beneficial impact, especially in the spring-summer period. The annual working module temperature distribution (averaged over the 2005-2009 period) is plotted in *Figure 10.* The graph shows that for 19% of the time (data recorded every day between 5:00 and 22:00) the plant operated at temperature higher than 40°C, and for 6.5% of the time over 60°C; these temperatures are high enough to produce a partial recovery of the defects inside the atomic structure of a-Si. In particular, *Figure 11* shows that in winter the plant very seldom reaches temperatures above 40°C, while in summer the plant operated at above 40°C for about 40% of the time and above 60°C for about 17% of the time.

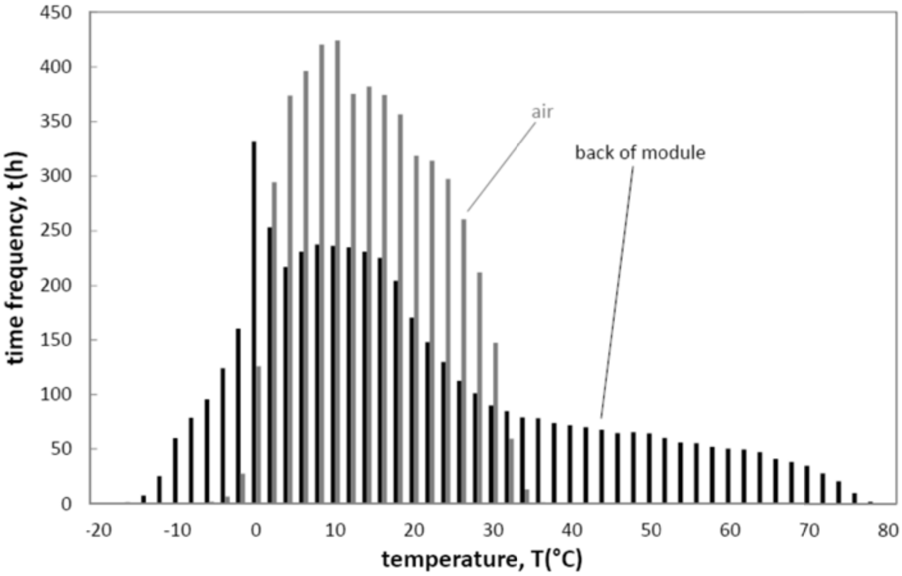

Figure 10. *Annual distribution of the working module temperature of the CPT Solar plant compared with air temperature. Period 2005-2009 (5 whole years).Temperatures measured on the rear of the module from 5:00 to 22:00.*

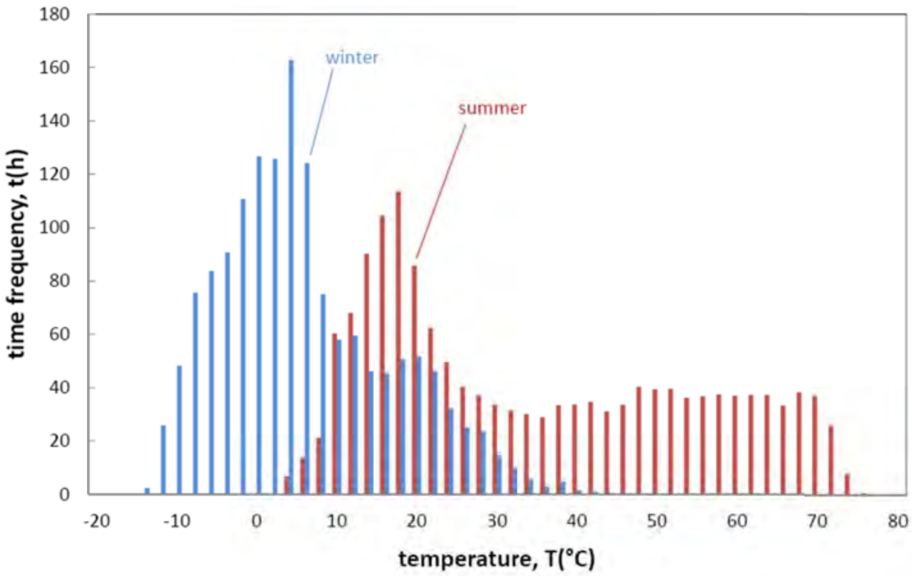

Figure 11. *Distribution of the working module temperature of the CPT Solar plant. Comparison between summer period (June, July and August) and winter period (December, January and February). Temperatures measured on the rear of the module from 5:00 to 22:00.*

Figure 12 shows the annual yield of the three reference strings over the period April 2004-June 2010. Except for the year 2008 (when, due to maintenance work to the electric grid, the plant was switched off from May 27th to July 23rd), the plant generated almost the same amount of energy. The same figure shows the average monthly yield of the plant. The graph clearly shows that a large portion of the annual energy is produced during the summer months (approximately 41% in June, July, August) while less than 10% of the total is produced in the winter months (approximately 9% in December, January and February).

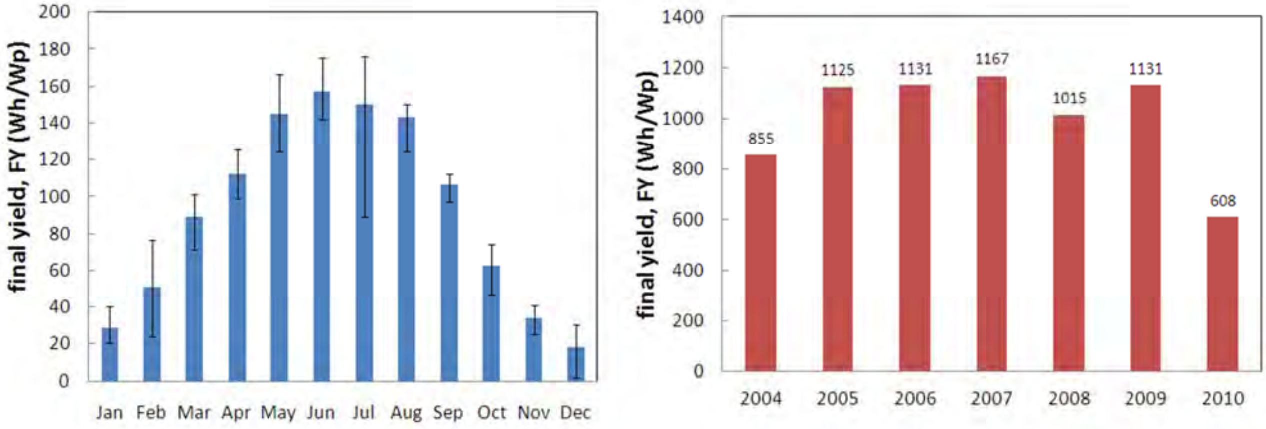

Figure 12. *Performance Ratio of the CPT plant, period April 2004-June 2010.* ***Left:*** *Monthly Average Final Yield of the three reference strings (1,5,9). Bars represent maximum and minimum monthly values recorded since 2004.* **Right:** *Annual Yield of the three reference strings (1,5,9). Note that data for 2004 and 2010 do not refer to the whole year.*

4.2 Annealing and degradation process on Uni-Solar modules

Amorphous silicon performances are strongly influenced by the Staebler-Wronski effect. Annealing mainly depends on the module temperature: the higher the temperature, the more effective the defects recovery [Luc06]. Degradation mainly depends on Light Soaking (LS) duration and it has been shown that the LS mechanism does not have any activation energy threshold, but is largely dependent on total irradiation dose [Nik08]. Under real operating conditions, the sun shines, producing a degradation of the module power but at the same time it heats the module, partially recovering its defects. As a first approximation, the effects of these two processes can be linearly combined, but in order to better define each of them, they must be analysed independently. Recovery of defects could be performed by annealing the module in a dark oven, while a module cooling system would be required in order to perform degradation independently. In this study no cooling system was used during the light soaking process, but the back module temperature was monitored in order to quantify the potential annealing effect.

Annealing effects were investigated thoroughly by means of an air-heating oven and electric heater foils. Degradation process were analysed outdoors (different seasons and different module configurations such as module electric load) and indoors by means of a steady state simulator. The reversibility of the whole annealing-degradation cycle was also investigated.
Figure 13 shows typical annealing and degradation processes. The degradation process leads to a decrease in module power that is noticeable during the first hours of light soaking but after 10-20hours (at 1000W/m^2) tends to reach a stabilized power level. This stabilized level depends on different parameters such as: module temperature during the process, module electrical configuration, etc..

The annealing process is also very rapid during the first hours of the process. After 12 hours it reaches a power level that, depending on T, amounts to approximately 70%-90% of the final power level (see *Figure 16*). After roughly 30 hours, the power stabilizes; this level depends on various parameters but mainly on the annealing temperature; the annealing process shown in *Figure 13* was performed at 100°C.

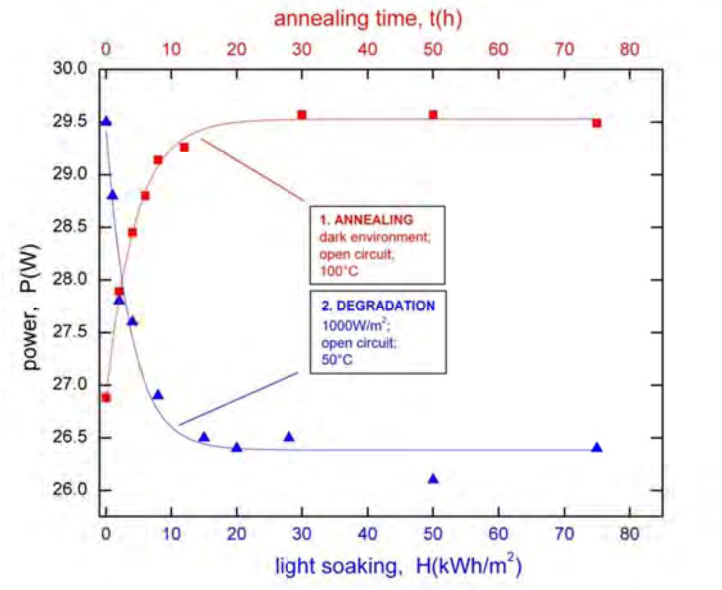

Figure 13. *Comparison between annealing and light-soaking effects on the module power. These depend on various parameters; here both processes were performed indoors: annealing (dark environment, open circuit configuration, T_{AN} = 100°C) and light-soaking (G~1000W/m^2, open circuit configuration, T_{LS} ~ 50°C). The module initially underwent the annealing process and was subsequently light soaked.*

4.2.1 Degradation. Influence of light intensity, electric load and season

Under light soaking, module power decreases rapidly during the initial period, but the rate of decrease slows down until power reaches a stabilized level, as shown in *Figure 13*.
The degradation trend is well described by an exponential decay curve:

$$P(H) = \Delta P \cdot e^{-\frac{H}{H_0}} + P_{MIN}$$

where H is the insolation (Wh/m^2), H_0 is the typical insolation constant (Wh/m^2), ΔP is the maximum degradation amplitude (W), and P_{MIN} is the stabilized power value (W). Although this is a very simple approximation, it agrees with the hypothesis of the self-limiting degradation effect presented in [Cue99].

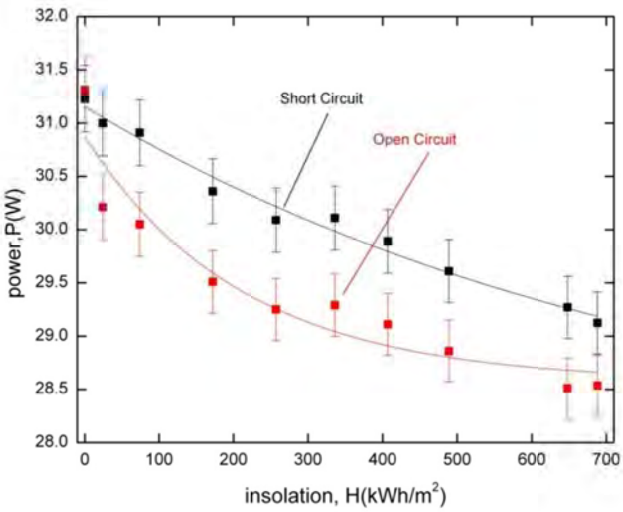

Figure 14. Influence of the *module electrical load influence on the degradation. Outdoor degradation of two Uni-Solar modules (3j): one kept under short circuit configuration; the other kept under open circuit configuration.*

Light-soaking induces defects into the a-Si atomic structure, but its intensity could be enhanced or decreased by other factors. This study analyses the effect of the **module electrical load**. Module electrical load affects the inner electrical field and hence charge carrier mobility (electrons and holes) and their recombination. A change in the module electrical load therefore modifies the effectiveness of the light-induced effect. In particular, it has been shown that degradation under open circuit configuration is more effective than under short circuit configuration [Kla07].

During the June-November period (almost 130 days and 700kWh/m^2), two modules were exposed outdoors on a quasi-horizontal inclination. One was kept under short circuit (SC) configuration while the other was under open circuit (OC). Every two weeks the modules were measured indoors with a pulsed solar simulator. The results can be seen in *Figure 14*. After approximately 700kWh/m^2, the OC module underwent a power degradation of around 9% in comparison with the 7% of the SC module. Module degradation behaves differently, particularly during the first weeks: the OC module degrades more quickly, but subsequently the two modules behave rather similarly.

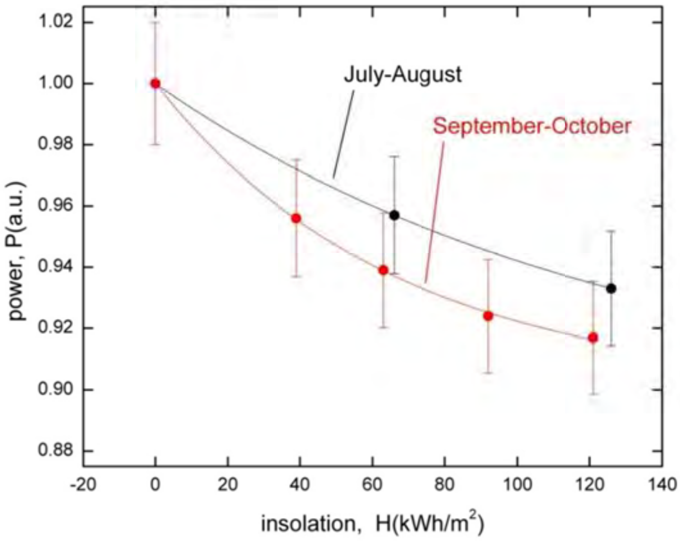

Figure 15. *Comparison between outdoor initial degradation processes performed in different seasons on the same Uni-Solar module (3j): black points represent degradation during the warm season (July-August) while red points represent degradation during a colder season (September-October). For process parameters, see Table II.*

Outdoor initial degradation is also affected by the **season** during which the module undergoes the light soaking. In particular, with equal irradiation values, the initial degradation is slower during the warm season than during the cold season, as seen in *Figure 15*. *Table II* shows the fit parameters related to the curves of the figure are shown. The light soaking conditions of the two degradation processes are similar (module under maximum power point (MPP), total irradiation of about 120kWh/m^2), except for the distribution of the working module temperature: the working time during which the temperature was higher than 40°C is 33% of the total duration for the Jul-Aug period, compared with 24% for the Sep-Oct period.

This difference in degradation rapidity could be explained by considering that, as a first approximation, the effects of degradation and annealing could be linearly combined, therefore degradation during warm period proceeds more slowly because it is combined with a more effective annealing process.

Table II. *Comparison between outdoor degradation processes performed in different seasons (see Figure 14). The main difference in the fit parameters is the H_0 value representing the degradation rapidity (the lower the value, the faster the degradation): degradation is slower in July-August than in September-October.*

Light soaking conditions		
Season	**Jul-Aug**	**Sep-Oct**
Electrical Configuration	MPP	MPP
Insolation *[kWh/m²]*	126	121
%T > 40°C	33%	24%
Power degradation	0.07	0.09
Degradation rapidity, H_0 *[kWh/m²]*	81	69

4.2.2 Annealing. Influence of temperature and time.

Tests were conducted to achieve a better understanding of the effect of annealing duration and temperature on defects recovery. These tests deal with the effectiveness of the recovery. A temperature range slightly broader than the outdoor working module temperature range was considered (40-120°C). Preliminary tests showed that there is a maximum recovery level for each temperature, and that 30 hours of annealing time are generally sufficient to reach this level. During the test, the module underwent annealing processes at different temperatures: 40°C, 60°C, 80°C, 100°C and 120°C. Prior to annealing, the modules underwent a light soaking exposure in order to set a similar starting level for the different annealing processes. The power was measured with a pulsed solar simulator under standard test conditions, after 0, 4, 8, 12, 30 hours. *Figure 15* shows the results obtained.

Recovery curves at different temperatures have similar shapes: power increases more rapidly in the first hours of annealing and more slowly afterwards. In fact, the higher the temperature, the faster the recovery: for example, at 120°C, the level reached after 12h is 90% of the final level, while at 80°C this percentage is only 70%. Moreover, the stabilized power level for each temperature seems to increase linearly with the temperature in the 40-80°C range, while at higher temperatures the recovery level increases more slowly with the temperature.

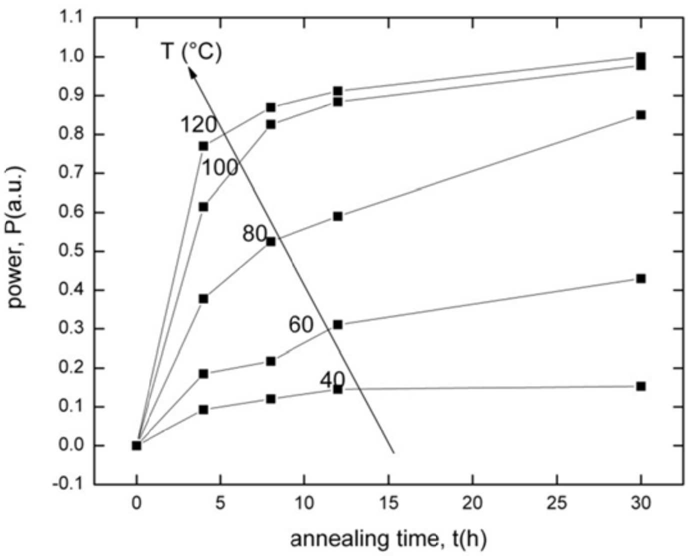

Figure 16. *Recovered power dependence on annealing duration and temperature for a Uni-Solar module (3j). All values have been normalized setting '0' as the starting level and '1' as the level reached after 30h at 120°C.*

4.2.3 Annealing. Indoor and outdoor comparison.

During hot summer days, a back insulated module may reach a working temperature of more than 80°C. Outdoor annealing was performed on two Uni-Solar modules on a very clear-skied summer day (between 9:00-17:00), in order to save energy by exploiting the sun warming power.

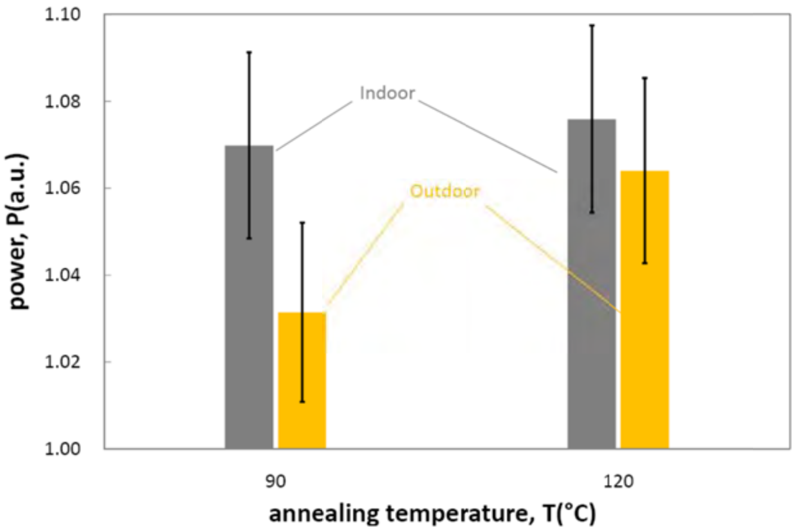

Figure 17. *Annealing efficiency for indoor (oven) and outdoor (electric foil heater) heating processes after 9h of annealing time.*

Electric foil heaters were used to heat one module to 90°C and the other to 120°C. In order to be able to compare indoor and outdoor annealing efficiency, the power reached after 9h of annealing was normalized to the power before the annealing. *Figure 17* shows that the outdoor annealing was less efficient than the indoor annealing, for both annealing temperatures (90 and 120°C). This is probably due to heating losses through radiation from the front of the module and also to the degradation caused by sunlight exposure during the outdoor process (indoor annealing was performed in a dark environment). These outcomes agree with similar tests presented in [Luc09].

4.2.4 Annealing-Degradation cycles. Process reversibility

The SUPSI-ISAAC Institute has been monitoring a 2.88kWp single junction a-Si PV plant since 1988 [Cam98]. Significant degradation occurred in the first months. The degradation intensity decreased after 20 years, and is still taking place. A possible explanation of this effect is that summer recovery (due to temperature) is only partial, so new defects build up every year (because of light soaking), decreasing the module power [Fan09]. Several annealing-degradation cycles were performed on the Uni-Solar modules in order to understand this phenomenon. The annealing process was carried out indoors, always maintaining the same parameters: 30 hours at 120°C, while the degradation parameters were different on each occasion since it was performed outdoors. Three complete degradation-annealing cycles and a fourth degradation cycle are shown in *Figure 18*.

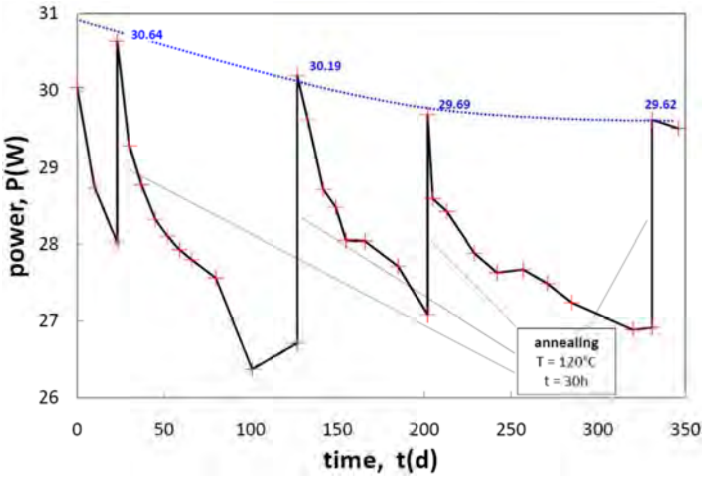

Figure 18. *Reversibility of annealing-degradation cycles. Annealing was performed under the same conditions (30h at 120°C) but the power level reached after the annealing process decreases (blue line).*

The first degradation period took place in summer and was very brief, so the degradation amplitude is quite small. The second degradation took place in autumn and winter, the third in spring and the fourth again in summer. The recovered level after each annealing was always slightly lower than the level reached in the previous one. Referring to the idea of different types of defect proposed in [Cue99], it is possible to explain this continuous degradation as due to the formation of defects that are not annealed at a temperature of 120°C. In this view, the accumulation of these types of defects produces the decrease of the recovered level.

4.3 Annealing and degradation effect on three a-Si based technologies

It is well-known that the Staebler-Wronski effect is a bulk effect [Zho86]; the intensity and rapidity of annealing and degradation processes therefore depend on cell thickness. This study compares the annealing and degradation effects on three different a-Si based technologies.

The three technologies are:

- *triple junction* from Uni-Solar;
- *double junction (micromorph)* from PRAMAC;
- *single junction* from VHF.

The amorphous silicon cell (or sub-cell) thickness of the different modules lies between 0.1µm and 0.3µm.

Light soaking was performed indoors by means of a steady state solar simulator. Module temperature was monitored by a PT100 attached to the rear of the module. The effects of the light soaking are shown in *Figure 19* and *Table III*. In particular, from the fit parameters shown in the table, it seems that degradation in single junction modules evolves more slowly (H_0) and produces a smaller power decrease (P_{MIN}) than in the other two technologies.

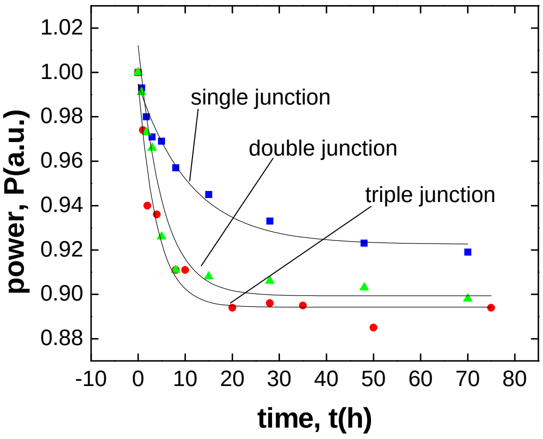

Figure 19. *Indoor Degradation. Comparison between three a-Si based technologies (single junction, double and triple junction). Light soaking parameter: 1000W/m*^{2}*; simulator class: C/C/B; modules temperature: see Table III.*

Table III. *Degradation comparison between three a-Si technologies after 70h of light soaking. Fit parameters concerning Figure 17 (see reference formula in blue).* T_{AV} *is the average temperature during light soaking process.*

$P(H) = (\Delta P \cdot \exp(-H/H_0) + P_{MIN})/P_0$	H_0 (kWh/m^2)	P_{MIN}	T_{AV} (°C)
Triple junction	4.0	89%	46
Double junction (micromorph)	5.2	90%	56
Single junction	11.2	92%	38

Indoor light-soaking seems to produce almost the same effects (process rapidity and degradation amplitude) on the double and triple junction models. These results differ appreciably from the previous comparison between various a-Si based technologies performed at our institute and found in the literature [Kro97], [Ast09]. Contrary to the results of our study, in these papers single junction a-Si modules record the higher degradation, probably because of their thicker cells, while the triple junction modules, with thinner subcells, record the lower degradation. The main difference between the tests performed in this study and those of the previous works is that here light-soaking was performed indoors. The steady state spectrum that was used is clearly different from the AM1.5; in particular, it has higher intensity in the blue range (300-600nm) and lower intensity in the red/near IR range (600-1100nm).

This difference in spectrum could influence degradation through three main aspects: *photon absorption depth*; *light induced creation of defects* and *power measurements*.

Absorption depth. For a-Si, on average, blue wavelengths are absorbed in the first 0.5µm of the module, while the red/near IR wavelengths can run through the module up to about 1µm. So the indoor degradation performed with our steady state simulator probably produces an effective degradation on the first cell layers but not on the deepest ones. The triple junction and micromorph models consist of a series of sub-cells so the first cell (a-Si in both cases) is strongly affected by the light-soaking. Since the Isc and FF of the whole cell depends strongly on the Isc and FF of each single sub-cell, a degradation that occurs mainly on the first sub-cell could significantly affect the performance of the whole cell. In the case of the single junction model, the induced-defect density is probably not homogeneous along the cell, as also shown in [Kla07], leading to a lower power decrease.

Light-induced creation of defects. During the electron promotion from valence to conduction band, the energy surplus (difference between E_{ph} and E_G) is dissipated through thermal relaxation (phonon-lattice scattering). This energy induces defects into the atomic structure (SW effect). Blue photons have more energy than red ones, therefore the amount of energy dissipated during this process is greater than for the AM1.5 spectrum. This fact enhances the degradation intensity.

Power measurements. In this test, module power was measured by means of a maximum power point tracker during the indoor light soaking process, therefore under a steady state lamp spectrum. This spectrum is noticeably different from AM1.5 and produces measurement values different from those in the AM1.5 spectrum. The relative power changes (occurring during degradation) could be affected by these differences.

After the light soaking, the module underwent an **annealing** process, which was conducted outdoors in an air heating oven (dark conditions) at a temperature of 120°C. *Figure 20* shows the results. The most noticeable difference between the 3 technologies is the shape of the recovery curve of micromorph module. The recovery rapidity of the micromorph is lower than the other 2 technologies, in fact, the recovery level reached after 8h represents approximately 90% of the final level for single and triple junctions but only 65% for micromorph. Another difference concerns the recovery level after 30h, which is approximately 7% higher than the initial level for the triple junction, 14% for the single junction and around 17% for the micromorph.

The degradation amplitudes of single and triple junction technologies are in agreement with the values observed in outdoor tests conducted at our institute, while, in comparison with the other two technologies, the power recovery of the micromorph module is higher than that recorded by the previous comparison performed at ISAAC.

This high power recovery for micromorph could be explained considering the spectrum of the light that produces the degradation. Regarding the micromorph, the rich blue light-soaking spectrum means that the degradation is very effective on the a-Si subcell (the microcrystalline subcell does not degrade under AM1.5 spectrum), so the degradation is almost complete only for micromorph (unlike the single and triple junction). The micromorph recovery is therefore a full recovery and in relative amplitude is higher than the other two technologies. The difference between amplitude of degradation (see *Figure 19*) and recovery (see *Figure 20*) of the three technologies could also be enhanced by the fact that, during light-soaking process, module power was measured under a blue-rich spectrum in comparison with the "quasi AM1.5" spectrum of the solar simulator (class A/A/A) used to measure module power during the annealing process.

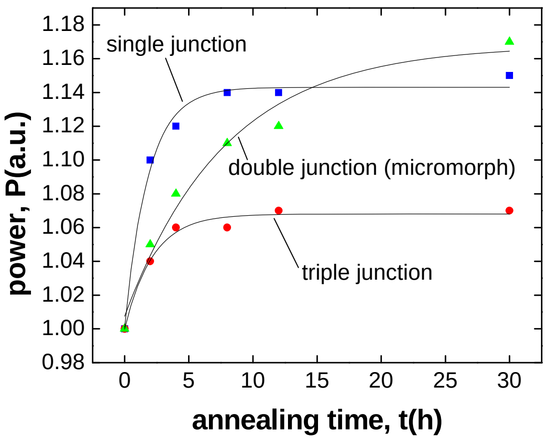

Figure 20. *Indoor Annealing. Comparison between three a-Si based technologies: single, double and triple junction. Annealing temperature: 120°C.*

4.4 Spectrum variation and Staebler-Wronski effect on a-Si

As shown in *Figure 7,* the spectral response of the single junction a-Si module lies in the 300nm - 750nm range and is therefore narrower than the crystalline range (300-1200nm). So an a-Si module is more sensitive to sun spectrum variations than a c-Si module.

Sun spectrum varies during the year, mainly because of the variation of the sun height in the sky. When the sun is higher in the sky (summer), the light path in the atmosphere is shorter, so the sun spectrum on the Earth's surface is more blue-rich, whereas, when the sun is lower, the light path is longer and the spectrum becomes more red-rich. Due to its typical spectral response, the collection of light increases and consequently the power of an a-Si module is greater for a blue rich spectrum and smaller for a red rich one. Different approaches may be adopted in order to characterize the spectrum with a single number, (Average Photon Energy [Min07], Air Mass [Ken06], Useful Fraction [Got04],…). In this study we chose to use the Air Mass (AM) value approach.

AM is a value related to the length of the light-path in the Earth's atmosphere. The AM value is obtained through geometrical calculation; its minimum value (1) is when the sun is at the Zenith and its maximum value (around 40) is when the sun is on the horizon. AM values are calculated assuming very clear sky conditions (clouds generally increase the blue component of the sun spectrum). Therefore outdoor measurements were always taken when very few (or possibly no) clouds were in the sky. Measurements were taken on different days over the year and on the same day at different hours. Measurement values have been corrected to 1000W/m^2 according to the international standards [IEC60891].

From the results, shown in *Figure 21*, the dependence of a-Si short circuit current on AM value seems to be linear. Isc varies by about 25% in the AM range considered (from 1 to 5), decreasing for higher AM values (red rich spectrum). This effect is strong if compared to the c-Si module (see *Figure 21*) for which the Isc value varies by about 6-7% in the same range. Moreover, the effect on c-Si is opposite, the short circuit current of c-Si increases for higher AM values. These results largely agree with those presented by Kenny [Ken06].

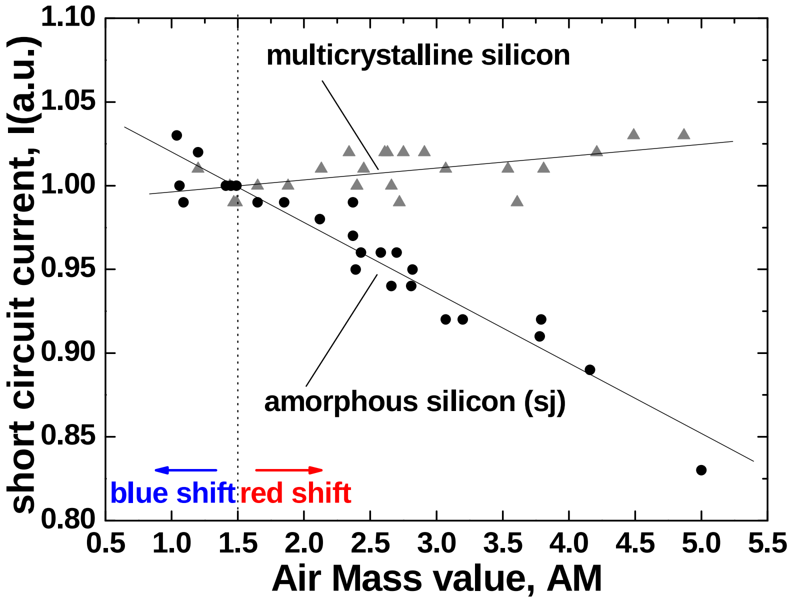

Figure 21. *Short circuit current dependence on sun spectrum. Comparison between amorphous silicon (sj) module and multicrystalline silicon.*

4.4.1 Time dependence comparison between the two effects

One possible way in which to distinguish the combination of the 2 effects (Staebler-Wronski and spectrum variation) is to consider their time dependence. SWE depends on the combined effect produced by module temperature and light soaking; at our latitude, this combination leads to a power maximum around August–September and to a minimum around January-February [Fis09], [Fan09]. Spectral effects mainly depend on the sun height in the sky (AM dependence) and - by measuring only on days with very clear skies - a power maximum is assumed to occur on June 21st and a minimum on December 21st. So the periods of the two phenomena are different and not “in phase”.

This is seen in *Figure 22*, where the red crosses refer to outdoor measurements of a module that was stored indoors in the dark, so the power variation depends only on the spectrum variation. The minimum of this data set is around December and the maximum around June. The amplitude of this phenomenon in the period considered is approximately 15%. The blue crosses refer to indoor STC power measurements of a module kept outdoors, so the power variation is due to the Staebler-Wronski effect, and its minimum is around February. No maximum value was recorded in the period considered and the present amplitude is around 8%. The black crosses refer to the outdoor measurements of a module kept outdoors, so it is assumed to combine the two effects. Due of the time-phase difference, the combination of the two effects does not make a greater impact on the power in the period considered; the overall amplitude is approximately 10%.

The conversion efficiency of the a-Si module during the year depends on the spectral distribution of the light and on the density of defects in the material. In order to define its behaviour, it is necessary to consider both the *instantaneous* (AM dependency and temperature coefficients) and *long term* effects (dependence of degradation depth on sun spectrum and SW annealing and degradation). It should be borne in mind that outdoor measurements were taken on sunny days at around noon (winter time) when the daily AM value reaches a minimum, and are therefore istantaneous measurements. The daily produced energy is instead information coming from the integral of the power over the whole day and the energy production dependence on the sun spectrum will therefore not be linearly dependent on the power variation shown in *Figure 22*.

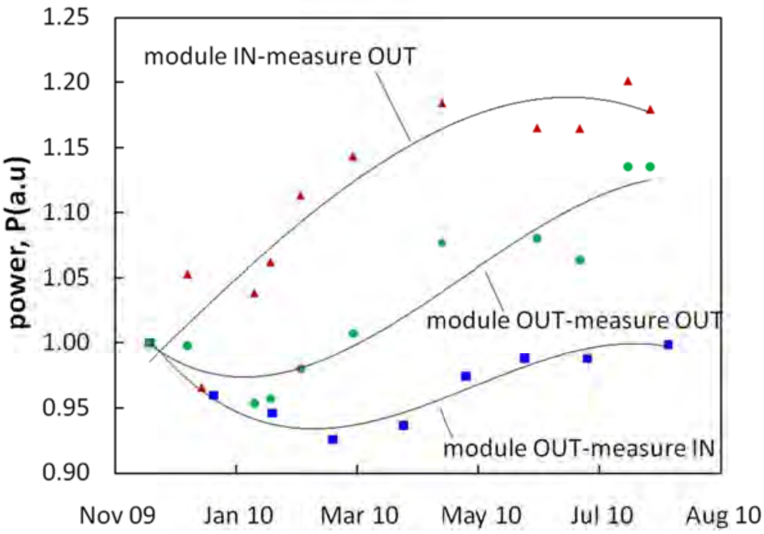

Figure 22. *Time dependence of Spectral effect and Staebler-Wronski effect.* ***Red triangles*** *represent the spectral effect (module kept indoors, measured outdoors);* ***blue squares*** *represent the Staebler-Wronski effect (module kept outdoors, measured indoors) and* ***green dots*** *are assumed to represent the combination of the two effects (module kept outdoors, measured outdoors).See also Table I. Note that the lines are simply visual aids.*

5 Conclusions

This project was the natural continuation of the previous CPT-project (2003-2006) aimed at showing the benefits arising from the building integration of an a-Si PV plant in a flat roof. The main outcome of this first project suggests that for Building Integrated Photovoltaic (BIPV) applications amorphous silicon technology is more suitable than crystalline silicon.

In this project, CPT Solar plant performances continued to be monitored and an in-depth analysis was conducted on the typical recovery and degradation behaviour of the Uni-Solar modules (constituting the plant). The behaviour of these modules was also compared with other technologies affected by the same phenomenon. Moreover a study aimed at separating the influence of the Staebler-Wronski effect from the sun spectrum variation throughout the year was also conducted.

The main outcomes of this work are:

1) <u>Monitoring of the CPT Solar plant</u>

- Despite the various maintenance work executed on the plant, the **CPT plant performance ratio is basically constant**, with an average annual value of around 85%.

2) <u>Annealing and degradation process on Uni-Solar modules</u>

- **Evolution of the initial outdoor degradation depends on the season**. The combined effect of annealing and degradation means that the warmer the season, the slower the degradation;

- **Evolution of the degradation depends on the module electric load**. Since the inner electric field depends on the external electric charge, degradation amplitude and rapidity are slower in short circuit configurations than in open circuit configurations;

- **Power recovered level depends on annealing temperature.** In a dark environment this level is reached after about 30 hours of annealing. A complete mapping of the recovered level on temperature and time dependence was conducted in the 40-120°C and 0-30h; range

- **Outdoor annealing is less effective than indoor annealing.** Heat radiation from the module front and degradation due to light soaking make outdoor annealing slower than indoor annealing;

- **The degradation-recovery process is not reversible for annealing temperatures of up to 120°C.** Light soaking during summer causes new defects to build up in a-Si atomic structures, but if the annealing temperature is insufficient to produce a full recovery, some of these defects persist after annealing. After a second degradation-recovery cycle, new not-recoverable defects are added to the previous defects, leading to a long term degradation.

3) Staebler-Wronski effect on three a-Si based technologies

- **The light soaking spectrum could have an influence on the degradation effect.** The light spectrum influences the depth of the light path into the module; moreover, a light spectrum with a higher average photon energy releases more energy and induces more defects into the atomic structure.

4) Spectrum variation and the Staebler-Wronski effect on a-Si.

- By considering their time period **it has been possible to separate between spectrum variation and Staebler-Wronski effects on a-Si.** In the period considered, the spectrum variation accounts for about 15% of the power variation, compared with 7% for the Staebler-Wronski effect.
  Because of their different time periods and “phases”, the combination of the two effects leads to an overall effect that is between the two and accounts for about 10% on the power variation in the period considered.

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6.1 Dissemination

2008:

- I.Pola, D. Chianese, L.Fanni and R.Rudel *„Analysis of annealing and degradation effects on a-Si PV modules“*, Poster presented at EUPVSEC, Valencia

2009:

- L.Fanni, I.Pola and D.Chianese *“Investigation of annealing and degradation effects on a-Si PV modules in real operating conditions”* Oral Presentation at 5th User Forum Thin-Film Photovoltaics, Würzburg

- L.Fanni and I.Pola *“Silicio amorfo comportamento anomalo ma utile”* Paper for the magazine “Fotovoltaici”

- L.Fanni *“Annealing Effekt von a-Si Systemen”* Oral presentation at Dünnschicht und Industriedacher Symposium, Paderborn.

- L.Fanni, I.Pola, E.Burà, T.Friesen and D.Chianese *“Investigation of annealing and degradation effects on a-Si PV modules in real operating conditions”* Poster presented at EUPVSEC, Hamburg

2010:

- L.Fanni, A. Virtuani and D.Chianese *“Seasonal power fluctuations of a-Si modules – comparison between sun spectrum variation and Staebler-Wronski effect”* Poster to be presented at EUPVSEC, Valencia

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