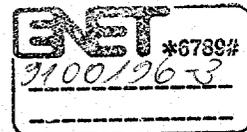


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## LONG-TERM BEHAVIOUR OF MONOCRYSTALLINE AND OF AMORPHOUS MODULES IN THE MEDIUM SIZE GRID CONNECTED PV PLANT TISO

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### ABSTRACT

On May 13th, 1982 the 10kW photovoltaic plant TISO was connected to the 220V, 50Hz public mains. It was the first intermediate size photovoltaic plant in Europe to be connected to a standard AC utility grid. The plant and the initial performance has been described in previous conferences. This paper reports on the state of the plant and of its components after ten years of operation.

A second PV system with a 4kW amorphous silicon generator has been working now for four and half years. Research is aimed at investigating the long and short term behaviour of thin film PV modules operating under real environmental conditions.

### 1. INTRODUCTION

A 10kWp monocrystalline silicon photovoltaic power plant has been working now for ten years at the Scuola Tecnica Superiore in Lugano, Switzerland. It was the first intermediate size photovoltaic plant in Europe to be connected to a standard AC utility grid. The plant and the initial performance has been described in previous conferences. The plant includes 288 flat-plate ARCO ASI-2300 modules with 37W nominal power each. The plant was initially equipped with a 10 kW monophasic inverter (Abacus Control Inc., USA) with a nominal input voltage of 192V. The modules were, therefore, connected in series of 12, thus forming 24 series divided into 3 sub-arrays. After 7 years of very satisfactory performance, the inverter broke down and was replaced.

From October 1989 to November 1991, 16 strings of the plant with 6 modules in series (30% of the total number of modules), were used to test the SOLCON inverter, a 3.3kW unit developed at the School of Engineering in Bienne, Switzerland.

In summer 1991 a new commercially available 15kW inverter (ECOPOWER, from Invertomatic SA, Switzerland) was installed and successfully connected to the grid. The input voltage of this inverter is  $\pm 380V$  and the efficiency at nominal load is better than 95%. The array had thus to be rewired in two arrays of six strings, each string having 21 modules (87.5% of the total number of modules)

The 4kWp amorphous silicon PV power plant was assembled in spring 1988. It is connected to the public power grid (220V/50Hz) through an automatic inverter unit and is intended to provide in-field operating experience of a-Si PV components integrated in a relatively large PV generator. Modules of three manufacturers were integrated in the system. After a few weeks all the modules of one make were replaced by modules of the same manufacturer but of a new model. Modules of the

same brand were wired in series and the strings were connected in parallel to a single inverter unit. The working voltage of the array is 195V.

Systematic monitoring of the performances of photovoltaic generators, direct measurement of the electric parameters of the modules, visual inspection and thermographic analyses of the array-field and inverter unit have been carried out in order to detect and understand any degradation processes of the components. Extensive data sets characterizing the operation of the plant are available for processing. Measurements of a number of modules from the PV-plant were repeatedly carried out at the European Solar Test Installation (ESTI) of the European Joint Research Centre in Ispra to detect possible loss of efficiency.

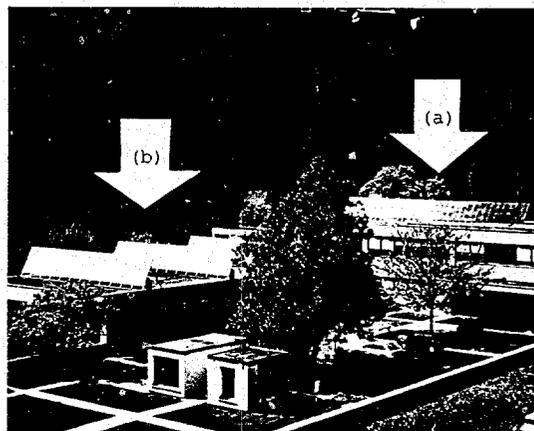


Fig. 1: View of the experimental grid connected, PV plant TISO:  
(a) 4kWp a-Si generator and  
(b) 10kWp monocrystalline Si array field

## 2. RESULTS AND OPERATING EXPERIENCE

### 2.1 10KW MONOCRYSTALLINE SILICON POWER PLANT

In ten years the plant has produced 62,542 kWh. The figures are not directly indicative due to the high number of interruptions for research reasons (in total 668 days out of 3793). The production of the fully operational plant would be around 100,000 kWh for 10 years (about 10,000 kWh/year).

In the first period - from May 1982 to September 1988 - the plant produced 50,458 kWh. It was disconnected for 116 days out of 2308 (5% of the time)

During the second period - from March 1990 to November 1991 - the plant produced 6,001 kWh being out of operation 39 days out of 602 (6.5% of the time).

In third period - from November 1991 until September 1992 - the plant produced 6,083 kWh having been disconnected 23 days out of 331 (6.9%).

The measurement at standard test conditions do not show any change in module performance (measurement error:  $\pm 2\%$  of the module power).

Five modules out of 288 had to be replaced: one was damaged by water infiltration in the terminal box; two modules were marked by bad internal contacts while two modules had problems in the terminal connections when the wiring was modified.

After ten years operation of the 10kW array, some aging effects could be detected, in particular: cracked cells, water infiltration, penetration of black sealant used along the frame, yellowing of the module surface underneath the cells, oxidation and corrosion of the frame. However no efficiency loss of the array was detected.

These defects were already describe in 1985 [3]. Since then, these defects have increased notably but until now they don't seem to have affected the efficiency of the plant. No cell failure was detected; this means less than one cell failure out of 10,080 in 10 years.

The principal weakness discovered in this kind of module is situated in its terminal box. Terminals directly attached to the back of the cells, water infiltration in the terminal box, overheating of the cell next to the terminal box, unsatisfactory water proofing and poor adhesive qualities of the terminal box are the principal flaws in the kind of connection.

### 2.2 4KW AMORPHOUS SILICON POWER PLANT

The efficiency of the PV generator is monitored under real operating conditions (ROC-efficiency) and at Standard Test Conditions. Figure 3 shows the behaviour of ROC-efficiency and air temperature vs. time.

After a strong initial deterioration (first two weeks) the ROC-efficiency stabilizes at about  $75 \pm 5\%$  of the initial value. Degradation and regeneration is cyclic and follows the evolution of the ambient temperature (daily mean values). During winter, efficiency decreases whereas it increases again during spring.

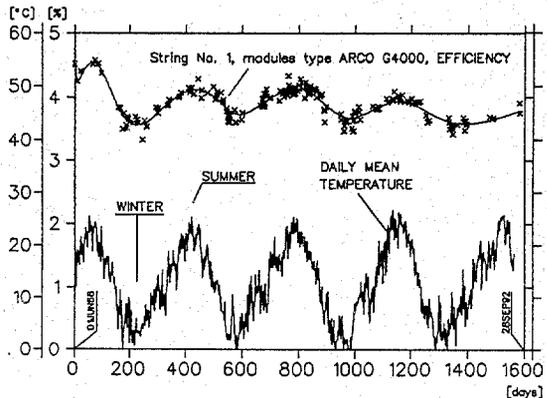


Fig. 2: Efficiency of the modules under real working conditions and ambient temperature vs. time

The efficiency measured at STC in spring 1992 confirms the figures measured in previous years. After 5700 kWh/m<sup>2</sup>, by April 1992, the ROC-efficiency seems to show a gradual but constant deterioration in the performance of the modules.

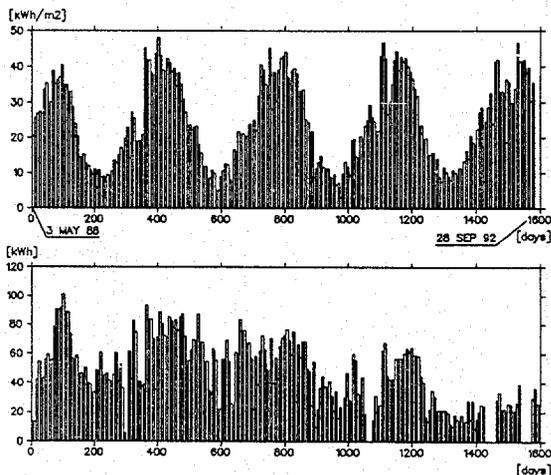


Fig. 3: Weekly irradiance on a horizontal plane (above). Energy production of plant (below).

Energy production figures also appear to indicate a reduction in the overall performance of the plant.

The reduction in efficiency and energy production is not linked to daily mean temperature or irradiance variation (see fig. 3 and fig. 4).

From ROC-efficiency measurements carried out over a number of years, it seems that mean efficiency of the modules decreases by roughly 2% a year. However, it is not possible to establish whether this is a steady deterioration with time, or whether it is a sudden loss after a period of stability.

The modules integrated in the 4kW amorphous silicon power plant were not reliable enough: electrical isolation, mechanical structures and internal wiring, being the most evident weaknesses. In our latest article [10] we gave the percentage of modules which broke down during the first months of performance: 3 out of 96 ARCO G4000, 11 out of 22 SOLAREX SA20, all CHRONAR (48 su 48) CSB.13.E and 1 out of 26 CHRONAR CT13. Since then no other failures have occurred.

## 2.3 INVERTERS

The monocrystalline silicon plant was originally equipped with a 10kW monophase inverter. This first inverter had teething problems resulting in 3 break-downs during the first year of operation. The first failure was due to faulty mechanical performance of the transistor mountings and insufficient electrical insulation; the second occurred as a result of deterioration in the quality of the electrical contacts (non-gold plated) belonging to the electronic printed circuits and the third was caused by the over heating of a resistor in the power supply. It should be noted that the inverter was the eighth of the first series. Afterwards the inverter worked very satisfactorily for 6 years (12,655 hours). Problems related to signal and power supply stability then occurred causing irreparable damage to the electronics.

The SOLCON inverter, from School of Engineering in Bienne (Switzerland) suffered only one breakdown as a result of incorrect handling during a trial experiment. It was possible, through systematic measurement, to improve the inverter software relating to maximum power point tracking.

In order to carry out a further tests on inverter units, the SOLCON was substituted in November 1991 with a new commercially available 15kW inverter from a swiss manufacturer. The power electronics of the inverter is based on IGBT transistor technology. This permits a performance level of over 95%. However control electronic is still made up of analogic circuits. Installation and tuning is more delicate both with respect to the first inverter, where peak power tracking is performed by sensing  $V_{oc}$  of a pilot module, and with respect to second inverter based on a microcontroller. The microcontroller system has a number of advantages especially regarding limit and sensitivity regulation.

The inverter used for the amorphous power plant (Abacus Control Inc., USA), had only one breakdown during 4 1/2 years of uninterrupted service. The breakdown was caused by incorrect power dimensioning of one resistor: the prolonged overheating of the resistor and the removal of the inverter to a warmer location resulted in the breakdown.

Figure 4 shows a termography of the print with the overheated resistor (temperature of over 100 degrees Celsius).

This kind of defect has been found in three out of five inverters used in the installations of the TISO research centre until now.

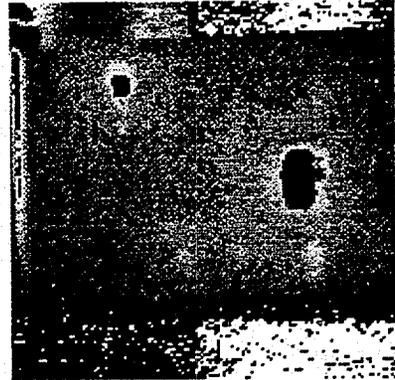


Fig. 4: Termography of an inverter print with overheated resistor.

## 3. CONCLUSIONS

Ten years of operation show that monocrystalline photovoltaic components are reliable and durable. There wasn't any loss of efficiency at all.

Only 1.75% of the modules broke down in ten years of operation. The photovoltaic field hardly needed any maintenance. A visual inspection of the array-field shows however deterioration of the materials. The weak spot in the modules used is to be found in the terminal box.

The 4kW amorphous silicon power plant has been operating for more than 1600 days. The efficiency level, which stabilized at about 75±5% after few weeks, now seems to be decreasing.

Plant production over the past year also indicates a worsening in the performance of the module.

The reliability of the a-Si modules integrated in medium-sized systems at a voltage level of about 200V proved to be a major problem. The modules with a polycarbonate frame did not have any isolation problems.

The inverter unit is a key component in a grid-connected photovoltaic system; efforts for more careful product quality control and better engineering are still needed. Thermographic analysis is an effective means of locating dimensioning errors.

In January 1991 the planning and construction of a new facility for testing components and systems in the field of photovoltaic technology was begun. It will consist of measurements of different types of silicon modules (mono-, poly- and amorphous ones), tests of components related to photovoltaic technology (inverters, regulators, protections, sensors, etc.), measurements on external systems and the setting up a database for external use. Particular attention will be given to the reliability of the modules when the latter are exposed to high voltages as in the case of medium to high power systems. The modules undergo a test procedure at 1.2kV for a one year period.

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#### 5. REFERENCES

- [1] M.Camani et al.: TISO 15: 15kW Experimental Photovoltaic Solar Power Plant; 4th EC-Photovoltaic Solar Energy Conference, Stresa, May 1982.
- [2] P.Ceppi et al.: Analysis of the First Year of Operation of the Photovoltaic Utility Interactive Plant TISO; 5th EC Photovoltaic Solar Energy Conference, Athens, October 1983.
- [3] M.Camani et al.: Performances of the Grid Connected Photovoltaic Plant TISO 15; 6th EC Photovoltaic Solar Energy Conference, London, April 1985.
- [4] M.Camani et al.: Die Netzgekoppelte Photovoltaische Anlage TISO 15, Resultate und Erfahrungen, 5. Symposium Forschung und Entwicklung in der Schweiz, EPF - Lausanne, October 1985.
- [5] P.Ceppi et al.: Behaviour of the Modules of the photovoltaic Plant TISO 15, 7th EC Photovoltaic Solar Energy Conference, Sevilla, Spain, October 1986.
- [6] M.Camani et al.: Die Netzgekoppelte Photovoltaische Anlage TISO 15, Bulletin SEV/VSE Nr.6, 1986.
- [7] M.Camani et al.: TISO:4 kW Amorphous Silicon, Utility Interconnected Power Plant; 8th EC Photovoltaic Solar Energy Conference, I-Florence, May 1988.
- [8] M.Camani et al.: Utility Interconnected 4 kW Amorphous Silicon PV Power Plant; 9th EC Photovoltaic Solar Energy Conference, D-Freiburg, September, 1989.
- [9] M.Camani et al.: TISO: Installation photovoltaïque de 4 kWp avec modules au silicium amorphe, raccordée au réseau; Photovoltaik-Nutzung 1990, Zürich, Januar, 1990.
- [10] D. Chianese et al.: TISO: 4kW Experimental Amorphous Silicon PV Power Plant, 10th EC Photovoltaic Solar Energy Conference, Lisbon, April, 1991.
- [11] M.Camani et al.: TISO: behaviour of a-Si modules in a 4kW grid connected photovoltaic plant; 26th Intersociety energy conversion engineering conference, US-Boston, August, 1991.
- [12] M.Camani et al.: Annual Project Reports: Lugano, 1988,1989,1990,1991.