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FLAT ROOF INTEGRATION

CPT SOLAR (AET IV)

Rapporto finale

elaborato da
Istituto di Sostenibilità Applicata all'Ambiente Costruito – ISAAC
Dipartimento Ambiente Costruzioni e Design – DACD
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ABSTRACT

Several big buildings in Europe, Switzerland and in canton Ticino have flat roofs. At present, 20-25% of the flat roof European market employs plastic materials like FPO or PVC as covering waterproofing membranes.

For standard crystalline silicon plants on flat roofs, modules are mounted on separated structures - optimally tilted and orientated - designed to withstand wind loads. The bearing structure is fixed by means of ballasts or the ballast itself functions as bearing structure. The natural ventilation of the modules is guaranteed by the open-rack bearing structure. The 15.4 kWp installation, composed of flexible amorphous silicon triple-junction modules, was at its creation the only one in Switzerland. In fact, the modules, placed nearly horizontally on the flat roof – with a 3° tilt –, are directly laminated to the flexible polyolefin (FPO) membranes. The resulting elements are so joined by means of hot air welding and form the waterproofing membrane covering the whole flat roof.

This kind of PV module integration presents the advantage of being very easy to install with very well-known technologies from the installers of covering membranes on flat roofs. Besides, contrary to standard fixing systems currently in use for PV plant on flat roofs, this kind of plant doesn't need either ballast loads or additional structures. Nevertheless the horizontal position implies a lower incident irradiation over the year with respect to the optimally tilted solution. The irradiation difference between a horizontal position and an optimal tilted one can reach -15%.

The main objective of this study was to verify in which order of magnitude the better thermal behaviour of a-Si compared to c-Si technologies (annealing mechanism and lower temperature coefficients) can compensate for losses due to the quasi-horizontal roof integration (lower irradiation and higher reflection), and thus be competitive in the new build flat roof market and in the refurbishment market.

The thermal insulation doesn't allow a ventilation of the modules as usually required by crystalline silicon PV modules. This leads to a heating of the modules and consequently to changes in the operating PV parameters. The temperature of the modules reaches 80°C, typically 40-45°C higher then the ambient temperature, during hot sunny days. Thus it reaches the level where the main degradation mechanism can be reversed. The second level of complete module regeneration was practically never reached. On the other hand the modules of the reference plants, which were not thermally insulated, never went above 60°C for the 3° tilt and 64°C for the 20° tilt, in the same climate conditions.

Partners in the project:

AET Azienda Elettrica Ticinese

Sarnafil

UNI-SOLAR

ti Repubblica e Cantone Ticino

Dipartimento delle finanze e dell'economia
Sezione Logistica

FLUMROC www.flumroc.ch

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INTRODUCTION

Only with solar energy can the production of photovoltaic electrical energy be distributed over the territory in a capillary and democratic way. The impact on the built environment can create problems of acceptance from the population. The first PV plants on flat roofs were marginally integrated into the building architecture and modules were generally fixed to natural ventilated bearing structures linked to ballasts.

Since the '70s the flat roof market has grown hugely and at the present time 20-25% of the flat roof European market deals with plastic coverings. The roofs of big industrial buildings, without technical elements which could shadow modules, are seen as ideal spaces for the installation of photovoltaic modules. Besides, in building renewals it is not always possible to add ballasts, necessary for the PV plants with crystalline silicon modules, to the existing structure

The idea for this project came from the matching of the mechanical characteristics of the roofing membranes with the mechanical, thermal and electrical characteristics peculiar to flexible amorphous silicon modules.

Crystalline silicon photovoltaic modules have a high negative power temperature coefficient and hence need a natural ventilation on their back surface. Amorphous silicon modules also have negative power temperature coefficients, but they are generally half those of crystalline modules and consequently their thermal power losses are much less important. Moreover, the overheating of the amorphous silicon modules above certain values leads to power recovery with respect to initial power degradation typical of this technology.

Flexibility represents another important characteristic for the matching of the two covering materials. The extremely thin amorphous silicon sheet (<1µm), deposited on metallic or plastic substrate, leads to a photovoltaic element with a high flexibility, which doesn't affect its functioning.

The PV modules lifetime (>30 years) is similar to the traditional flat roof with plastic material (30-40 years).

The flat roof of the professional school of Trevano (CPT) needed to be renewed due to infiltrations. The renewal was realized with a covering composed of a Sarnafil T flexible polyolefin membrane joined with triple junction amorphous silicon PV modules, OEM from Uni-Solar company. The whole plant has a nominal power of 15.36 kWp (see Figure 1)

This project started in August 2003. The main goal was to analyse and verify if the particular characteristics of amorphous silicon combined to a waterproofing membrane without back ventilation but thermally insulated, could compensate for energy losses due to the quasi-horizontal position.

To avoid water and dust deposition, modules were installed with a 3° tilt. The module inclination was done by laying insulation elements preformed with the correct tilt. Due to the roof gutter position the different series were north-south oriented.

The results were interesting and beyond the initial project aims, and an important scientific publication was prepared on this subject.

All the results presented in this study refer to the climate of the southern alps and are not necessarily transferable to other climatic conditions.

Figure 1: AET IV – CPT Solar 15.4kWp PV power installation.

1 INSTALLATION DESCRIPTION

1.1 Single ply roofing system

FPOs (also known as TPO, thermoplastic polyolefin) have a good ecological profile and good long-term properties. Sarnafil T contains non-halogenated components. Under normal circumstances Sarnafil TG66/TS77 will have a service life in excess of 40 years (durability tests of Sarnafil state FPO membranes are in excellent condition after 30 years of outdoor exposure). These membranes are therefore compatible with PV modules with a lifetime in excess of 25 years.

The roofing membranes are joined by means of hot air welding (see Figure 2), creating a seam stronger than the membrane itself. The seams are created by overlapping adjacent sheets of membrane, the width of the overlap depending on whether the roofing system is mechanically fastened, adhered or ballasted. In this installation, the roofing system is mechanically fastened by means of equipment normally used for flat roof construction (see Figure 3).

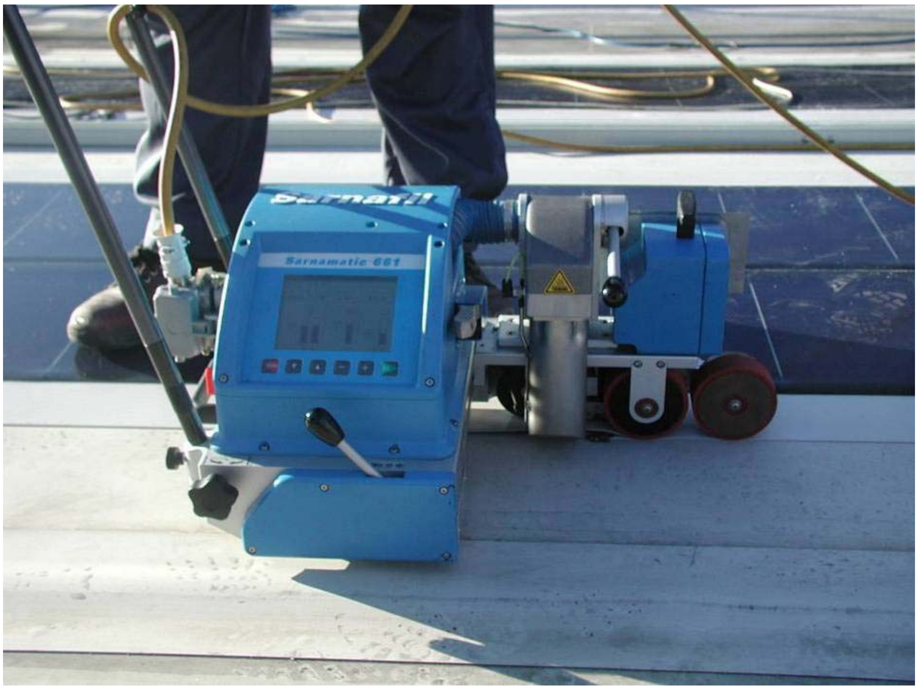


Figure 2: Hot air welding system.

Figure 3: Fixing system to roof.

The PV Sarnasol modules (see chapter 1.3) were created with the intent of substituting part of the roofing. Due to research and warranty reasons, the waterproofing layer was fully completed some months before. The PV Sarnasol modules were then fixed on the membrane forming a double flexible polyolefin waterproofing roofing.

1.2 Thermal insulation

The thermal insulation, in addition to the thermal building insulation role, functions as a support with a slight inclination of 3°. Due to the absence of surface inclination on the roof and the presence of gutters only on the north and south sides, the inclinations are oriented to east and west respectively (see Figure 4).

The insulation is made with insulating panels compact with FLUMROC MEGA stone wool. These panels are particularly suitable for treadable flat roofs.

Figure 4: Thermal insulation with 3° tilt for modules support.

1.3 Sarnasol PV module

Sarnafil - PV modules (named Sarnasol) are FPO membranes laminated together with 2 flexible amorphous silicon triple-junction modules connected in series and forming a flexible roofing element (see Figure 5). The triple-junction structure is composed of 1 hydrogenated amorphous silicon (a-Si:H) cell and 2 hydrogenated amorphous silicon-germanium (a-SiGe:H) cells, stacked in series.

Each 22-L-B a-Si module has a length of 5.5m, with Pn = 128Wp; Vm = 33V; Im = 3.88A; Voc = 47.6; Isc = 4.8A as specified from the manufacturer.

During the first period of operation, before typical initial degradation is completed, a-Si modules show 10% higher operating voltages and 4% higher operating current values.

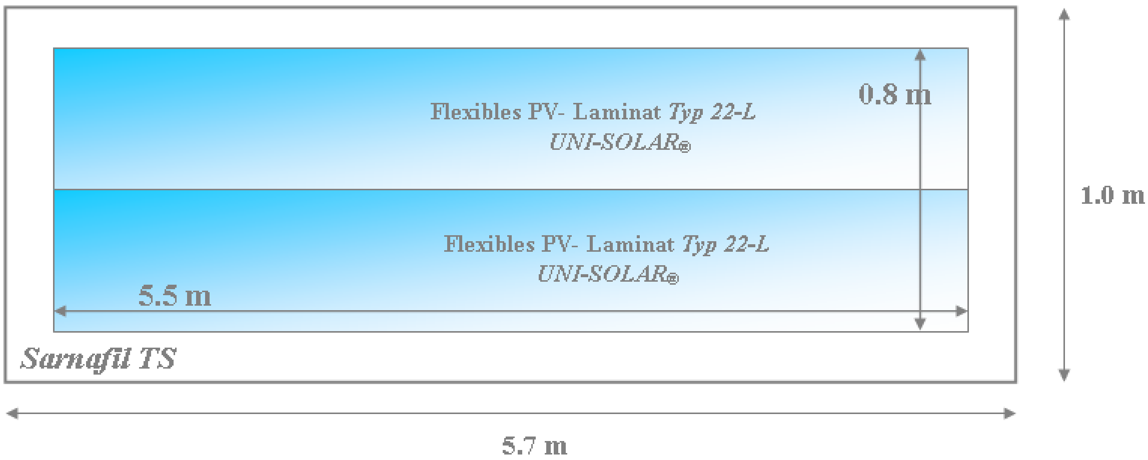


Figure 5: 256W Sarnasol PV module.

The module connections have been done with MC connectors. The cables are placed inside cable troughs on the roofing (see Figure 6).

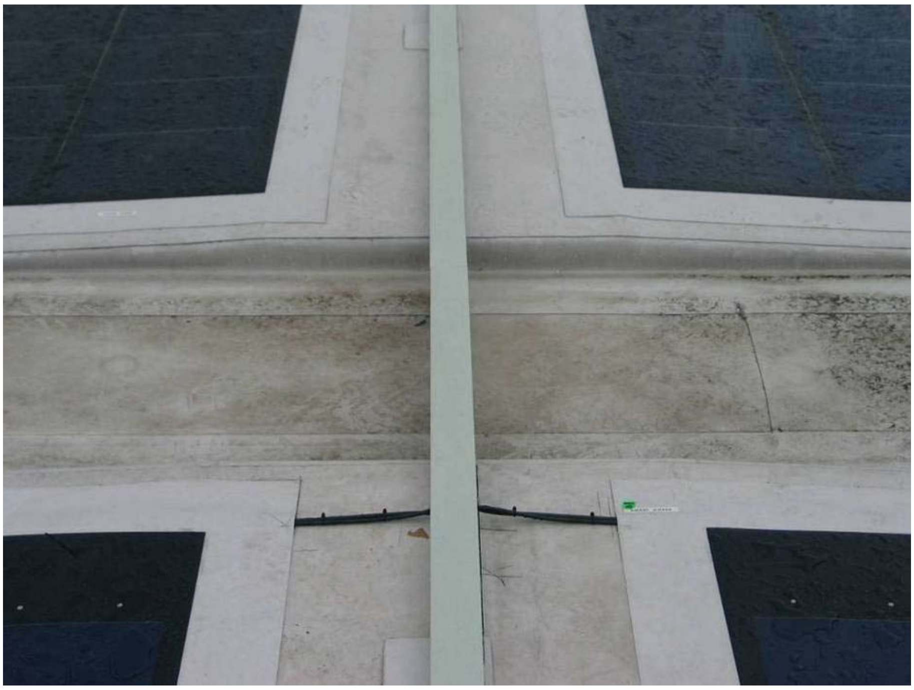


Figure 6: Cable trough for connecting cables of modules and signal cables of meteorological sensors (irradiance and temperature).

1.4 Grid connected PV system-15.36 kWp

The 15.36kWp power plant (named CPT – AET IV) is composed of 12 strings of 5 Sarnasol modules connected to three inverters SB5000TL with three independent MPPT capable inputs each. To each inverter, four strings are connected in a 2+1+1 configuration. Each string is composed of 5 Sarnasol-PV modules, each Sarnasol-PV module by two 22-L-B Uni-Solar laminates (total system: 60 Sarnasol modules). Figure 7 gives a schematic representation of the CPT plant and the reference plants.

The building itself is oriented 14° south while the series are oriented east - west with a nearly horizontal inclination of +/- 3°.

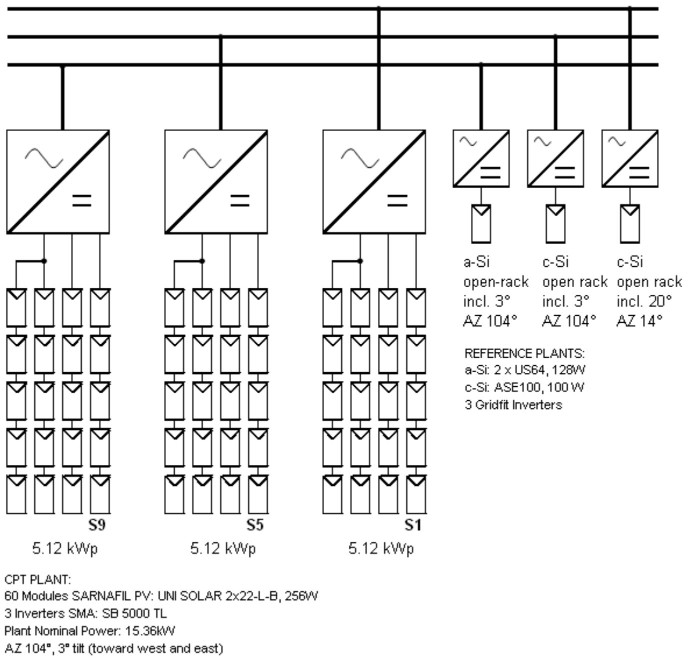


Figure 7: Schematic representation of the CPT plant and the reference plants.

1.5 Inter-comparison PV module

For inter-comparison reasons, 3 small open-rack plants with a-Si and c-Si modules were installed near the main PV plant.

The comparison plants (see Figure 8) were installed on the roof of the data acquisition centre located to the south of the main plant. Two Unisolar US64 a-Si triple junction modules were placed at a 3° tilt without thermal insulation and were linked up to form a plant with 128Wp power. Two sc-Si modules were installed open-rack, one with a tilt of 3° and the other one with one of 20°.

All three plants were linked to the public grid using 3 small GRIDFIT 250 inverters, one for each plant.

For most of the inter-comparisons between the reference modules and the CPT-plant, 3 strings of the latter were selected, namely strings #1, 5 and 9. The reason for this choice is essentially due to their orientation of AZ 104° and a tilt of 3° towards west, which corresponds exactly to that of the a-Si and c-Si reference modules also tilted at 3° west. Consequently, the irradiation conditions should be the same.

Figure 8: Inter-comparison PV systems with 3 small open-rack plants with a-Si and c-Si modules.

1.6 Monitoring data acquisition system

In addition to the inverters, a separate monitoring data acquisition system was used. Precision shunts and isolated signal converters and transmitters for current and voltage DC respectively were used. Data monitoring and acquisition was done by means of two Agilent Data Loggers. The main parameters - electrical, meteorological and thermal ones - were recorded each minute from 5am to 10pm. Before lamination, in order to measure cell temperature, PT100 temperature sensors were fixed under 4 PV modules placed on different parts of the plant, as illustrated in Figure 9. Further temperature sensors were placed under 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. The results for current and voltage accuracies were 1.2% and 0.7% for the CPT plant and 0.6% and 0.01% for the open-rack reference plants respectively. Accordingly, the expected uncertainties of the data analysis on dc-side should not exceed 1.4%.

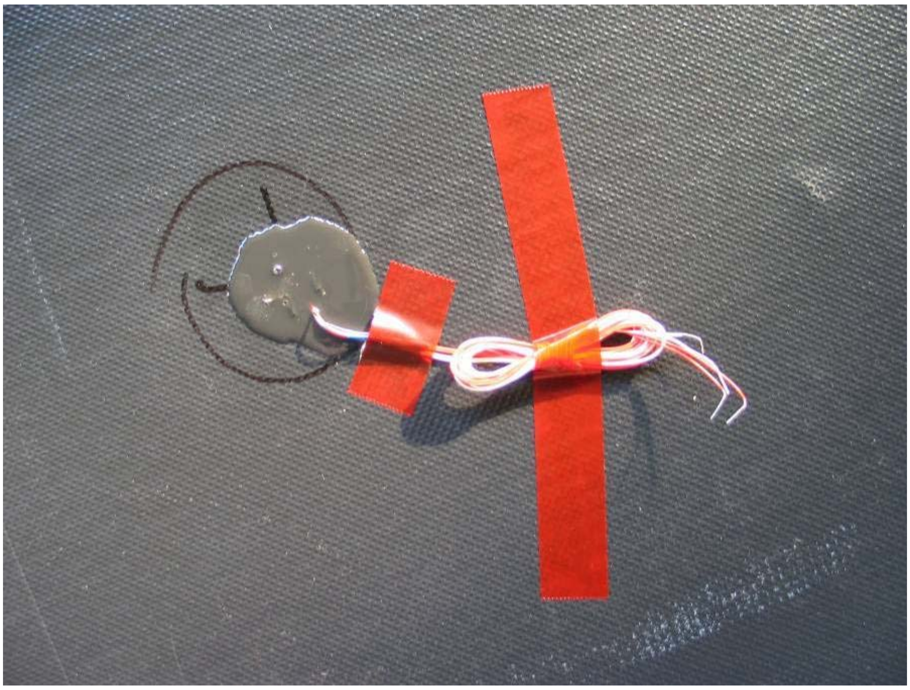


Figure 9: Temperature sensor PT100 installed before lamination of the Unisolar module with FPO membrane.

2 WORK CARRIED OUT AND RESULTS ACHIEVED

2.1 Abstract

The work carried out on the data analysis and summarized in this report, is based on 3 years of plant operation, namely from the beginning of 2004 to the end of 2006. For the 3 open-rack plants this was done after their installation, starting from the beginning of 2005.

The analysis of the CPT-plant behaviour was essentially done in two steps. On the one hand, the performances on ac-side were studied. At this time the main interest was on the investigation of its Performance Ratio and energy yield, for which a comparison with the estimated production (based on measured meteorological data) was done. On the other hand, the analysis was focused on the comparison of the CPT-plant with the open-rack plants (reference modules). The characteristics analysed were taken for the dc-side. Besides, with the aim of better understanding the thermally insulated nearly horizontal plant behaviour, we analysed and quantified the irradiation difference and optical losses with respect to a 20° tilted open-rack c-Si power plant.

This study has highlighted the benefits of an amorphous thermally insulated BiPV horizontal installation, such as CPT-plant. In fact the higher working temperatures of CPT-plant has allowed enhanced annealing effects on amorphous cells and so better performances compared to the open-rack solution. Moreover, the better thermal behaviour and annealing processes of a-Si compared to c-Si technologies could almost entirely compensate for losses due to the nearly horizontal roof integration

The average annual energy production of the CPT plant, during 3 years of operation (01.2004-12.2006) was 1066 kWh/kWp. This result exceeded expectations, being almost comparable to a 20° tilted open-rack c-Si power plant, despite the lower irradiance and higher reflection losses with respect to the latter.

2.2 Inverter performance

The plant is equipped with 3 transform-less inverter SB5000TL (SMA). To each inverter 4 strings are connected in a 2+1+1 configuration. Using 3 independent DC/DC converters (MPPT), it is possible to optimise the modules' location at different tilts without affecting the plant efficiency.

For horizontal plants, the "inverter nominal power / modules nominal power" ratio is usually lower than 0.8. But during the initial period of functioning working voltage (Vm) and current (Isc) of a-Si modules could be higher than 11% and 4% respectively and during plant design this fact has to be taken into account. In this case, for quasi-horizontal plant with a-Si modules, installation in the winter period is the optimum.

The inverter efficiency is slightly higher than expected (94.7% at 330 V) and, at 15% of the nominal power (Pn, ac), the inverters global efficiency is higher than 95% ($\eta \geq 90\%$ at 5% of Pn,ac). The maximum efficiency was equal to 97.2% at 7.5 kW (50% of Pn, ac). These characteristics are shown in Figure 10.

The nominal power has not been reached yet (December 2003 – December 2006).

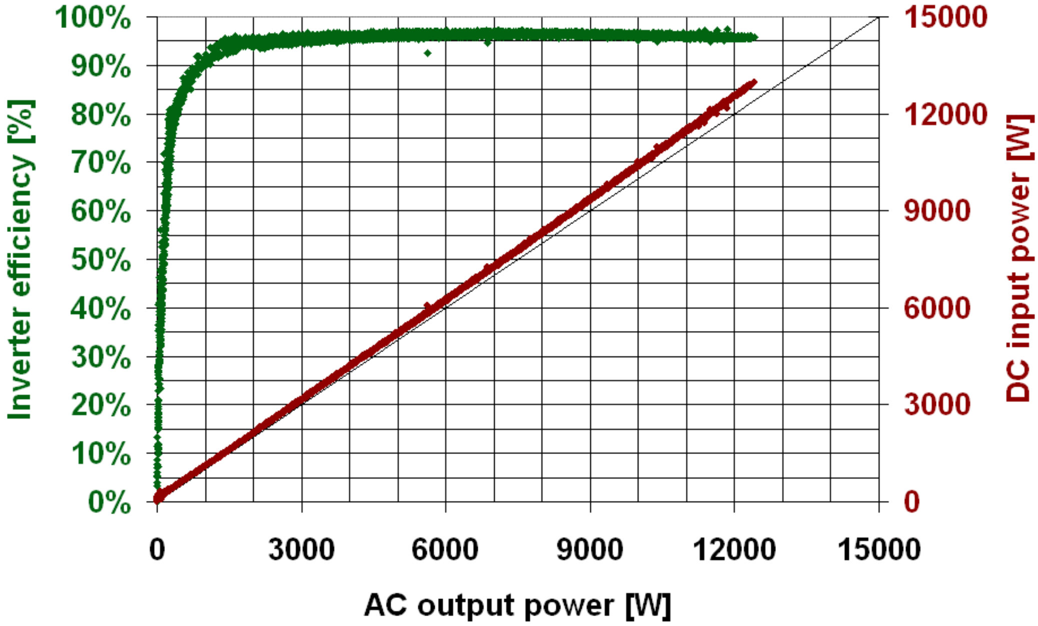


Figure 10: Inverters (3 x SB5000TL) working efficiency vs. AC output power and DC power vs. AC power.

SMA inverters similar to the SB5000TL show MPPT static efficiency higher than 99%, as measured for the SunnyBoy 3800 in [9], whereas the MPPT static efficiency of the GRIDFIT is guaranteed higher than 98% by the manufacturer. Unfortunately, for the MPPT static efficiency we didn't foresee a direct measurement at the working voltages and powers. The input voltage effects on the inverter behaviour and the efficiency variation, at a given power, depends on the input voltage., i.e. the module temperature.

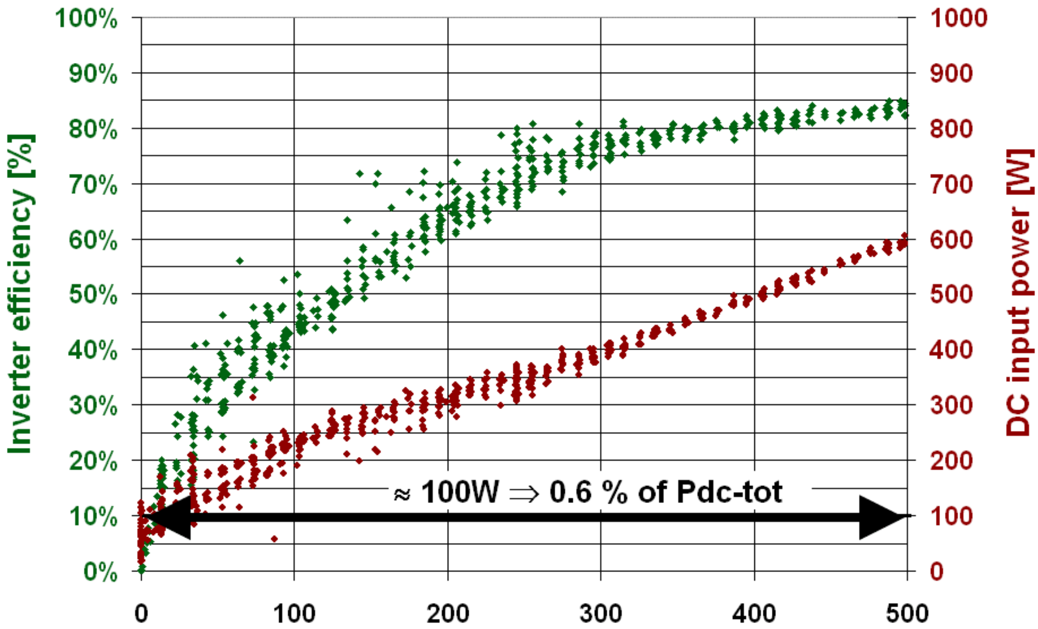


Figure 11: Threshold level and inverter efficiency at lower power (3.3% of Pn,ac).

The initial threshold level is about 100 W, corresponding to 0.6% of the inverter input nominal power (DC) as indicated in Figure 11.

2.3 Module temperature behaviour

The modules temperature behaviours observed for the years 2004, 2005 and 2006 were very similar. As a matter of fact, the temperature on the back of the module (Tbom) of the plant showed maximum values around 80°C and the mean temperature increased by up to 40-45°C above the ambient temperature, which went up to 35°C (see Figure 12). For modules mounted on an open-rack structure, the mean temperature was 20-25°C above the ambient temperature.

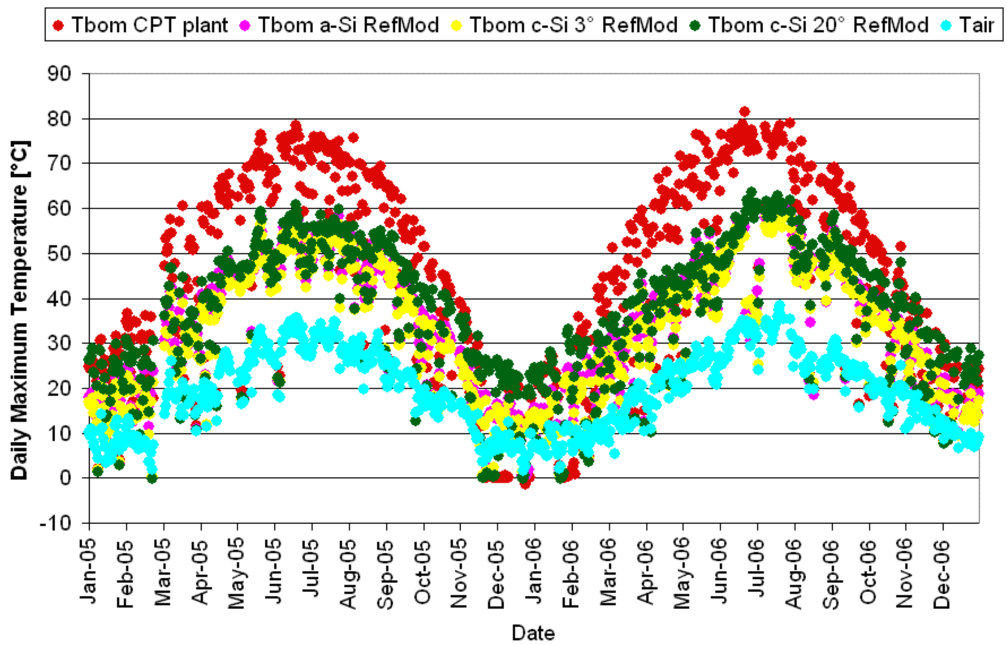
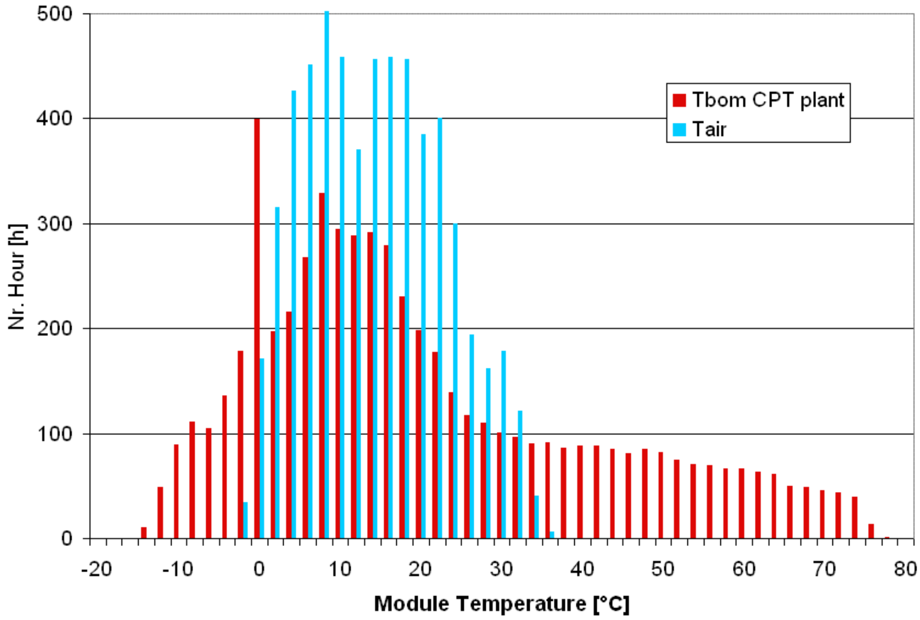


Figure 12: Daily maximum ambient temperature (Tair) and back-of-module temperature (Tbom) of thermally insulated a-Si modules (CPT-plant) and open-rack a-Si and c-Si modules.

A significant energy rating of the CPT-plant is attained thanks to the lower power temperature coefficient (γ) and thermal annealing of a-Si modules, as presented in section 2.5.3.

In Figure 13, the hourly temperature frequencies in 2006 for the CPT-plant and the three reference modules are represented.



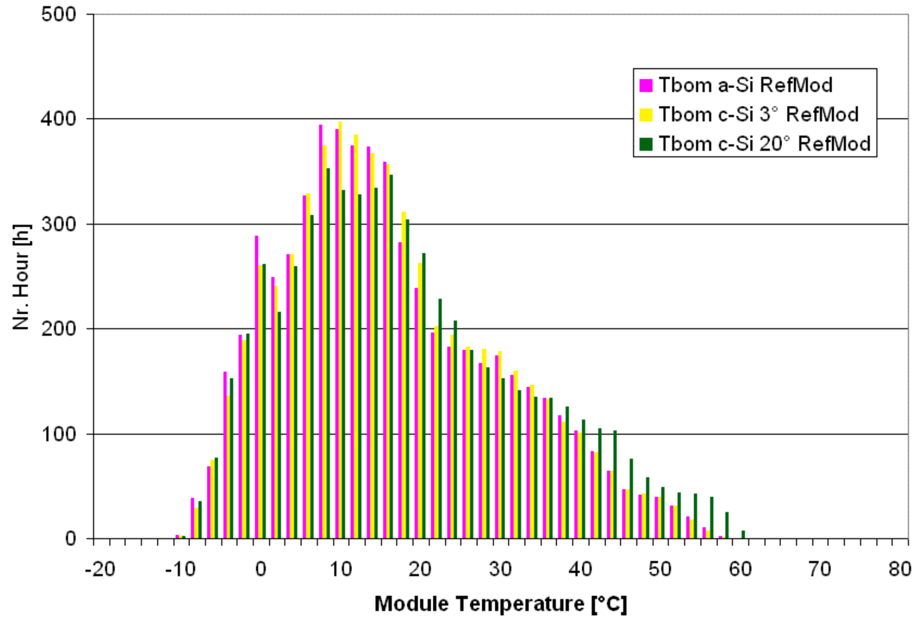


Figure 13: Operating time vs. ambient temperature and CPT module temperature (up) and open-rack reference modules temperature (down).

As we can see, the temperature of the CPT-plant exceeded the value of 40°C for more than 1000 hours of the year 2006 (same result was observed for 2004-2005, as presented in [11] and [12], where more than 350 hours of operation were recorded above 60°C and around 10 records at 80°C and more). Thus the second level of complete module regeneration was practically never reached. Whereas for the modules of the reference plants, not thermally insulated, temperatures never went up 60°C for the 3° tilt and 64°C for the 20° tilt, in the same climate conditions.

Temperatures of -14°C (with Tamb = -4°C) are reached during the night, when the modules irradiate towards the sky. On the other hand, the temperature of non-thermally insulated modules do not go below -10°C. Accordingly, during the early hours of the morning, at low irradiance, the low module temperatures can create voltages at the input of the inverter which are higher than those normally present in an open-rack ventilated structure. In planning a plant similar to the CPT one, it is necessary to size the inverter so that the voltages do not exceed the input voltage limit of the inverter.

Figure 14 shows the temperature behaviour of the Performance Ratios on the dc-side of strings #1 of the CPT-plant (thermal insulated a-Si modules), the a-Si reference module (open-rack, tilt 3°) and the c-Si module (open-rack, tilt 3°), for solar irradiance in the range between 790 and 810 W/m^2. The selected period is of one month between May and June 2005.

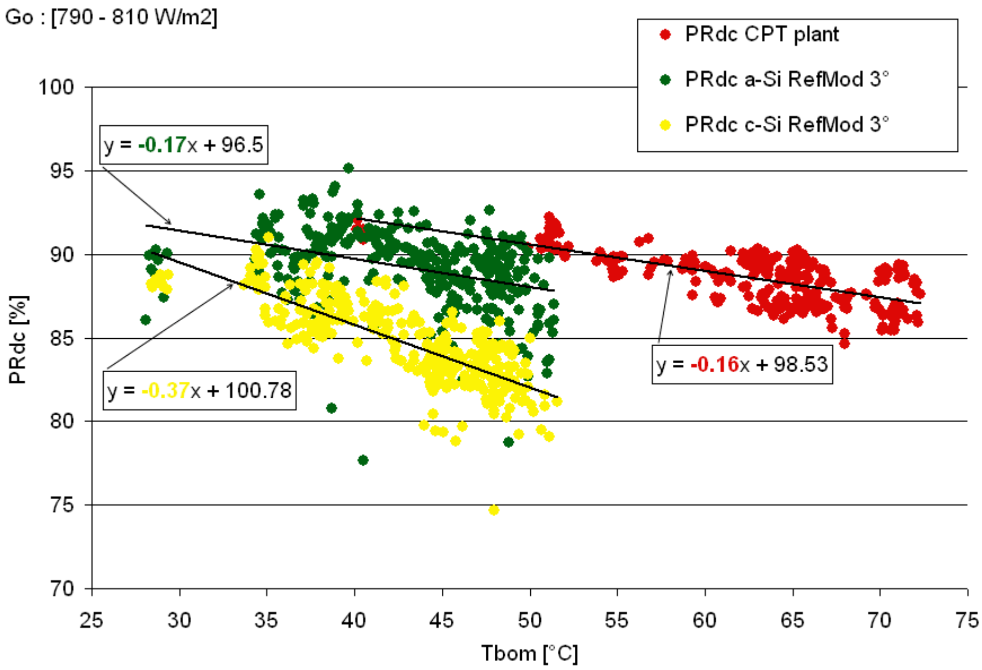


Figure 14: Performance ratio PRdc vs. module temperature Tbom at G: 790-810 W/m2 (May-June 2005) for string1 of CPT plant and a-Si and c-Si reference modules a 3° tilt.

It is noticeable, in this graph, that c-Si has twice as high a power decrease with increasing temperature as a-Si. In other words, a temperature increase in a-Si modules twice as high as in open-rack c-Si modules would generate the same power losses. This result is typical for the period analyzed. In fact, looking at other months, the situation showed some changes; the power thermal behaviour of the a-Si plants were quite variable, whereas those of the c-Si plants did not change much. For instance, during March 2005 the CPT plant even showed a power increase with increasing temperature.

These changes of the power thermal behaviour for a-Si modules are a consequence of power seasonal fluctuations due to annealing and light-induced degradation effects, as well as spectrum variations of incident sunlight. Nevertheless, the trend observed is characterized by a power decrease with increasing temperatures for a-Si plants lower than for c-Si plants, which often resulted as being twice as high.

The results presented in [1], showed that the efficiency recovery for triple junction modules does not seem to be very effective for temperatures around 65-75°C, even for hot periods of 12-24 hours (partial recovery of approx. 20% after 3 days of heating), whereas, a temperature increase up to 85°C caused remarkable recovery for a relatively long heating period of 12 hours (standard annealing of laboratory samples only takes 2-3 hours). Referring to these results, one can deduce that in the CPT-plant, the efficiency recovery is only partial. In fact temperatures of 85°C are never reached and even temperatures around 75°C are attained only for a few hours during hot, sunny days, as presented in Figure 15.

However, these results should be evaluated carefully because the modules tested in [1] were not heated in real outdoor conditions. Nevertheless, the higher working temperature for the CPT integrated plant with respect to the open-rack structure seems to play a fundamental role in its performance as described in the next section.

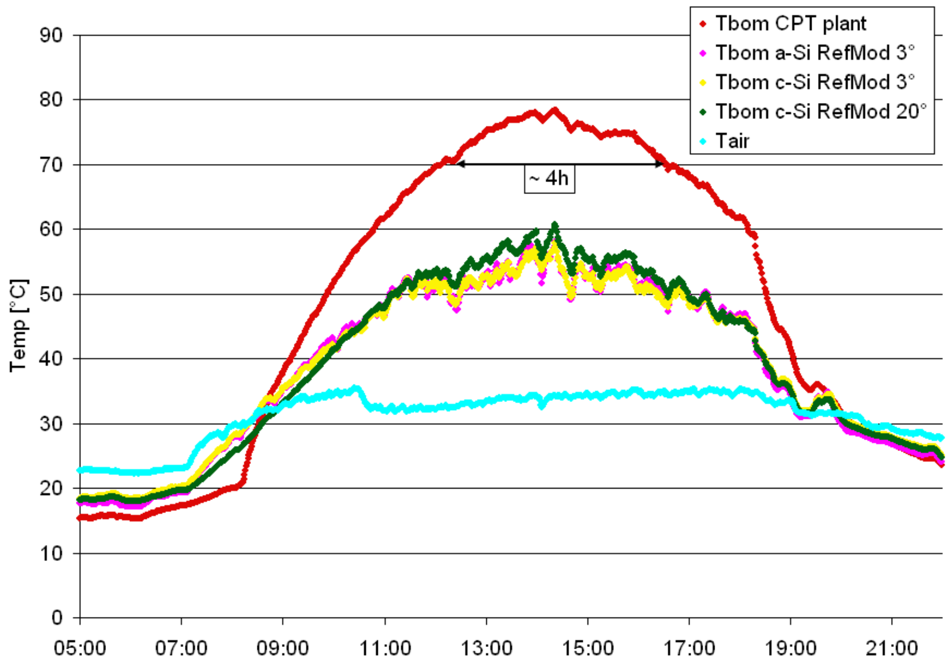


Figure 15: Ambient temperature (Tair) and back-of-module temperatures (Tbom) of CPT plant end reference modules during a hot sunny day (27th of June 2006).

2.3.1 Annealing and degradation mechanisms

Generally the degradation is separated into `slow' and `fast' degradation components. The terms `slow' and `fast' refer to the ease with which the degradation can be reversed by the annealing process. A typical array of a-Si modules in open-rack condition shows a recovery of part of the initial performance during outdoor exposure, as observed in [2], [3] and [4]. Two reversible mechanisms can adequately represent this phenomenon:

1. Defects generated by slow-degradation mechanisms are characterized by large activation energy (≥ 0.9 eV) and can be removed from the solar cell in discernible amounts by annealing at temperatures higher than 80°C approximately.
2. Defects introduced by the fast-degradation mechanisms exhibit annealing behaviour consistent with a low activation energy (< 0.3 eV), and the anneal rates at 50°C are large enough to affect device performance significantly.

For triple junction modules, like the one composing the CPT plant, the temperature for fast annealing is higher, around 60-65 °C. In fact, due to the three junctions, the relative built-in potential is very high, which makes the effect of material quality (degradation/annealing) much less pronounced.

The two annealing mechanisms, together with a lower power temperature coefficient compared to c-Si modules, can almost entirely compensate the low irradiation and the high reflection due to the nearly horizontal roof integration, as observed for the CPT-plant and presented here.

2.4 Energy production

Essentially, the energy production analysis followed two lines. Firstly, the measured energy production was compared to the predicted one simulated in PVsyst, referring to the measured meteorological data. Later in 2006, the comparison of energy production of the CPT-plant and the reference modules was analysed.

2.4.1 Measured and predicted energy production

The monthly energy production was simulated with the model used for amorphous silicon modules in the PVsyst 3.21 simulation program with ISAAC-TISO adjusted parameters and compared to the real energy production with the same measured meteorological conditions. The result is presented in Figure 16.

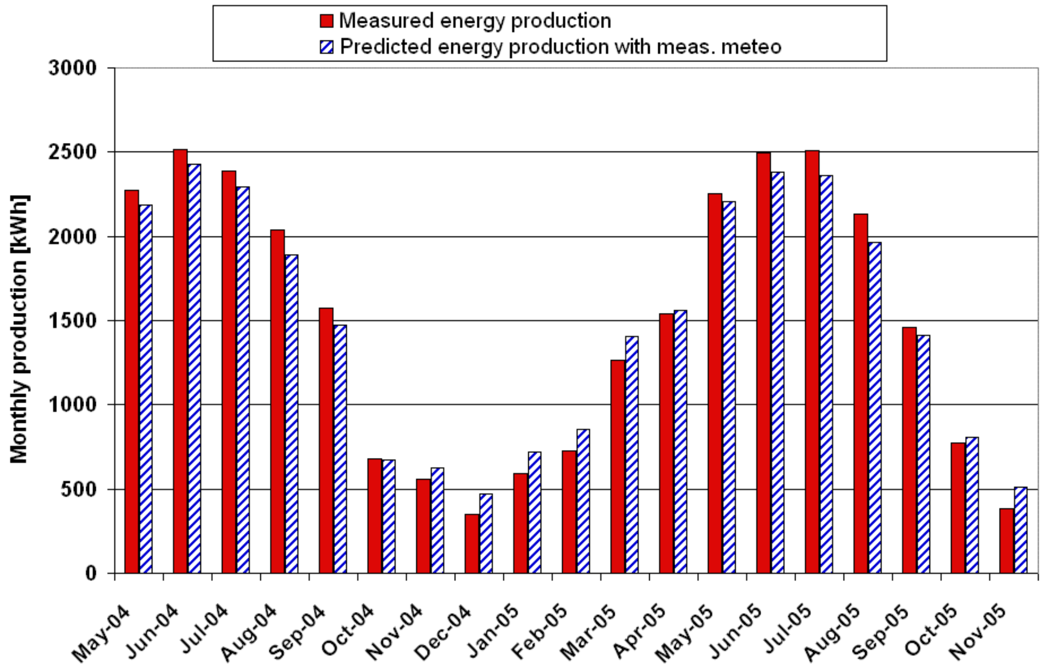


Figure 16: Predicted and real energy production.

As we can see from Figure 16 and in details in **Table 1**, the estimated production of the 5 colder months is over estimated, whereas, in warmer months, it is lower compared to the real production. This differences are due to thermal annealing and light-induced degradation effects, spectrum variations of incident sunlight and snow covering of the flat roof which are not included in the model used.

Month	Real energy [kWh]	Predicted energy [kWh]	Diff. Real/Pred. [%]
May 2004	2277	2186	4.16
June 2004	2515	2429	3.56
July 2004	2385	2297	3.82
Aug. 2004	2039	1888	8.00
Sep. 2004	1575	1471	7.04
Oct. 2004	682	671	1.59
Nov. 2004	559	624	-10.36
Dec. 2004	349	470	-25.71
Jan. 2005	590	717	-17.66
Feb. 2005	728	855	-14.89
Mar. 2005	1267	1405	-9.83
Apr. 2005	1544	1561	-1.12
May 2005	2253	2203	2.25
June 2005	2496	2378	4.98
July 2005	2508	2363	6.14
Aug. 2005	2130	1963	8.52
Sep. 2005	1463	1415	3.38
Oct. 2005	772	808	-4.42
Nov. 2005	384	509	-24.64

Table 1: Comparison between real and simulated (with measured meteorological data) monthly energy production. In bold, the winter cold period.

The simulation of energy production carried out with real measured meteorological data (from 1.5.2004 to 30.4.2005) and with crystalline silicon modules on an open-rack structure tilted at 20° and south oriented, shows a Yf production = 1150 kWh/kWp, resulting only 7.2 % higher than the real measured final yield of the CPT plant (1073 kWh/kWp). The difference of 7.2 % is small considering the lower irradiation level of the nearly horizontal CPT plant compared to a 20° tilted and south oriented plant. As a matter of fact, the annually measured difference was around 15% less for the CPT. Optical losses are also more important for horizontal installations than tilted one, as illustrated in section 2.6.

In Figure 17 the monthly energy productions of CPT plant during the years 2004, 2005 and 2006 are compared. The main differences are due to snow periods (in 2005 and 2006) and to an inverter breakdown in 2006. Other less important differences are due to different meteorological conditions and therefore irradiance levels.

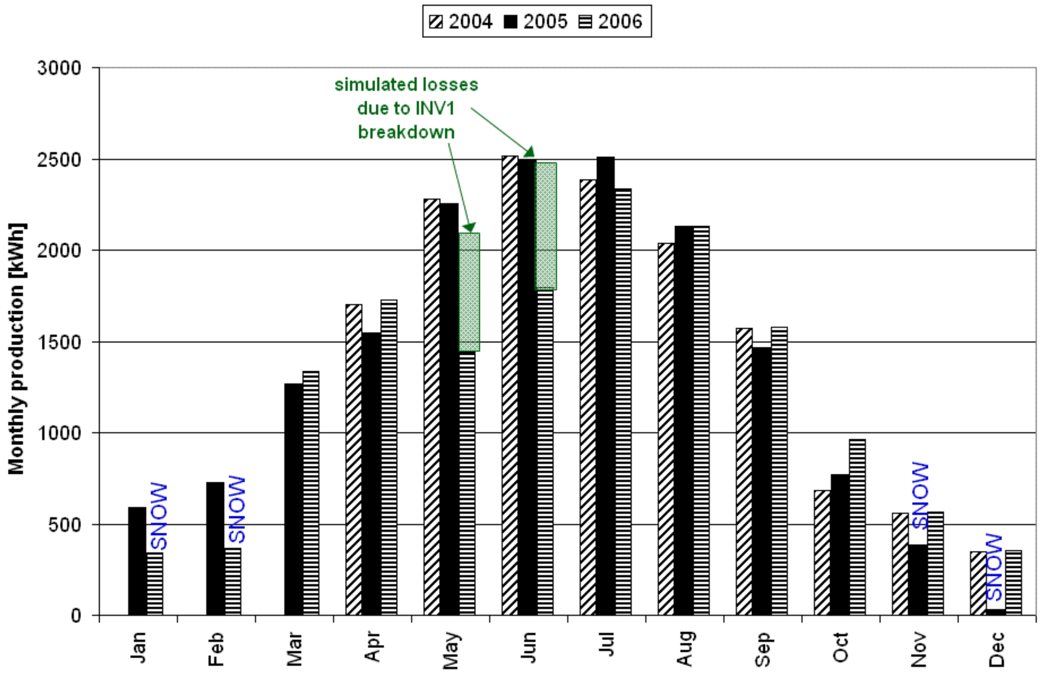


Figure 17: Comparison of monthly energy productions in 2004, 2005 and 2006.

Table 2 summarizes the yearly plant production and final yield for the 3 years of CPT-plant operation.

			Simulation without snow cover	
Year	Meas. energy production [kWh]	Yf [kWh/kWp]	Meas. energy production [kWh]	Yf [kWh/kWp]
2004	16679	1086		
2005	16166	1053	16580	1079
2006	14939	1060 *	15524	1098
average	15928	1066	16052	1089

* Estimated without inverter breakdown

Table 2: Yearly energy production and final yield of CPT-plant

The decrease in plant production in 2005 and 2006 is essentially due to the snow period, as previously explained. As a matter of fact, during the winter season 2005-2006 (see Figure 17), starting from the end of November and during the following 3 months, the snow partially covered the plant, affecting its production. The thermally insulated surface did not allow the snow to melt on the modules, unlike the reference modules, due to their ventilation on the back. Between the months of November 2005 and February 2006, the plant lost about 65 kWh/kWp.

Besides, the enhanced energy reduction in 2006 is mainly due to an inverter breakdown which caused plant partial operation from the 4th of May to the 25th of June 2006. In fact, looking at the final yield (and so not considering inverter failure by assuming 2/3 of installed power for the period of plant partially in operation) the value in 2006 was 1'060 kWh/kWp, close to that in 2004 (1'086 kWh/kWp).

In comparison c-Si module plants situated in Ticino produced in 2004-2006 on average 1095 kWh/kWp (see [10], resulting only around 2.7% higher than the average CPT plant production during the same period (1066 kWh/kWp). Besides, it is noticeable from the simulation without snow presented in Table 2 that the nearly horizontal CPT plant, in case of no snow or at least not important snow covers, can reach production levels very close to those of optimally oriented c-Si module plants.

This means that the better thermal behaviours of a-Si technologies compared to c-Si modules can almost entirely compensate for losses due to the quasi-horizontal roof integration.

2.4.2 Measured energy yield of CPT plant and reference modules

The comparison with the reference modules was made for the dc-side. The comparison of the MPPT static efficiency of the inverters was not possible. Nevertheless we foresee replacement of the reference module inverters soon, each with a new MPPT3000 device (developed and assembled at ISAAC institute) for which the MPPT static efficiency has been verified.

The monthly Final Yield values for strings #1, 5 and 9 and reference modules on the dc-side (Yfdc) are reported in Figure 18. It is noticeable in this graph that the CPT-plant, compared to the two reference modules tilted at 3°, reached increasingly higher values except during the snow period formerly discussed (Nov 05 – Feb 06). On the other hand, compared to the c-Si reference module tilted at 20° and orientated south (AZ 14°), the CPT Final Yield (dc-side) was higher during the warmest months, from May to August, where recovery processes mostly occur.

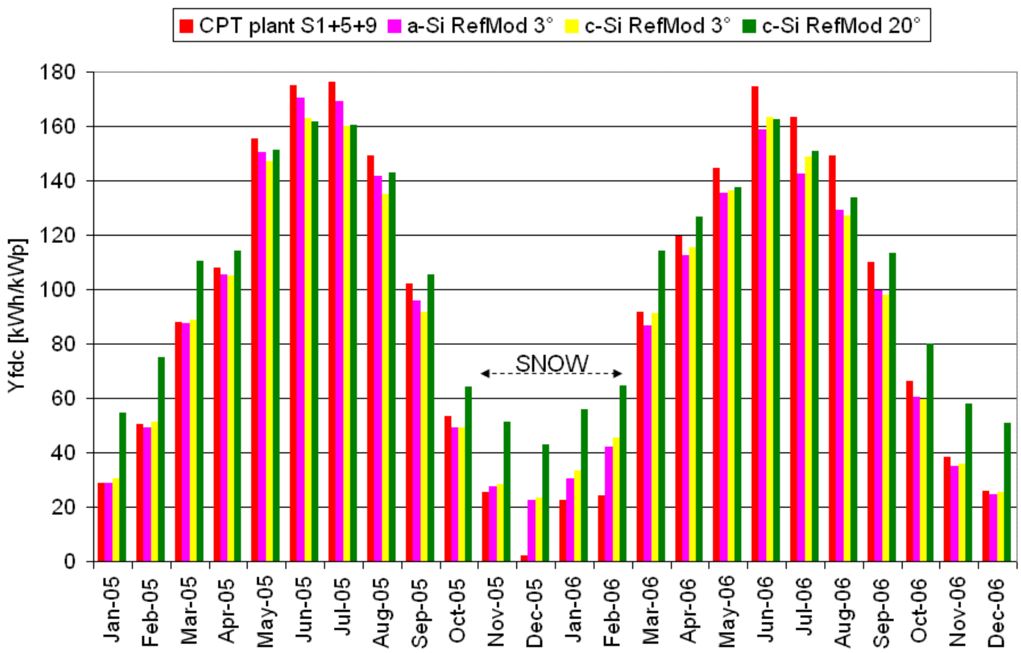


Figure 18: Normalized monthly energy dc production (Final Yield dc) of 3 strings (#1, 5 and 9) of the CPT-plant and the reference modules.

In 2006, from mid May to mid September the inverter of a-Si reference module had some incorrect working operation which caused power decreases during this period. The result of this malfunctioning is clearly visible on Figure 18. In fact, the monthly final yield of the a-Si reference module in the discussed period is lower than the values for the c-Si reference modules. This was not the case for 2005, where a-Si plants showed better final yields compared to c-Si.

In 2005-2006 the average yearly Final Yield on the dc-side (annual Yfdc) of the CPT-plant (1122 kWh/kWp) was 9.6% lower than the c-Si reference module tilted at 20° (1241 kWh/kWp) and higher than the two reference modules tilted at 3°. Once again, this difference is affected by the snow period. In fact, simulating the annual Final Yield (dc-side) in case of no snow cover (see also Table 3) referring to the daily irradiation values, the CPT-plant result was 6.8% higher than the a-Si reference module tilted at 3°tilt and 7.5% lower than the c-Si reference module at 20° tilt.

			Simulation without snow cover	
Annual Yfdc [kWh/kWp]	Year 2005	Year 2006	Year 2005	Year 2006
CPT	1114	1131	1142	1174
a-Si RefMod 3°	1097	1057	1100	1070
c-Si RefMod 3°	1073	1080	1076	1091
c-Si RefMod 20°	1234	1248	1244	1262

Table 3: Normalized energy dc production (Final Yield dc) of CPT-plant (strings #1, 5 and 9) and reference modules with and without snow (simulated).

It is important to note that this difference of 7.5% is obtained in spite of the lower irradiation level for the CPT-plant, which in total was 14.7% (period 2005-2006) less than for the c-Si module tilted at 20° and oriented south.

2.5 Performance Ratio

Similarly as for the energy production analysis, the Performance Ratio (PR) is composed of two main studies. Firstly, we investigated the yearly evolution of Performance Ratio on the ac-side (PRac) for the CPT-plant, focusing on its dependence on daily insolation and maximum module temperature. Afterwards we compared the Performance Ratio on the dc-side of the CPT-plant with that of the references modules.

2.5.1 Performance Ratio vs. daily insolation

The Performance Ratio (PR) is defined as:

$$PR_{ac} = \left(E_{ac,d} / P_n\right) / \left(H_{i,d} / G_{STC}\right)$$

where Eac,d [kWh.d] is the daily energy production (AC side); Hi,d [kWh/m2.d] is the daily incident insolation; Pn is the nominal power and Gstc is the STC irradiance [1kW/m2].

Analysing 2006 , the Performance Ratio PR on the ac-side of the CPT-plant (see Figure 19) exceeded 80% in the warm period (from March to the end of October). For daily irradiation lower than 5 kWh/m², the PR could exceed 90%. In the same warm period, the average PR on the ac-side (PRac) was 84.0%. The same behaviour can be observed in power variation with respect to irradiance where a working efficiency of 7% can be reached at lower irradiance. On the other hand, in c-Si modules, a decrease in performance can be observed at low irradiance.

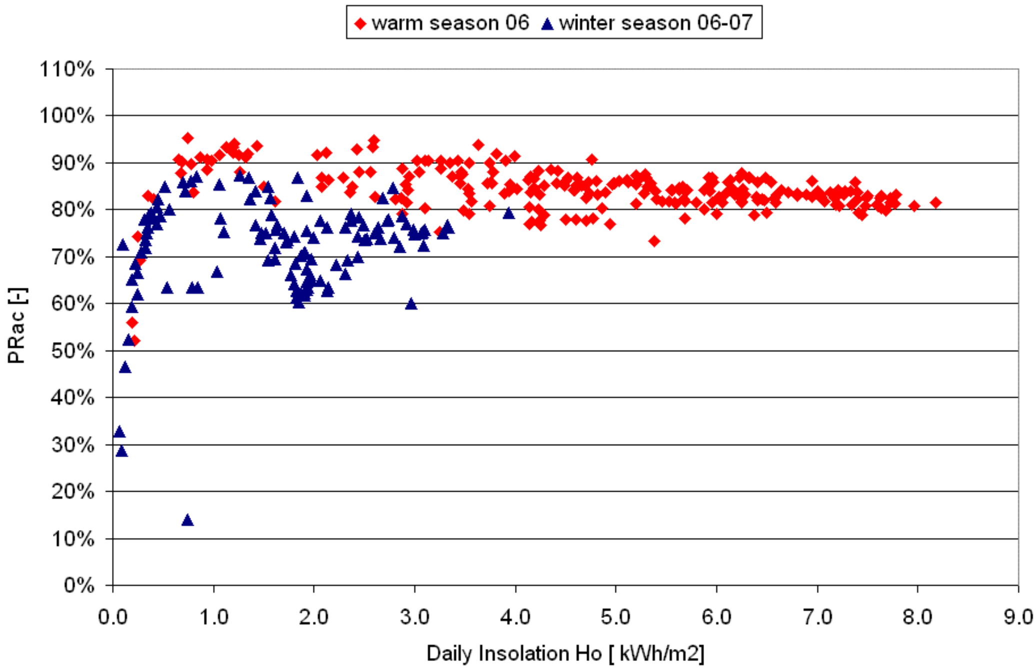


Figure 19: Daily PRac vs. daily incident insolation Ho,d.

In the winter season, the Performance Ratio was clearly lower and ranged between 60% and almost 90% (average PRac was 72%). However, normally, the winter period (November – February) has a small effect on overall plant production (only 13%). This is mainly due to the reduction of a-Si performance at low temperature, lower incident energy (daily irradiation above 5 kWh/m² is not possible because of the nearly horizontal position of the modules), higher optical losses of the modules placed on a flat roof (see chapter 2.6) and spectral losses.

Annual PRac in 2005 and 2006 were 76.2% and 76.6% respectively. In comparison, in 2004 the annual PRac was 83.5%. The reduction of the yearly PR in 2005 and 2006 compared to 2004 was caused by snow which covered the system for an exceptionally long period of time. Although the plant performance was penalised by snow, its yearly PR (ac-side) was still among the average PR for PV power plants in the same area (southern Switzerland).

2.5.2 Performance Ratio vs. daily maximum module temperature

As presented in section 2.3 (Module temperature behaviour), the trend observed is characterized by a power decrease with increasing temperature for a-Si plants lower than for c-Si plants, which often resulted in being twice as high. Thus the negative effect of thermal insulation of the array, namely power losses due to module heating, is about half the magnitude of c-Si modules. The decrease in operating performance is due to negative temperature coefficients during daily overheating.

In a-Si modules, other positive mechanisms combine with the negative effect of the temperature coefficient on daily temperature increase. In fact, a typical array of a-Si modules in open-rack condition shows a recovery of part of the initial performance during outdoor exposure. This phenomena is related to the two reversible thermal annealing mechanisms previously described (section 2.3.1).

Figure 20 shows the daily PRac related to the daily maximum ambient and module temperature. There is a period, which corresponds to warm summer spell, where the

Performance Ratio is relatively stable, varying between 80 and 90%. During the cold winter period, the PR falls below 70% before recovering with the onset of the next warm period.

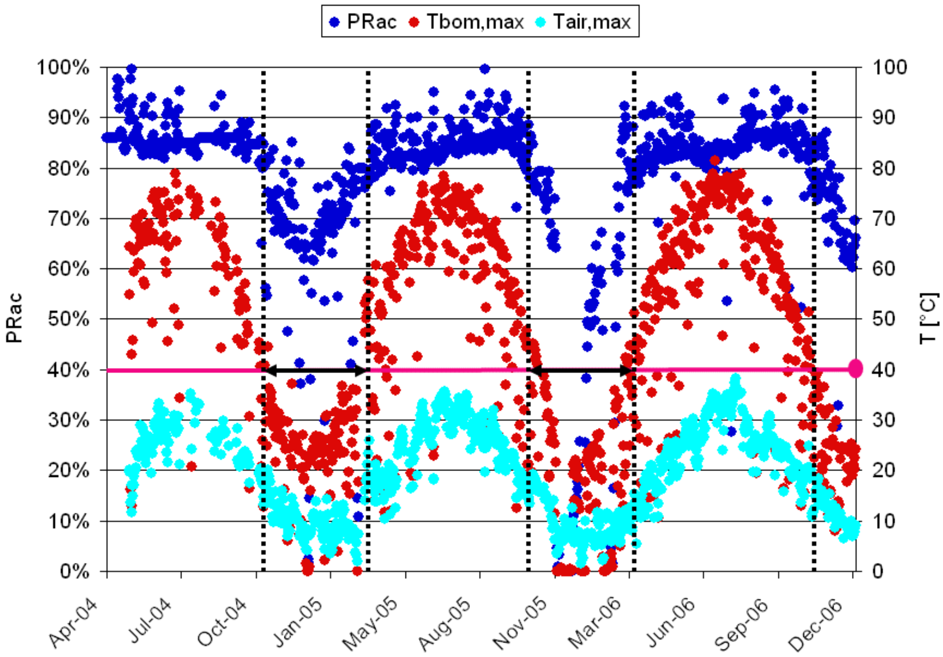


Figure 20: Daily PRac and daily maximum ambient and module temperature, from 01.04.2004 to 31.12.2006.

The period of reduced PRac coincides with the period where maximum module temperature doesn't exceed 40°C, as indicated in Figure 20 between dashed lines. However these months at low PR also coincide with the period of low incident insolation resulting in low plant energy production, as is clearly visible in Figure 21, thus not affecting the good annual production of the plant.

Another important result for the thermal insulated CPT plant, clearly observable in Figure 20, is its regular working behaviour between one year and the next. This was verified during its three years and more of operation, where any relevant decrease in plant performance was observed. As previously discussed, the main differences are due to snow periods (in 2005 and 2006) and to an inverter breakdown in 2006.

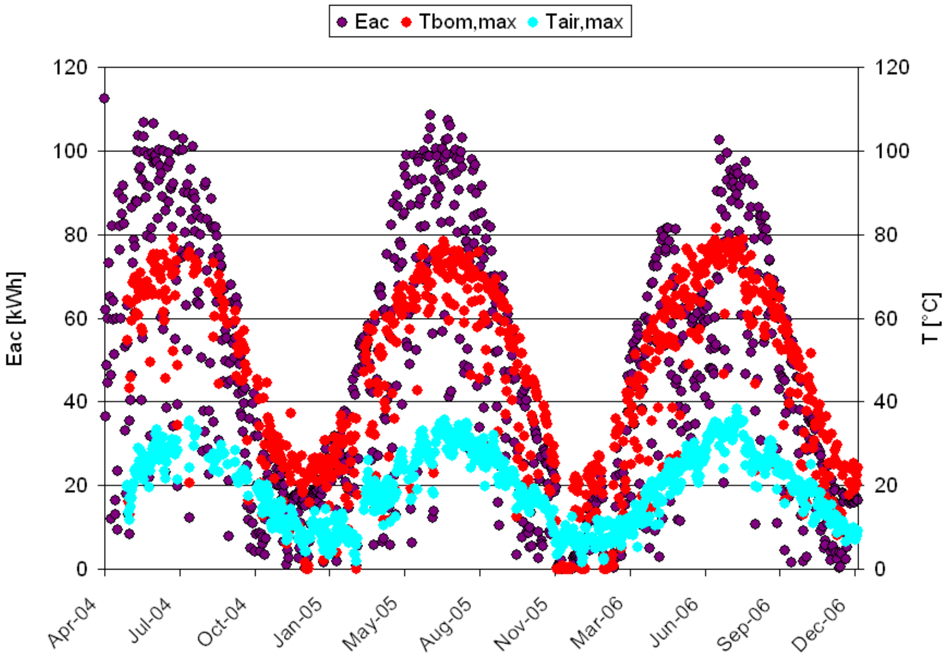


Figure 21: Daily production Eac and daily maximum ambient and back-of-module temperature.

Figure 22 shows the daily PR on dc-side of the CPT-plant (string #1, 5 e 9) and the reference modules for the 2005-2006 period and for irradiation higher than 2 kWh/m^2.day. The daily irradiation for the c-Si reference module at 20° tilt and AZ 14° was obtained with PVsyst using the transposition Hay's model. As input, the data of the global (Go) and the diffuse (Gd) irradiance on the horizontal plane and the ambient temperature, recorded each minute from 5 am to 22 pm at the CPT-plant site, were used.

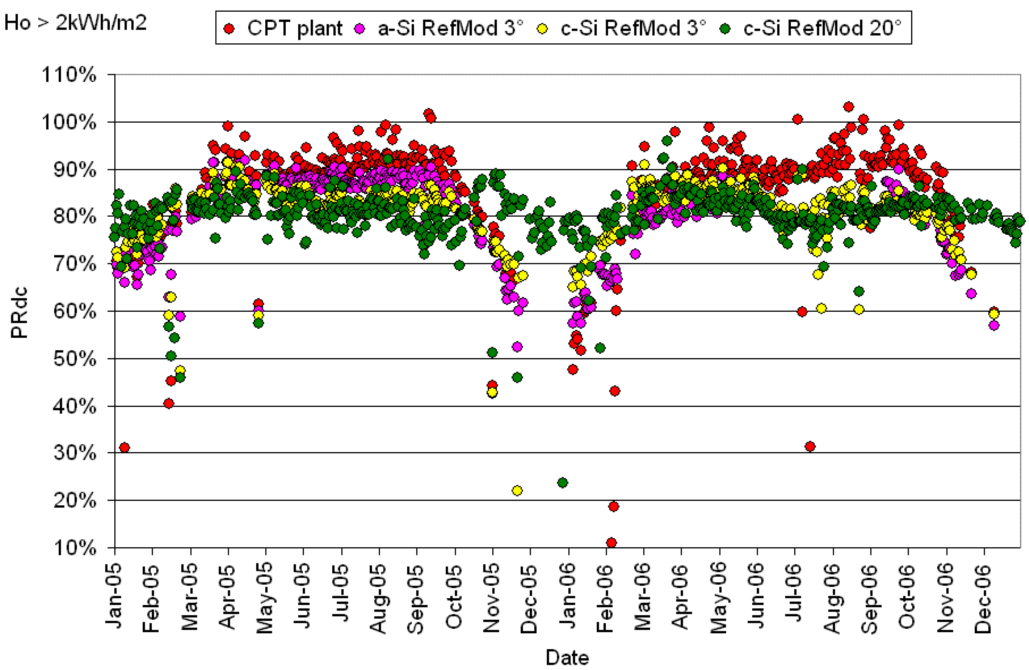


Figure 22: Daily PRdc in 2005-2006, for irradiation Ho > 2 kWh/m^2.day.

It is interesting to note the evident PRdc increase for the thin film technology (CPT-plant and a-Si reference module) during the warm period (May-September) as opposed to the c-Si modules, which decreased as a result of the temperature increase. In fact during this period, the temperatures on the back of all the modules (Tbom) showed maximum values rarely lower than 40° C, as shown in Figure 12.

From April to October, both in 2005 and 2006, the PRdc of the CPT-plant was always higher than those of the three reference modules, of which the c-Si tilted at 20° showed the lowest values. Besides, the PRdc difference between the CPT-plant and the c-Si tilted at 20° increased quite regularly, reaching a maximum of more than 10% (PRdc of plant above 90%) during the period from July to September, after which the plant showed a constant decrease of PRdc. By mid October, its PRdc was around 85% while one month later it dropped to almost 70%.

2.5.3 Enhanced annealing effects on amorphous thermally insulated BiPV

Results presented in Figure 22 clearly show the seasonal performance variations of the two a-Si plants. This behaviour is characteristic of a-Si devices and has been presented in many published measurements, as for example in [3].

Some authors explain that a major contribution to these seasonal performance variations is due to variation in the incident spectrum, as reported for example in [5] and [6] whereas others describe these as a result of seasonal annealing and light induced degradation effects. Thus far, we did not consider spectral measurements in our data analysis and thus did not look at spectral effects. Nevertheless the direct comparison of the thermally insulated CPT plant with the open-rack a-Si reference plant, oriented as the main plant, turned out to be very useful, highlighting the important annealing effect observed on the thermally insulated CPT plant. As a matter of fact, after having reached the highest temperatures (around 80°C) and for a period of about 4 months, the CPT plant showed a performance ratio around 5% higher than that of the a-Si reference plant, as clearly shown in Figure 23.

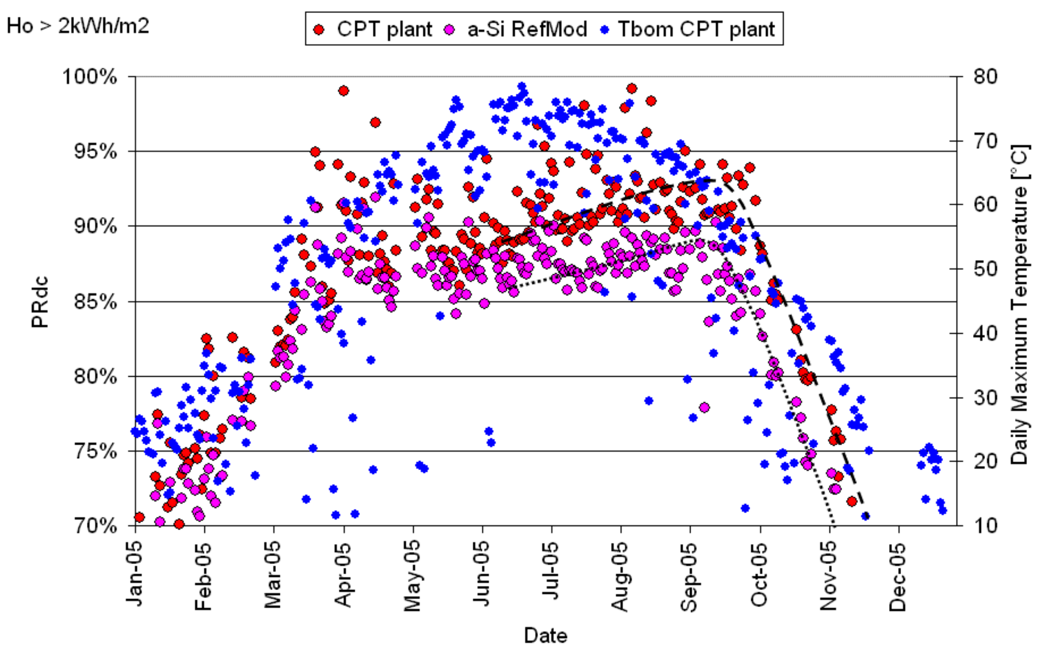


Figure 23: Daily PRdc for a-Si plants and Tbom of CPT plant, for irradiation Ho > 2 kWh/m^2.day.

Considering the influences of other effects, like spectral variations, light induced degradation and optical losses identical on the two installations (same modules with same orientation), we attribute the 5% increase to an enhanced annealing on the CPT plant with respect to the open-rack plant.

Starting from the beginning of September, for the reference modules tilted at 3°, and as seen almost one month later for the CPT-plant (sign of higher partial recovery with respect to the open rack structure, followed by a slow degradation period), the respective PRdc decreased constantly, whereas the situation for the c-Si tilted at 20° was quite stable at around 80%. In fact, due to the low sun elevation during winter, the optical loss effects are dominant for the nearly horizontal modules with regard to the c-Si at tilt of 20°, as presented in the next section.

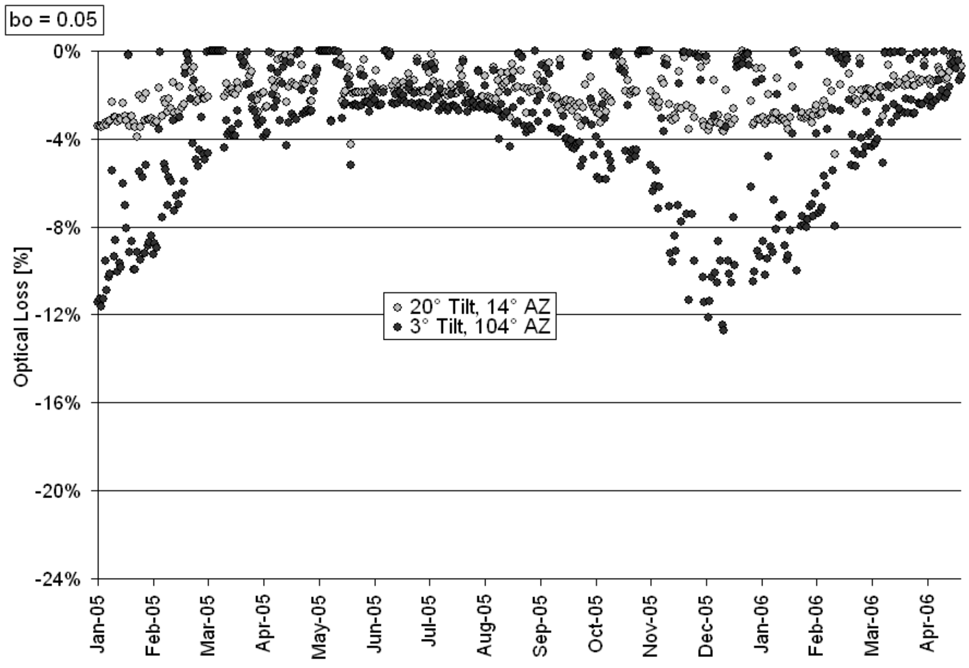
2.6 Optical Losses

As formerly discussed, many authors have studied the influences of different effects on the seasonal performance variations of a-Si devices. The main discussions are based on seasonal spectrum variation, operating temperature, angle of incidence and light induced degradation effects.

In our case, as mainly discussed so far, we focused on operating temperature. On the other hand, given the almost horizontal installation of the thermally insulated plant, we analysed the influence of optical losses, which are less relevant for tilted installations.

In order to quantify the optical losses, and at the same time to throw light on degradation and spectral effects, the reflection losses for the CPT-plant and the reference modules were simulated with PVsyst. The ASHRAE-model with bo=0.05, bo=0.1 (simulating the reflections) and also with bo=0.0 (simulating no reflection) was applied. Choosing the ASHRAE model assumed having flat surfaces on top of the modules composing the different plants. This is the case for c-Si modules, which actually present flat glass as cover, but not for the UniSolar laminates which are textured.

As input, a meteo file, with the data of the global (Go) and the diffuse (Gd) irradiance on the horizontal plan and the ambient temperature of the CPT-plant site recorded each minute from 5 am to 22 pm, was created. The results are shown in Figure 24, where the optical losses (with bo=0.05 and bo=0.1) are represented in percentage with respect to the ideal no reflection case. These results correspond to the difference in percentage between the global irradiation corrected for incidence (IAM) for the reflection cases and that without reflection.



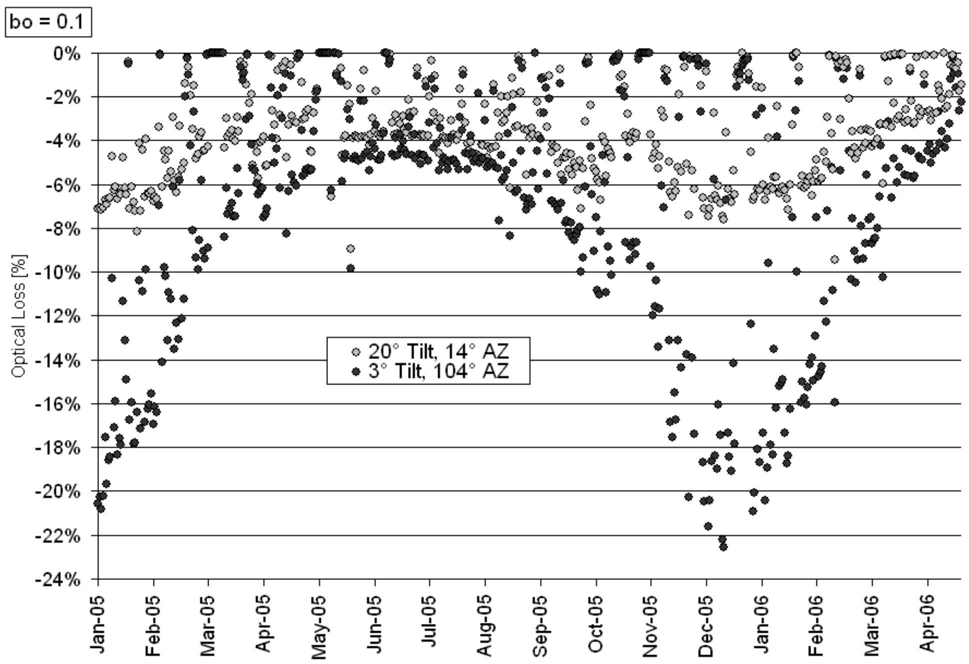
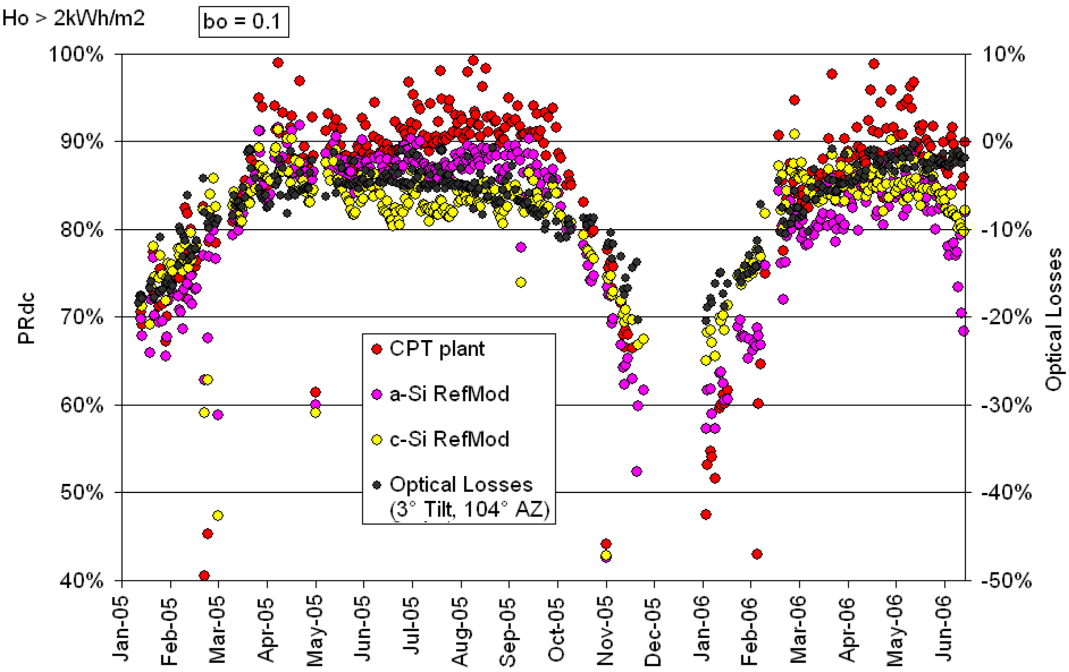


Figure 24: Daily optical losses simulated with PVsyst for the 3° and 20° tilted installations at the CPT-plant site, with bo=0.05 (top) and bo=0.1 (bottom).

For bo = 0.05, the daily optical losses during the winter season can reach values above 10% for the 3° tilted installation and only around 3-4% for the c-Si reference module tilted to 20° and orientated south (AZ 14°). During the summer period, the reflection losses are very close for both the mentioned cases, at around 2%. Choosing bo = 0.1 the daily optical losses turn out more important, reducing performance by more than 20% for the 3° tilted installation and by 6-7% for the c-Si tilted to 20°, during winter. The summer reflection losses are again similar, accounting for around 3-4% for both systems.

The results presented in Figure 24 showing little optical loss correspond in both cases (bo=0.05 and 0.1) to cloudy or bad weather days, where the beam irradiance and thus also the reflection losses are low.

Superimposing curves of Figure 24 with the corresponding PRdc values of Figure 22, it appears clear that the changes during winter for the PRdc evolutions are well matched by the optical losses. This comparison is represented in the two charts of Figure 25, where the bo=0.1 has been chosen.



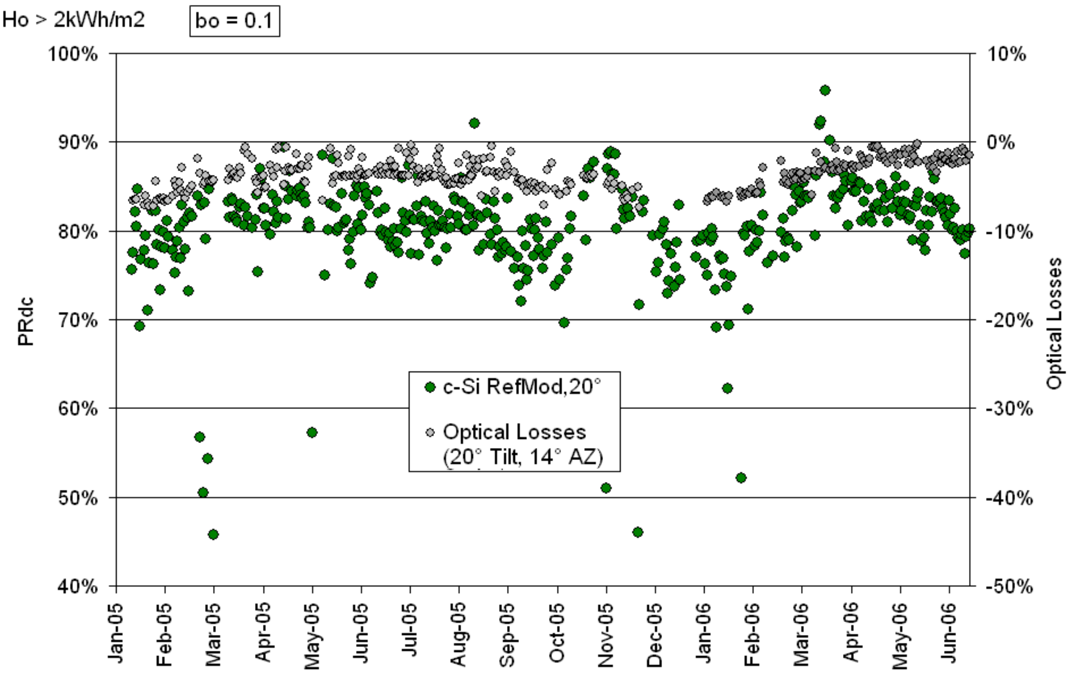


Figure 25: Daily optical losses (calculated) and PRdc values for the 3° (top) and 20° installations (bottom) at the CPT-plant site.

In many cases, the optical losses during the winter periods match the PRdc decreases, especially for the c-Si module at 3° tilt during the first months of the years 2005 and 2006. For the CPT plant and the a-Si module, the PRdc decreases are generally more important compared to the corresponding calculated optical losses. The texturisation should not be responsible for this difference. In fact, as presented in [8], the texturisation on module covers leads to a lower angle dependence of the Isc compared to the flat glass solution. Instead, the reason for this increased subsidence for a-Si installations could be attributed to light induced degradation not compensated by thermal annealing and additional spectral losses occurring during winter for a-Si technology, as discussed in [7]. In the same manner, referring to the results presented in [5] and [6], one could explain performance variations observed for the a-Si plants as a consequence of spectral sunlight variations. Moreover, their results showed the influence of spectral changes which are much more important in multi-junctions than for single junctions (where annealing dominates seasonal performance).

From the results obtained with PVsyst, we calculated the total optical losses, expressed as the ratio between the total incident irradiation in case of reflection and the total incident irradiation in case of no reflection. For bo=0.1, the total optical losses from October 2005 to February 2006 (winter period) were 13.2% for the 3° tilt plants and 5% for the c-Si module tilted at 20°, whereas the total optical losses for 2005 were 3.8% for the c-Si module tilted at 20° and 6.5% for 3° tilt plants. This means that the optical losses for the nearly horizontal system were approximately 3% more than that at 20° tilt and oriented south.

2.7 Performance Ratio comparison

Referring to the previous results, it has been possible to correct the PRdc of Figure 22 for the corresponding optical losses, obtaining the PRdc values as if the irradiation on the outer surface of the modules corresponded exactly to that on their solar cells (no reflection).

For two c-Si ASE100 reference modules, placed one at 3° tilt (AZ 104°) and the other at 20° tilt (AZ 14°), the results after optical correction seem to be more correct for the bo=0.1 case than for bo=0.05, as expected considering the comparison in Figure 25. This result is pointed out in Figure 26, where the corrected PRdc for the two c-Si reference modules at 3° and 20°, with bo = 0.05 and 0.1 are presented.

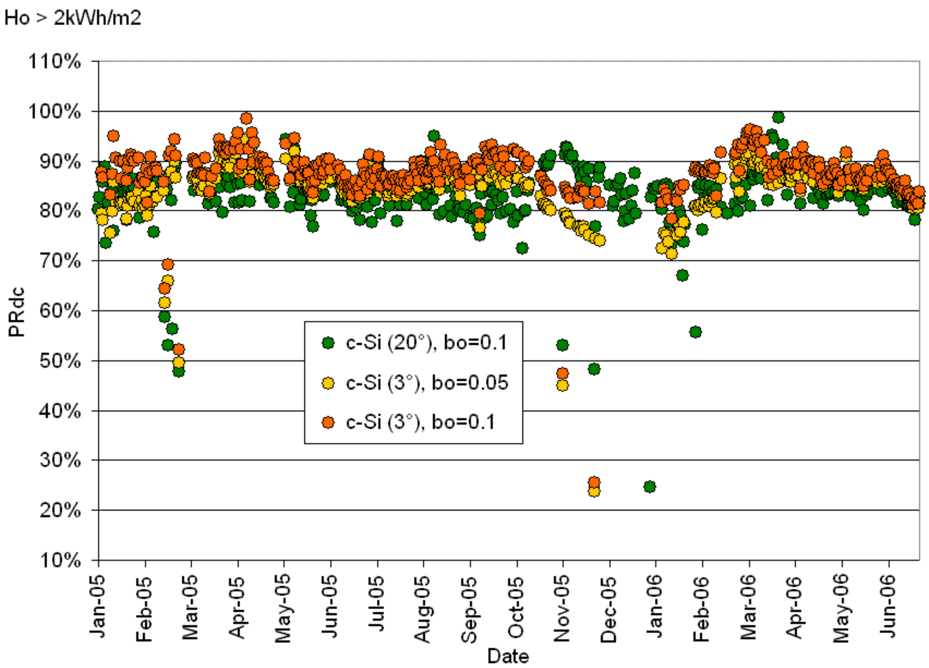


Figure 26: Comparison of daily PRdc values of c-Si modules (3° and 20°) corrected with optical losses (bo=0.05 and 0.1).

As shown, for bo=0.05, the difference between the corrected PRdc of the 3° and 20° tilted ASE100 is still around 10% during the winter period, whereas with bo=0.1, corresponding to higher reflection losses, the corrected PRdc data of the two c-Si reference modules are close to each other.

Figure 27 shows the corrected PRdc data obtained from the calculated optical losses with bo equal to 0.1.

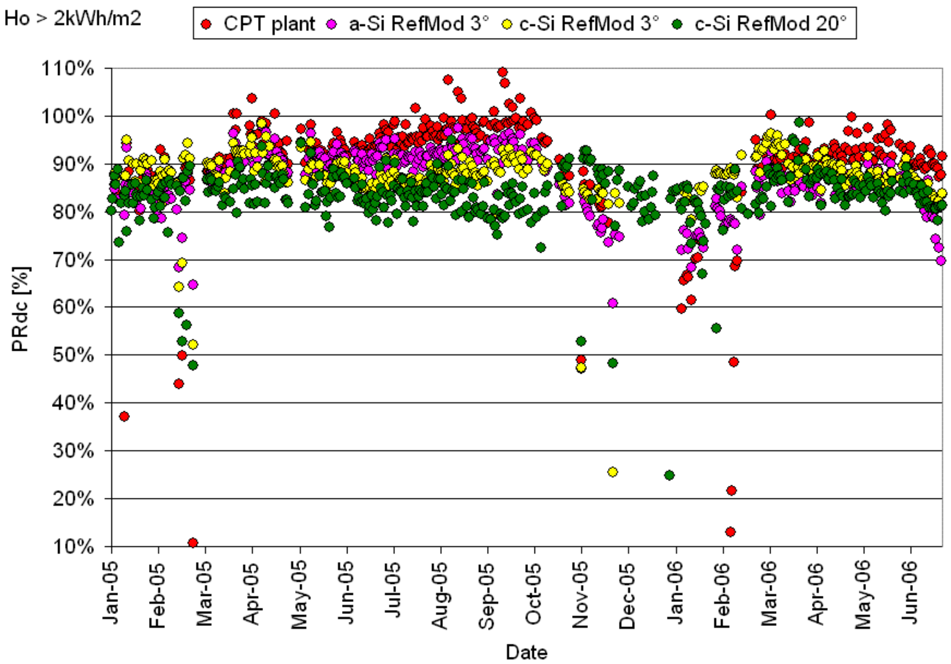


Figure 27: Optical loss corrected PRdc data (bo=0.1).

As expected, the situation changes mainly for the almost horizontal installations during winter, where, after optical correction, the PRdc subsidence for the 3° tilted systems turns out lower. In fact, for the 3° tilt c-Si module, its corrected PRdc behaviour is very similar to that of the 20° tilted module. On the other hand, even after optical loss correction, the a-Si modules still showed a visible decrease of their PRdc during the winter period. As discussed formerly, this can be explained as a consequence of light induced degradation and additional spectral losses. This seems to be an important result, suggesting that further study is required. It is also interesting to note the PRdc increases during the warm period for the a-Si modules. For instance, the CPT shows PRdc values of around 100% from August to mid October 2005, around 15% (10% without optical correction) higher than the corresponding data for the c-Si module tilted at 20°. Besides, the corrected PRdc for the CPT plant is seldom below 90%, except for the period from November to end of February.

2.8 Electrical and physical plant conditions

As consistently presented in section 2, the thermal insulated CPT plant has shown a regular working behaviour during its three years and more of operation, characterized mainly by improved performances with respect to the open-rack installation and likewise higher production levels than expected.

Concerning the electrical part, the main problems are characterized by:

- An inverter breakdown at the beginning of May 2006 which caused a plant partially in operation from the 4th of May to the 25th of June 2006.

- In 2006, from mid May to mid September the inverter of a-Si reference module had some incorrect working operation which caused power decreases during this period.

No problems on sensors (temperature, irradiance) or other electrical plant parts and equipments (modules, cables, connectors…) were observed, whereas, concerning the mechanical plant characteristics, some observable marks appeared on the modules. These come from the fall of little stones and other objects released very likely from crows. In particular, the first module at the north side of string 1, presents a little fissure on its front surface where, due to infiltrations, a white stain appeared (see Figure 28).

Some little problems of adhesion between modules and membrane were observed on the plant.

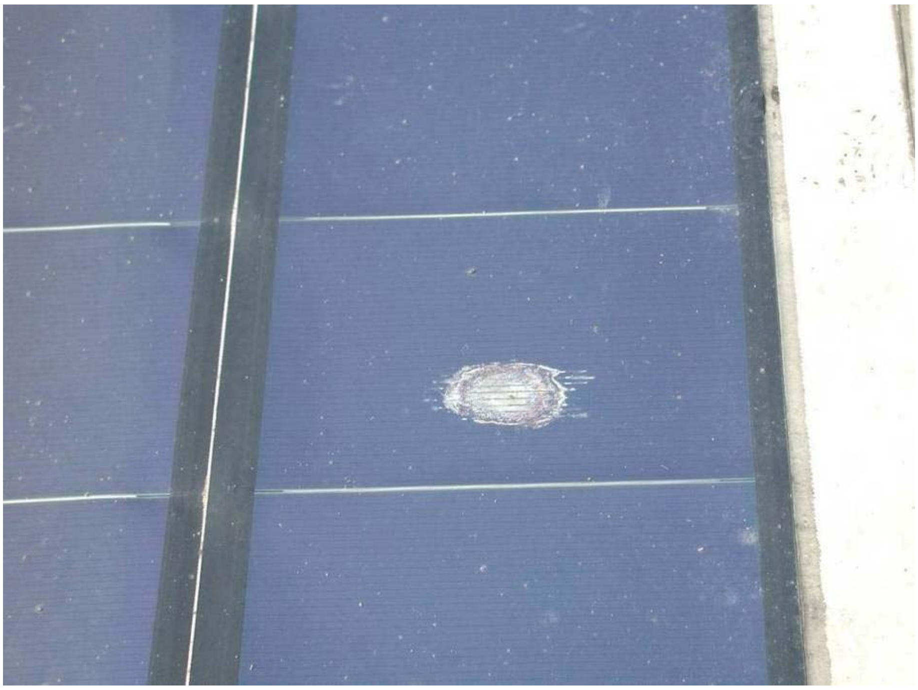


Figure 28: Fissure on module front surface with water infiltration (1st module at north side of string 1).

2.9 Surf-station

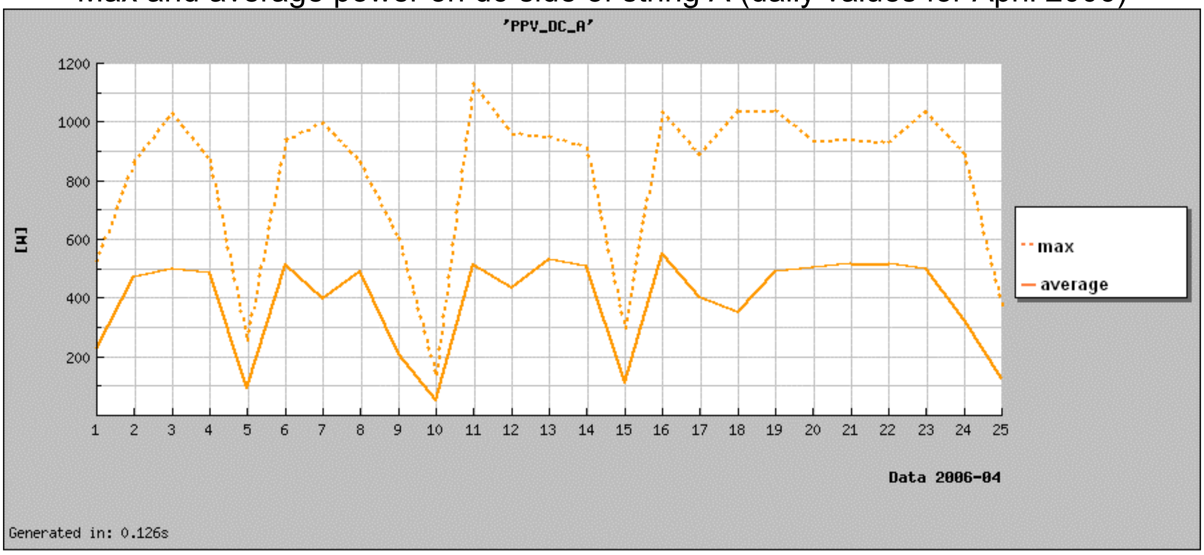
In the local professional school (Centro Professionale di Trevano - CPT), a touch-screen visualization system (see Figure 29) was installed for students to familiarize themselves with the photovoltaic system installed on the school roof (see [11]).

The idea was to allow students access to general information on operational electrical plant characteristics, as well as to surf and explore the PV field.

Figure 29: Surf-station Inputech with touch-screen panel.

The main work was carried out by a student of the CPT school. The idea was to develop a computer program for the monitoring of the plant power production and its statistics. At present, the production data are transferred each 10 minutes to a database. On request of the user, the data can be consulted, through browser, producing daily, monthly or annual graphs. Some examples are presented in Figure 30.

Max and average power on dc-side of string A (daily values for April 2006)



Total plant produced energy (daily values for April 2006)

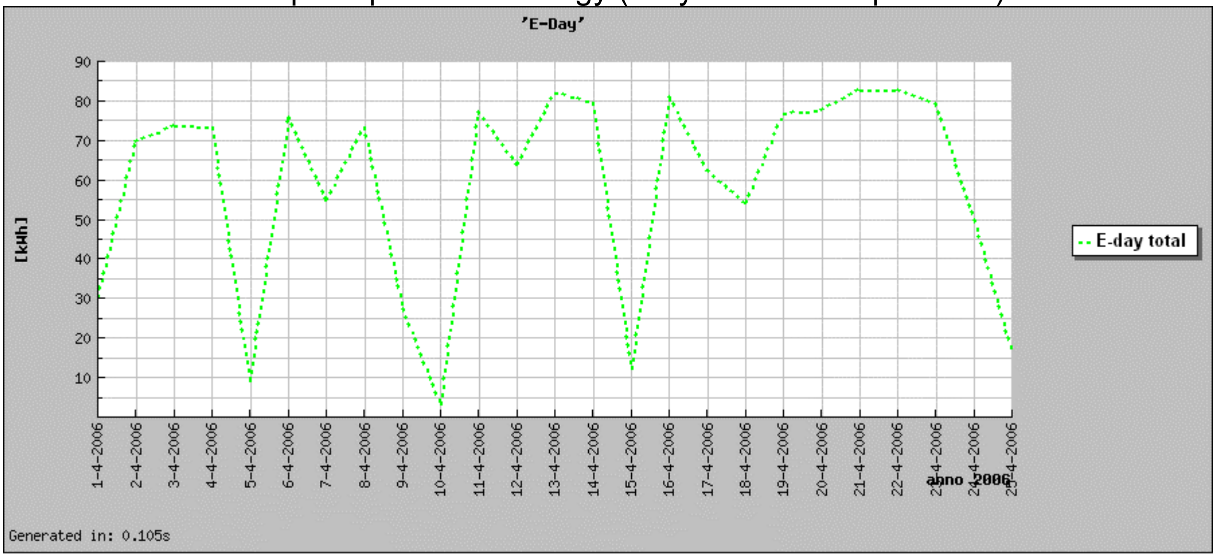


Figure 30: Examples of plant monitoring graphs obtained with the surf-station.

Essentially the program is composed of 2 parts. The first part consists of the transfer of the production data from an Excel file, generated by the DataControl software of SMA, to a database. The latter is composed of two tables; in one are saved the data of each channel and in the other the summarizing data. The details of these two tables are described below:

<u>LogCanali</u>

Parameter	**Description**
SNCanale	Serial number of registration channel
DataOra	Date and time of data record
Pac	Actual power on ac-side (grid connection)
Riso	Internal resistance
FaultCurrent	Leakage current
Upv_Ist_DC_A	Actual voltage of A string
Upv_Ist_DC_B	Actual voltage of B string
Upv_Ist_DC_C	Actual voltage of C string
PPV_DC_A	Actual power of A string on dc-side
PPV_DC_B	Actual power of B string on dc-side
PPV_DC_C	Actual power of C string on dc-side
E_Total	Total produced energy on ac-side
H_Total	Total production time
H_On	Total working time
PowerOn	Working cycles
E_Total_DC_A	Total energy of A string on dc-side
E_Total_DC_B	Total energy of B string on dc-side
E_Total_DC_C	Total energy of C string on dc-side

LogRiassuntivi

Parameter	Description
SerialNumber	Serial number of summarizing data sheet
DataOra	Date and time of data record
Pac	Actual power produced on ac-side (grid connection)
E-Total	Total energy produced on ac-side
E-Today	Actual produced energy
OperatingTime	Total operating time
PowerOn	Working cycles
EnergyValues	Number of days of yield

The second part allows the monitoring of the various statistical results through a browser. Generally speaking, the user has the choice to graphically visualize statistical results in real time or from a database.

3 NATIONAL AND INTERNATIONAL COLLABORATIONS

- Sika - Sarnafil International AG, Sarnen (CH), flexible polyolefin (FPO) waterproofing membrane.
- Sika - Sarnafil AG, Sarnen e Sarnafil Ticino, Lamone (CH), design and construction supervision of laying of covering membrane and Sarnasol modules, lamination of Sarnasol modules.
- Uni-Solar (USA), tiple junction a-Si photovoltaic module.
- FLUMROC, Flums (CH), thermal insulation.
- Azienda Elettrica Ticinese, Bellinzona (CH), owner of CPT Solar installation.
- Cantone Ticino – logistics section, Lugano-Trevano and Bellinzona (CH), owner of the CPT building.

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5 CONCLUSIONS

In this project, we analysed the behaviour and the energy yield of a 15.36 kWp PV system based on flexible triple-junction amorphous silicon modules laminated together with a single ply roofing system. The PV plant was integrated and thermally insulated on a flat roof of a professional school located in the south of Switzerland.

The purpose of this study was to verify if the better thermal behaviour and annealing processes of a-Si compared to c-Si technologies can compensate losses due to the nearly horizontal roof integration.

The following points were clarified:

- Building Integrated PV systems (BiPV) combine architectural functions of building materials and electrical production in a harmonious way. Good-quality BiPV design needs new materials to meet architectural needs. For flat roof integration, the mechanical characteristics of FPO membranes allow combination with thin film flexible a-Si triple-junction modules as a waterproofing system.
- The thermally insulated nearly horizontal modules showed temperatures higher than for modules mounted on an open-rack structure. Thermally insulated a-Si modules reached almost 80°C and the mean temperature increased by up to 40-45°C above the ambient temperature, which went up to 35°C at 1000W/m^2. For modules mounted on an open-rack structure, the mean temperature was 20-25°C above the ambient temperature, with highest recorded temperatures of around 65°C for the 20° tilt plant. On the one hand, the high temperature of the thermally insulated modules created higher power losses due to a negative temperature coefficient, but on the other, the higher temperature reached the level where the main degradation mechanism can be reversed and better thermal annealing can be observed.
- The temperature of the CPT-plant exceeded the value of 40°C for more than 1000 hours in 2006 (the same result was observed for 2004 and 2005), where more than 350 hours of operation were recorded above 60°C, with some maximum values around 80°C, whereas the modules of the not thermally insulated reference plants almost never went above 60°C, in the same climate conditions.
- The average annual energy production of the CPT plant, during 3 years of operation (01.2004-12.2006) was 1066 kWh/kWp. This result exceeded expectations, being almost comparable to a 20° tilted open-rack c-Si power plant, despite the lower irradiance and higher reflection losses with respect to the latter.
- In comparison, c-Si module plants situated in Ticino produced, in 2004-2006, on average 1095 kWh/kWp, resulting only around 2.7% higher than the average CPT plant production during the same period (1066 kWh/kWp). Besides, it is noticeable from the

simulations without snow that the nearly horizontal CPT plant, in case of no snow or at least not important snow covers, can reach production levels very close to those of c-Si optimally oriented module plants. In fact, the calculated losses due to snow, which covered the system during an exceptionally long period of time, amount to about 65 kWh/kWp.

- **This means that the better thermal behaviour and annealing processes of a-Si compared to c-Si technologies can almost compensate for losses due to the nearly horizontal roof integration.**
- In 2005-2006 the average yearly Final Yield on the dc-side of the CPT-plant was 1122 kWh/kWp, namely 9.6% lower than the c-Si reference module tilted at 20° (1241 kWh/kWp) and higher than that of the two reference modules tilted at 3°. It is important to highlight that this difference is obtained in spite of the lower irradiation level for the CPT-plant, which was in total 14.7% (period 2005-2006) less than for the c-Si module tilted at 20° and oriented south. These performance differences are also the result of the snow period. As a matter of fact, simulating the annual Final Yield (dc-side) in case of no snow cover, the CPT-plant results were 6.8% higher than the a-Si reference module tilted at 3°tilt and 7.5% lower than the c-Si one at 20° tilt.
- The direct performance comparison of the thermally insulated CPT plant with the open-rack a-Si reference plant (same module type and orientation as the CPT plant) highlighted the important annealing effect observed on the thermally insulated plant. The latter, after having reached the highest temperatures (around 80°C) and for a period of about 4 months, showed a performance ratio around 5% higher than that of the open-rack a-Si plant.
- Due to low sun elevation during winter, not only the irradiation was lower but also the optical loss effects were more dominant for the nearly horizontal modules with regard to the 20° tilted c-Si module. In order to quantify the optical losses, and at the same time to throw light on degradation and spectral effects, the reflection losses for the CPT-plant and the reference modules were simulated with PVsyst, using the ASHRAE-model. Optical losses for nearly horizontal modules were significant during the winter, partially affecting their low performance in this period.
- From October 2005 to February 2006 (winter period) the calculated optical losses were 13.2% for the 3° tilt plants and 5% for the c-Si plant at 20° tilt. For a Si plants, the PRdc decreases were generally more important compared to the corresponding calculated optical losses. These differences can be attributed to additional loss effects, like spectral variations and light induced degradation effects, as some authors have demonstrated. On the other hand, the total optical losses for 2005 were 3.8% for the c-Si module tilted at 20° and 6.5% for the 3° tilted plants. This means that the optical losses for the nearly horizontal system were approximately 3% more than those at 20° tilt and oriented south.
- Referring to the calculated optical losses, it has been possible to correct the PRdc, obtaining the PRdc values as if the irradiation on the outer surface of the modules corresponded exactly to that on their solar cells (no reflection). Setting the “incidence angle modifier coefficient” bo=0.1, the resulting optical losses better match the PRdc subsidence (observed in winter period) for the 3° tilted systems with respect to the bo=0.05 case. The CPT shows PRdc corrected values of around 100% from August to mid October 2005, resulting about 15% (10% without optical correction) higher than the corresponding data for the c-Si module tilted at 20°.

In this study we have demonstrated that a-Si technology represents an ideal choice for thermally insulated BiPV. In fact, due to higher working temperatures of thermally insulated BiPV plant compared to open-rack installation, better thermal annealing can be observed. Moreover, we have verified that the better thermal behaviour and annealing processes of a-Si compared to c-Si technologies can almost entirely compensate for losses due to the nearly horizontal roof integration.

These results further underline the benefits of thermally insulated amorphous silicon plants integrated on sloping roofs. In fact, this leads to enhanced annealing effects, due to higher working temperature, higher irradiance and lower optical losses with respect to horizontal integration.

Figure 31: Swiss Solar Prize 2005, category E (photovoltaic installations): the solar homage 2005 was given to the CPT PV solar installation:

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