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Photovoltaic noise barrier at the A9-highway in The Netherlands

Results of the monitoring programme

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Preface

This work has been carried out for NUON International / Duurzame Energie under contract numbers DE/EV/237 and DE/EV/300, and for the European Commission under contract number SE/068/97/NL/DE/CH.
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Abstract

A large photovoltaic energy system has been integrated into a noise barrier at the A9-highway near Ouderkerk aan de Amstel in The Netherlands. The PV-system consists of 720 AC-modules with inverters of type A and 1440 AC-modules with inverters of type B. The monitoring activities within the project are performed by ECN in co-operation with Fraunhofer ISE. This document describes the results of the monitoring programme during the first 2 years of operation. The main conclusions are:

- The AC-modules with type A inverters perform very well and have a low failure rate
- The AC-modules with type B inverters perform less good and have a higher failure rate. The reasons of the lower performance are the lower inverter efficiency and the occurrence of grid interference. Modifications on the PV-system to prevent the grid interference are ongoing.
- Accumulated traffic dust on the modules causes significant energy losses.

The main recommendations are:

- Global monitoring should be continued for the assessment of the results of the modifications and for detecting possible failures in the future.
- Annual cleaning of the modules after the winter season should be considered.

CONTENTS

1. INTRODUCTION

A large photovoltaic energy system has been integrated into a 1650-meter long noise barrier at the A9-highway in The Netherlands. The realisation took place in the frame of a demonstration project, financially supported by the European Commission and the Netherlands Agency for Energy and Environment (NOVEM). The following partners carried out the project.

- NUON International / Duurzame Energie (co-ordinator and owner)
- Netherlands Energy Research Foundation, ECN
- TNC Energy Consulting GmbH
- TNC Consulting AG
- Fraunhofer Institut für Solare Energysysteme

The main subcontractor was Shell Solar Energy who manufactured the PV-modules and installed the entire PV-system turnkey. The PV-system was put into operation on December 1st, 1998. On that date a two-year monitoring programme started in co-operation with Fraunhofer ISE. This report presents the monitoring results obtained from December 1st, 1998 until December 1st, 2000.

2. PV-SYSTEM AND MONITORING SYSTEM

The PV-system consists of 2160 AC-modules, each with a nominal power of 95 W_p. Each of the AC-modules feeds in on a low voltage grid through 12 cabinets, as depicted in figure 1.
In each cabinet 180 AC-modules are connected to the grid. Two different types of AC-modules are used:

- Cabinets 1, 2, 11 and 12: per cabinet 180 modules (Shell Solar Energy, RSM 95 AC) with inverters of type A
- Cabinets 3 through 10: per cabinet 180 modules (Shell Solar Energy, RSM 95 AC) with inverters of type B

The PV-system is mounted on a noise barrier along the A9-highway near Ouderkerk-aan-de-Amstel in The Netherlands (latitude 52˚ 22' North, longitude 4˚ 54' East). The modules have a tilt angle of 50 ˚. As a consequence of the small curvature of the noise barrier the azimuth angles of the modules are not identical. The azimuth angles of the modules near the cabinets 2, 5, 8 and 11 are 193˚, 198˚, 202˚ and 207˚ respectively.

The monitoring system is based on a decentralised data acquisition system (ref. [1]). It consists of the following parts.

- <u>Global data acquisition</u> units consisting of 12 kWh-counters with digital data output in the 12 cabinets. The global monitoring is based on the monitoring of the daily energy production of each of the twelve cabinets and the daily irradiation. The kWh counters have been manufactured by Camille Bauer (type U 1689, class 2). They are used in combination with 30/5 A current transformers manufactured by ABB, type TAQ2, class 0.5. The irradiation on the modules of the twelve cabinets is obtained from the analytical monitoring results (see below).
- <u>Supervision data acquisition</u> units consisting of 360 Wh-counters, integrated in the inverters of 360 AC-modules, equally distributed over the twelve cabinets. The monitoring is based on daily readings of the produced energy using the build-in Wh-counter of each of the monitored AC-modules. The readings of the build-in Wh-counters of the inverters have been compared with the kWh-counters used for the global monitoring (reference [2]). From this comparison it was concluded that the Wh-counters of inverter type B have a too low accuracy for absolute energy measurements. However the readings can be used for comparing the energy production of the inverters with the other inverters of the same type.
- <u>Analytical data acquisition</u> units positioned at four of the 2160 modules. The selected modules for analytical monitoring are the most central modules of the cabinets 2, 5, 8 and 11. The measured quantities are listed in table 1. The quantities from the analytical data acquisition units are measured continuously with a sample period of about 6 s and the results are condensed into values of the average, maximum, minimum and standard deviation of each measured quantity, based on periods of 10-minutes.

The decentralised data acquisition units are connected via one single twisted pair cable to a measurement PC. The measurement results are stored on the hard disc of the PC and are transported via a telephone line to ECN every night for subsequent evaluation.

3. GLOBAL MONITORING RESULTS

The monthly energy productions of the 12 cabinets have been determined from the readings of the corresponding 12 kWh-counters on the first day of each month. The readings are taken at 12:30 h each day. As a consequence the measured energy production of each month is in fact the energy production between 12:30h on the first day of the month and 12:30 h on the first day of the following month. The monthly energy production of the 12 cabinets are given in table 2. Table 2 shows also the production data for the complete period of 2 years.
The in-plane irradiations in the corresponding periods have obtained by integration of the reference cell data from the analytical monitoring programme between 12:30 h on the first day of the month and 12:30 h on the first day of the following month. Since the analytical monitoring programme has been interrupted a number of times due to technical problems with the monitoring equipment the measured irradiance data are incomplete. The data set has been completed by using hourly irradiation data in the horizontal plane, measured by The Royal Netherlands Meteorological Institute (KNMI) in De Bilt. The data of De Bilt have been translated to the in-plane irradiations using the models of Orgill&Hollands and of Perez.
The monthly irradiation data are given in table 3. Table 3 shows also the monitoring fraction (the fraction of the time for which the irradiation has been obtained by the measurements).

The energy production data of table 2 and the corresponding data of the in-plane irradiations of table 3 have been used to calculate the performance ratio's per cabinet. The total energy productions over the 2-year period and the corresponding irradiation in the horizontal plane have been used to calculate the final yield of the cabinets for a reference irradiation of 1000 kWh/m2. The performance ratio's and the final yields are based on a nominal power of 95 Wp per module at STC. The results are shown in table 4. The performance ratio's obtained per cabinet for the complete period of 2 years are also presented in figure 2.
The table and figure show significant differences in the performance of the AC-modules per cabinet. This will be evaluated further in the following paragraphs.

The modules with inverter type A show a good performance compared to other noise barrier mounted PV-systems (ref. [3], [4])

4. SUPERVISON MONITORING RESULTS

The energy productions of the individually monitored AC-modules have been determined per month by subtracting the Wh-reading at the beginning of the month from the reading at the end of the month. In case the measured energy production of an AC-module is zero or negative it is concluded that the combination of module, inverter and monitoring device has been defective during that month. The defective combinations are marked with an exclamation mark in appendix 1. During the monitoring period some of the monitoring devices have been disconnected because of human mistakes or because of technical problems. In these cases the combinations are marked with a question mark in appendix 1, meaning that no information is available on the performance of these combinations. Although only 1 out of 6 AC-modules were addressed in the supervision monitoring programme, the results of appendix 1 have been used to estimate the percentage of defective combinations (module, inverter, monitoring facility) per inverter type for each month. These percentages are shown in figure 3. The percentages in figure 3 are an upper estimate of the number of defective AC-modules because possible defective monitoring facilities contribute to the observed percentage.

The percentage of defective combinations of inverter type A has been less than 1% during the total monitoring period. The percentage of defective combinations of inverter type B has increased from less than 1 % at the beginning of the monitoring period to almost 6 % in January 2000. Hereafter it dropped to less than 3% in May 2000. The reason of this sudden decrease is unknown. Starting in September 2000 modifications were being made on the PV-system (see also paragraph 5.5). During these activities the PV-system has partly been switched of. No recordings of this were made and as a consequence it can only be assumed that the high percentage of defective combinations of inverter type B starting at September 2000 are caused by the temporary modification activities.

5. ANALYTICAL MONITORING RESULTS

5.1 Monthly efficiency data

Monthly energy and irradiation data have been determined from the analytical data acquisition system by multiplication of the averaged power and irradiance data by the duration of the various months. In contrast to the global monitoring (chapter 3) no data from KNMI have been used. The DC-power values have been determined by multiplication of the averaged DC-current and DC-voltage of each 10-minute period. The DC-energies have additionally been corrected to a module temperature of 25 °C using a temperature coefficient for the power of -0.4 % / K. The data determined for the 4 AC-modules (near cabinets 2, 5, 8 and 11) are shown in table 5.
Using the values of table 5 the corresponding efficiencies have been determined on a monthly basis (see table 6). The module efficiency has been determined using the DC-energy, the in-plane irradiation and the net cell area (0.72 m^2). The module efficiencies of the modules near cabinets 2, 8 and 11 are more or less equal. The module efficiency of the module near cabinet 5 is significantly lower. This will be discussed in the following paragraphs.
Comparing the values of the module efficiency with the values of the module efficiency at 25 °C shows that the so-called temperature loss is 4.5 %.
The efficiency of inverter type A (cabinets 2 and 11) is significantly higher than the efficiency of inverter type B (cabinets 5 and 8). This will be elaborated in paragraph 5.4.

5.2 Module efficiency

The module efficiency has been determined for 4 AC-modules using the DC-power data and the reference cell irradiance data obtained in the 10-minute measuring periods. The efficiency values are based on the net module area (72 cells of 10 x 10 cm2) and are corrected to a module temperature of 25 °C using a temperature coefficient for the power of -0.4 % / K. The module efficiency of the modules in the period from December 1st 1998 till December 1st 2000 is presented as a function of the irradiance in the figure 4.
The module efficiency is not only a characteristic of the module but it is also influenced by the DC-voltage as set by the inverter. For this reason also the corresponding DC-voltages are given (figure 5). The voltages have been corrected to a module temperature of 25 °C using a temperature coefficient for the voltage of -0.4 % / K. Figure 5 shows significant differences in the DC-voltage applied by the two types of inverters. Comparing the module efficiencies of the best module of each type (cabinets 2 and 8) shows that the difference in applied voltages corresponds to only a small difference in the efficiency.
Figure 5 shows a large difference between the module efficiency in the two modules of type B (cabinets 5 and 8). The lower efficiency of the module of cabinet 5 is elaborated further in paragraph 5.5.

5.3 Effect of traffic dust

During the monitoring the in-plane irradiance is measured using reference cells, made of the same materials as the PV-modules. In this way the response of the reference cell is as close as possible to the response of the modules regarding spectral sensitivity, reflections of the glass, accumulated dust etcetera. In the end of May 1999 the 4 reference cells were cleaned while the modules remained uncleaned. The module efficiencies have been determined using the data of two weeks before the cleaning and also using the data of two weeks after the cleaning. This resulted in a seemingly decrease of the efficiency of the four modules with a similar magnitude (see figure 6). This shows that the dust on the reference cells and on the modules caused an irradiation loss of about 8 %. If the dust on the modules is not distributed evenly over the 72 cells per module the energy loss due to the dust can be even more than 8 % due to the mismatch

effect. Neglecting this effect and assuming that the amount of dust on the reference cells before cleaning is typical for the averaged yearly situation it is estimated that the dust on the modules accounts for an energy loss of about 8 %.
The effect of cleaning reference cells in May 1999 on the monthly results is less pronounced (see table 6, module efficiency @ 25 °C). This leads to the assumption that the accumulation of dust and its natural cleaning reaches equilibrium relatively fast. Therefore the effect of the pollution of the irradiance sensors over the complete monitoring period is assumed to compensate for the effect of the pollution of the modules. As a consequence the measured performance ratios and reference yields do not include the effect of the traffic dust on the modules.

5.4 DC / AC efficiency

The efficiency of the conversion from DC-power to AC-power by the two types of inverters has been determined as a function of the DC-power. The results (see figure 7) show a significant difference in the efficiencies in the low power range between the inverters of type A (cabinets 2 and 11) and of type B (cabinets 5 and 8). This difference in conversion efficiency accounts for a difference in annual energy output of 6 % between the modules with the inverter of type A and type B.

5.5 Grid interference

It has been observed that the AC-module near cabinet 5 frequently showed low values of the power at high irradiances. This is illustrated in figure 8. This figure shows the module efficiency, as defined in paragraph 5.2, obtained by all individual 10-minute measurements in august 1999. This effect was examined in more detail by dedicated measurement campaigns using laboratory equipment. It was demonstrated that the inverters located at a large distance from the 10 kV-transformer switched themselves off during short moments as a result of grid interference, despite of the fact that the inverter design was in full compliance with all international standards. After recognising the phenomenon the manufacturer modified the inverter which solved the problem. This is illustrated in figure 8, showing the module efficiency obtained in august 2000. Comparing the data in figure 8 of August 1999 with August 2000 shows that in august 2000 no dropouts occur. Furthermore the figure shows differences in the module efficiency at low irradiances. These differences are probably caused by effects of dust and are not due to the dropouts. Starting from august 24, 2000 all inverters of type B were modified. At the end of the monitoring period (December 1st, 2000) this work was not completed yet.
To estimate the energy loss due to the dropouts the module efficiency of the AC-module near cabinet 5 has been determined for the complete period of 2 years including and excluding the dropouts. The results including the dropouts, identical to the results in figure 4, and the results excluding the dropouts are shown in figure 9. If the dropouts had not occurred the energy production of the AC-module near cabinet 5 had been 5 % higher than the measured energy production. This accounts only partly for the difference in the efficiency of the module near cabinet 5 and 8 (table 6). The remaining difference of about 6 % in the module efficiency is probably caused by production tolerances of the modules and by the effects of dust. Since the effect of the grid interference is not equal for all inverters, the energy loss of 5 % of the inverter near cabinet 5 cannot be seen as an average for all modules of the cabinets 3 through 10. For this reason the results of the modifications on the inverters can only be judged by continuation of the global monitoring programme.

5.6 Irradiation distribution and module temperature

The annual distribution of the irradiation as a function of the irradiance has been determined in the plane of the modules near cabinet 5 and in the horizontal plane. These data have been obtained by dividing the measured distributions over the 2 year period by a factor 2. The results are shown in figure 10.

The increase of the module temperature above the ambient temperature has been measured during the 2 year period as a function of the irradiance. The results for the module near cabinet 5 are shown in figure 11.

6. CONCLUSIONS

The global monitoring has led to the following conclusions:

- The performance ratio defined for the 12 cabinets over the monitoring period of 2 years range between 58% and 75%.
- The corresponding yields, defined for a standard climatic year in the Netherlands, range between 600 and 800 kWh/kWp.
- The performance of the AC-modules equipped with inverters of type B is significantly lower than the performance of the AC-modules with inverter type A.

The supervision monitoring has led to the following conclusions:

- The number of defective combinations of module, inverter and monitoring device of the AC-modules with inverter type A has been 1 out of 120 (0.8 %) during the complete period of 2 years.
- The number of defective combinations of module, inverter and monitoring device of the AC-modules with inverter type B has increased to about 6 % during the complete period of 2 years.

The analytical monitoring has led to the following conclusions:

- The maximum power point trackers of the two types of inverters show a very different behaviour. This however causes no significant differences in the utilisation of the available solar energy.
- A rough estimate of the reduction of the annual energy production caused by the accumulated traffic dust on the modules is 8 %. This effect is not included in the above mentioned performance ratios and reference yields.
- The conversion efficiency of inverter type B is significantly lower than of inverter type A at low values of the input power. This accounts for a difference in the annual energy production between the AC-modules with inverter types A and B of 6 %.
- Unexpected grid interference of the AC-modules with inverter type B caused an energy loss of 5 % in one of the AC-modules.
- The increase in module temperature above the ambient temperature is 40 K at an in-plane irradiance of 1000 W/m^2. The fact that the module temperatures deviate from 25 ˚C causes an energy loss of 4.5 %.

In summary the main conclusions are:

- The AC-modules with type A inverters perform very well and have a low failure rate
- The AC-modules with type B inverters perform less good and have a higher failure rate. The reasons of the lower performance are the lower inverter efficiency and the occurrence of grid interference. Modifications on the PV-system to prevent the grid interference are ongoing.
- Accumulated traffic dust on the modules causes significant energy losses.
- Annual cleaning of the modules after the winter season should be considered.
- Global monitoring should be continued for the assessment of the results of the modifications and for detecting possible failures in the future.

7. REFERENCES

[1] C.W.A. Baltus et al: A photovoltaic data acquisition program for supervision monitoring of a large number of AC-modules; 2nd world conference and exhibition on PV-solar energy conversion; pp 2360 - 2363; 6 - 10 July 1998, Vienna, Austria.

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[3] Th. Nordmann, A. Frölich, L. Clavadetscher: "Eight years of operation experience with two 100 kWp PV sound barriers"; 14th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 30 June – 4 July 1997 (p. 1124 – 1127).

[4] Th. Nordmann et. al. "Integrated PV noise barriers: six innovative 10 kWp testing facilities, a German/Swiss technological and economical success story!"; 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria 6-10 July 1998 (p. 2486 – 2491).

8. TABLES

Table 1: Measured quantities of the analytical monitoring programme

Quantity	sensor	transducer	range	location
AC-output power		Camille Bauer, type Sineax PQ502, class 0.5	0 / 115 W	central module of cabinets 2, 5, 8 and 11
DC-voltage	Voltage divider, 10 kΩ/39 kΩ,	Knick type 11310	0 / 50 V	central module of cabinets 2, 5, 8 and 11
DC-current	ABB shunt, type DER, 60 mV/4A,	Knick type 11206	0 / 4 A	central module of cabinets 2, 5, 8 and 11
Module temperature	AD 590LF	AD 2B57A-1	-100 / 150 ^{o}C	central module of cabinets 2, 5, 8 and 11
Irradiance (array plane)	Reference cell, Shell Solar Energy	Knick type 11215A	0 / 2400 W/m^2	above central module of cabinets 2, 5, 8 and 11
Global irradiance (horizontal)	Pyranometer Kipp & Zonen type CM11	Knick type 11202A	0 / 3800 W/m^2	above central module of cabinet 5
Ambient temperature	Miery Meteo type 308	Miery Meteo type 11150B	-30 / 40 ^{o}C	above central module of cabinet 5

from	till	KWH1	KWH2	KWH3	KWH4	KWH5	KWH6	KWH7	KWH8	KWH9	KWH10	KWH11	KWH12	Total	period
01-12-98 12:30	01-01-99 12:30	427	446	383	332	351	347	373	367	377	361	418	395	4576	Dec-98
01-01-99 12:30	01-02-99 12:30	439	460	391	284	308	345	388	422	389	374	443	419	4664	Jan-99
01-02-99 12:30	01-03-99 12:30	776	817	703	470	567	543	671	689	678	640	779	739	8072	Feb-99
01-03-99 12:30	01-04-99 12:30	943	995	883	667	744	695	860	874	864	806	963	927	10221	Mar-99
01-04-99 12:30	01-05-99 12:30	1425	1499	1371	1029	1151	1046	1338	1355	1347	1235	1482	1431	15708	Apr-99
01-05-99 12:30	01-06-99 12:30	1793	1880	1752	1584	1661	1470	1773	1756	1818	1691	1914	1864	20955	May-99
01-06-99 12:30	01-07-99 12:30	1628	1707	1560	1278	1403	1278	1574	1556	1587	1462	1712	1673	18417	Jun-99
01-07-99 12:30	01-08-99 12:30	1808	1902	1772	1467	1553	1453	1768	1766	1804	1673	1907	1867	20740	Jul-99
01-08-99 12:30	01-09-99 12:30	1404	1475	1343	1086	1171	1123	1213	1326	1361	1287	1466	1434	15690	Aug-99
01-09-99 12:30	01-10-99 12:30	1225	1286	1147	954	1027	971	995	1142	1167	1082	1243	1210	13449	Sep-99
01-10-99 12:30	01-11-99 12:30	925	968	842	715	790	748	724	834	847	763	909	869	9933	Oct-99
01-11-99 12:30	01-12-99 12:30	606	630	533	456	510	494	459	533	540	485	593	556	6397	Nov-99
01-12-99 12:30	01-01-00 12:30	397	410	341	311	334	329	289	337	335	306	382	359	4129	Dec-99
01-01-00 12:30	01-02-00 12:30	359	372	293	270	292	296	253	293	290	265	344	322	3648	Jan-00
01-02-00 12:30	01-03-00 12:30	759	791	671	604	642	610	674	682	682	618	751	714	8197	Feb-00
01-03-00 12:30	31-03-00 12:30	779	811	689	656	704	640	708	705	707	641	791	761	8590	Mar-00
31-03-00 12:30	01-05-00 12:30	1280	1330	1172	1057	1126	1035	1182	1174	1179	1069	1288	1246	14139	Apr-00
01-05-00 12:30	01-06-00 12:30	1656	1725	1563	1414	1506	1350	1486	1575	1590	1446	1692	1666	18670	May-00
01-06-00 12:30	01-07-00 12:30	1609	1677	1520	1430	1518	1329	1347	1558	1563	1446	1671	1656	18323	Jun-00
01-07-00 12:30	01-08-00 12:30	1315	1370	1210	1141	1148	1091	1081	1254	1268	1173	1377	1359	14787	Jul-00
01-08-00 12:30	01-09-00 12:30	1562	1629	1472	1317	1282	1240	1265	1462	1445	1374	1584	1563	17196	Aug-00
01-09-00 12:30	01-10-00 12:30	1005	1049	926	815	919	529	797	910	896	861	1012	988	10708	Sep-00
01-10-00 12:30	01-11-00 12:30	727	761	667	601	659	627	453	661	457	561	733	701	7606	Oct-00
01-11-00 12:30	01-12-00 12:30	397	413	164	221	333	338	283	341	322	102	380	356	3649	Nov-00
01-12-98 12:30	**01-12-00 12:30**	**25243**	**26403**	**23371**	**20158**	**21696**	**19927**	**21952**	**23572**	**23514**	**21720**	**25831**	**25077**	**278464**	**2 years**

Table 2: Produced energy per cabinet (kWh)

Period		Ho	Hi_1,2,3	Hi_4,5,6	Hi_7,8,9	Hi_10,11,12	Monitoring	period
from	till	kWh/m2	kWh/m2	kWh/m2	kWh/m2	kWh/m2	fraction	
01-12-98 12:30	01-01-99 12:30	17.9	34.8	32.8	32.4	30.9	1.00	Dec-98
01-01-99 12:30	01-02-99 12:30	20.3	36.1	34.4	34.1	32.8	1.00	Jan-99
01-02-99 12:30	01-03-99 12:30	37.3	62.7	61.3	61.1	59.9	0.57	Feb-99
01-03-99 12:30	01-04-99 12:30	63.6	78.2	75.1	74.3	73.3	0.77	Mar-99
01-04-99 12:30	01-05-99 12:30	111.9	117.8	114.8	114.3	114.0	0.67	Apr-99
01-05-99 12:30	01-06-99 12:30	158.2	150.4	148.7	148.5	148.3	0.70	May-99
01-06-99 12:30	01-07-99 12:30	155.1	136.2	136.6	134.7	133.2	0.87	Jun-99
01-07-99 12:30	01-08-99 12:30	168.0	157.5	158.1	156.6	155.6	0.67	Jul-99
01-08-99 12:30	01-09-99 12:30	118.6	119.6	118.7	116.8	114.8	0.97	Aug-99
01-09-99 12:30	01-10-99 12:30	87.3	102.4	100.9	99.0	97.1	0.96	Sep-99
01-10-99 12:30	01-11-99 12:30	49.5	74.6	72.4	70.3	68.5	1.00	Oct-99
01-11-99 12:30	01-12-99 12:30	26.1	48.3	46.5	45.5	44.3	1.00	Nov-99
01-12-99 12:30	01-01-00 12:30	16.4	32.6	31.1	30.3	29.4	0.97	Dec-99
01-01-00 12:30	01-02-00 12:30	19.0	29.7	28.2	27.3	26.5	1.00	Jan-00
01-02-00 12:30	01-03-00 12:30	38.4	58.4	56.4	55.1	53.8	1.00	Feb-00
01-03-00 12:30	31-03-00 12:30	55.8	61.7	60.2	58.9	58.6	0.96	Mar-00
31-03-00 12:30	01-05-00 12:30	100.0	100.7	97.8	95.5	95.3	0.94	Apr-00
01-05-00 12:30	01-06-00 12:30	148.6	133.6	130.8	128.6	124.9	1.00	May-00
01-06-00 12:30	01-07-00 12:30	156.3	129.4	128.2	126.4	126.8	0.96	Jun-00
01-07-00 12:30	01-08-00 12:30	126.4	105.2	104.4	103.2	99.4	1.00	Jul-00
01-08-00 12:30	01-09-00 12:30	128.3	123.9	120.9	121.6	119.9	0.97	Aug-00
01-09-00 12:30	01-10-00 12:30	72.5	80.7	77.7	76.4	79.2	1.00	Sep-00
01-10-00 12:30	01-11-00 12:30	42.6	57.3	55.0	54.8	57.7	1.00	Oct-00
01-11-00 12:30	01-12-00 12:30	20.4	31.9	29.5	29.4	30.5	1.00	Nov-00
01-12-98 12:30	01-12-00 12:30	1938.5	2063.5	2020.7	1995.1	1974.7	0.92	2 years

Missing data due to monitoring problems have been completed by data from KNMI

Table 3: Irradiation data, corresponding to the data in table 2.

from	till	PR1	PR2	PR3	PR4	PR5	PR6	PR7	PR8	PR9	PR10	PR11	PR12	period
01-12-98 12:30	01-01-99 12:30	72	75	64	59	62	62	67	66	68	68	79	75	Dec-98
01-01-99 12:30	01-02-99 12:30	71	75	63	48	52	59	67	72	67	67	79	75	Jan-99
01-02-99 12:30	01-03-99 12:30	72	76	66	45	54	52	64	66	65	63	76	72	Feb-99
01-03-99 12:30	01-04-99 12:30	71	74	66	52	58	54	68	69	68	64	77	74	Mar-99
01-04-99 12:30	01-05-99 12:30	71	74	68	52	59	53	68	69	69	63	76	73	Apr-99
01-05-99 12:30	01-06-99 12:30	70	73	68	62	65	58	70	69	72	67	75	73	May-99
01-06-99 12:30	01-07-99 12:30	70	73	67	55	60	55	68	68	69	64	75	73	Jun-99
01-07-99 12:30	01-08-99 12:30	67	71	66	54	57	54	66	66	67	63	72	70	Jul-99
01-08-99 12:30	01-09-99 12:30	69	72	66	54	58	55	61	66	68	66	75	73	Aug-99
01-09-99 12:30	01-10-99 12:30	70	73	65	55	60	56	59	67	69	65	75	73	Sep-99
01-10-99 12:30	01-11-99 12:30	72	76	66	58	64	60	60	69	70	65	78	74	Oct-99
01-11-99 12:30	01-12-99 12:30	73	76	65	57	64	62	59	69	70	64	78	73	Nov-99
01-12-99 12:30	01-01-00 12:30	71	74	61	58	63	62	56	65	65	61	76	71	Dec-99
01-01-00 12:30	01-02-00 12:30	71	73	58	56	61	61	54	63	62	59	76	71	Jan-00
01-02-00 12:30	01-03-00 12:30	76	79	67	63	67	63	72	72	72	67	82	78	Feb-00
01-03-00 12:30	31-03-00 12:30	74	77	65	64	68	62	70	70	70	64	79	76	Mar-00
31-03-00 12:30	01-05-00 12:30	74	77	68	63	67	62	72	72	72	66	79	76	Apr-00
01-05-00 12:30	01-06-00 12:30	72	76	68	63	67	60	68	72	72	68	79	78	May-00
01-06-00 12:30	01-07-00 12:30	73	76	69	65	69	61	62	72	72	67	77	76	Jun-00
01-07-00 12:30	01-08-00 12:30	73	76	67	64	64	61	61	71	72	69	81	80	Jul-00
01-08-00 12:30	01-09-00 12:30	74	77	70	64	62	60	61	70	69	67	77	76	Aug-00
01-09-00 12:30	01-10-00 12:30	73	76	67	61	69	40	61	70	69	64	75	73	Sep-00
01-10-00 12:30	01-11-00 12:30	74	78	68	64	70	67	48	70	49	57	74	71	Oct-00
01-11-00 12:30	01-12-00 12:30	73	76	30	44	66	67	56	68	64	19	73	68	Nov-00

01-12-98 12:30	01-12-00 12:30	72	75	66	58	63	58	64	69	69	64	76	74	2 years
Yield at Ho = 1000 kWh/m2		Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_10	Y_11	Y_12	Y_total
kWh/kWp		762	797	705	608	655	601	662	711	709	655	779	757	700

Table 4: Performance ratio's and reference yield per cabinet, obtainded from tables 2 and 3 with a STC-power of 95 Wp per module.

	Irradiation (kWh/m2)					DC-energy (kWh)				DC-energy @ 25 oC (kWh)				AC-energy (kWh)			
Month	Horiz.	Cab. 2	Cab. 5	Cab. 8	Cab. 11	Cab. 2	Cab. 5	Cab. 8	Cab. 11	Cab. 2	Cab. 5	Cab. 8	Cab. 11	Cab. 2	Cab. 5	Cab. 8	Cab. 11
Dec-98	17.83	34.3	32.3	31.9	30.4	2.92	2.30	2.65	2.58	2.87	2.27	2.60	2.54	2.65	1.86	2.20	2.34
Jan-99	19.66	34.5	32.9	32.6	31.3	2.89	2.34	2.76	2.67	2.84	2.29	2.71	2.62	2.61	1.84	2.24	2.40
Feb-99	34.01	51.8	49.4	48.9	47.5	4.47	3.76	4.19	4.10	4.41	3.72	4.12	4.05	4.05	3.12	3.49	3.77
Mar-99	61.68	75.5	71.8	70.9	69.9	6.50	5.34	6.19	6.02	6.71	5.50	6.37	6.23	5.86	4.39	5.21	5.50
Apr-99	91.82	92.8	88.3	87.4	87.2	8.13	6.66	7.73	7.61	8.29	6.79	7.87	7.78	7.34	5.52	6.54	6.95
May-99	149.11	135.7	133.3	133.1	133.2	11.49	10.43	11.32	11.22	12.13	11.05	11.97	11.93	10.39	9.07	9.84	10.23
Jun-99	159.52	140.7	141.1	138.7	136.6	11.35	9.75	10.99	10.88	12.03	10.36	11.65	11.60	10.29	8.33	9.49	9.95
Jul-99	170.52	160.7	160.9	158.1	155.6	12.78	10.19	12.38	12.24	13.94	11.09	13.49	13.41	11.61	8.60	10.83	11.19
Aug-99	122.48	123.2	122.1	120.1	117.9	9.95	7.89	9.50	9.42	10.63	8.42	10.14	10.12	9.05	6.62	8.22	8.62
Sep-99	85.34	99.5	98.0	96.2	94.3	8.13	6.68	7.65	7.53	8.64	7.11	8.14	8.07	7.41	5.67	6.62	6.91
Oct-99	49.91	75.0	72.8	70.8	68.9	6.32	5.34	5.87	5.65	6.50	5.49	6.01	5.84	5.74	4.51	5.01	5.14
Nov-99	26.17	48.2	46.4	45.3	44.1	4.08	3.34	3.80	3.65	4.10	3.35	3.80	3.67	3.71	2.74	3.20	3.33
Dec-99	16.57	33.0	31.5	30.7	29.8	2.82	2.41	2.52	2.43	2.76	2.36	2.45	2.38	2.57	2.01	2.10	2.23
Jan-00	18.78	29.4	28.0	27.0	26.2	2.47	2.17	2.22	2.13	2.40	2.10	2.15	2.07	2.22	1.73	1.76	1.93
Feb-00	38.29	58.2	56.3	54.9	53.6	5.13	4.61	4.75	4.62	5.11	4.60	4.72	4.61	4.66	3.94	4.03	4.19
Mar-00	56.04	61.9	60.3	59.0	58.6	5.36	4.88	5.05	4.96	5.38	4.89	5.06	4.99	4.82	4.06	4.18	4.43
Apr-00	93.27	93.6	90.8	88.4	88.3	8.16	7.36	7.61	7.51	8.41	7.63	7.85	7.79	7.38	6.35	6.52	6.71
May-00	148.96	133.8	131.1	128.9	125.2	11.33	10.30	10.79	10.51	12.05	11.01	11.52	11.29	10.28	8.98	9.38	9.43
Jun-00	151.56	125.2	123.8	121.9	122.2	10.62	9.70	10.25	9.84	11.31	10.18	10.94	10.58	9.65	8.42	8.89	8.81
Jul-00	124.83	103.9	103.2	102.2	98.3	8.86	8.37	8.59	8.26	9.29	8.64	9.03	8.73	8.04	7.12	7.30	7.37
Aug-00	129.24	123.2	120.0	120.1	118.4	10.49	9.79	10.15	9.86	11.21	10.32	10.87	10.63	9.56	8.59	8.87	8.90
Sep-00	73.11	81.4	78.3	76.9	79.8	6.97	6.31	6.50	6.35	7.30	6.64	6.81	6.70	6.35	5.41	5.54	5.73
Oct-00	42.83	57.5	55.2	55.1	57.9	5.01	4.55	4.65	4.54	5.11	4.68	4.72	4.67	4.57	3.88	3.92	4.11
Nov-00	20.34	31.7	29.4	29.2	30.4	2.73	2.36	2.47	2.35	2.69	2.35	2.44	2.34	2.46	1.91	1.99	2.13
Total	1902	2005	1957	1928	1906	169.0	146.8	160.6	156.9	176.1	152.8	167.4	164.6	153.3	124.6	137.4	142.3

Note: Missing data due to monitoring problems have been completed by linear interpolation on a monthly basis.

Table 5: Irradiation and energy data obtained by the analytical monitoring programme on 4 individual AC-modules

	Module efficiency (%)				Module efficiency @ 25 oC (%)				Inverter efficiency (%)				Performance ratio (-)			
Month	Cab. 2	Cab. 5	Cab. 8	Cab. 11	Cab. 2	Cab. 5	Cab. 8	Cab. 11	Cab. 2	Cab. 5	Cab. 8	Cab. 11	Cab. 2	Cab. 5	Cab. 8	Cab. 11
Dec-98	11.8	9.9	11.6	11.8	11.6	9.7	11.3	11.6	90.6	80.8	82.9	90.6	0.81	0.61	0.73	0.81
Jan-99	11.7	9.9	11.8	11.9	11.4	9.7	11.5	11.6	90.0	78.7	81.3	90.0	0.80	0.59	0.72	0.81
Feb-99	12.0	10.6	11.9	12.0	11.8	10.5	11.7	11.8	90.6	82.9	83.3	92.2	0.82	0.66	0.75	0.84
Mar-99	12.0	10.3	12.1	12.0	12.3	10.7	12.5	12.4	90.1	82.3	84.2	91.3	0.82	0.64	0.77	0.83
Apr-99	12.2	10.5	12.3	12.1	12.4	10.7	12.5	12.4	90.3	82.8	84.5	91.3	0.83	0.66	0.79	0.84
May-99	11.8	10.9	11.8	11.7	12.4	11.5	12.5	12.4	90.5	86.9	86.9	91.2	0.81	0.72	0.78	0.81
Jun-99	11.2	9.6	11.0	11.1	11.9	10.2	11.7	11.8	90.7	85.4	86.4	91.4	0.77	0.62	0.72	0.77
Jul-99	11.0	8.8	10.9	10.9	12.0	9.6	11.8	12.0	90.9	84.4	87.5	91.5	0.76	0.56	0.72	0.76
Aug-99	11.2	9.0	11.0	11.1	12.0	9.6	11.7	11.9	90.9	83.8	86.6	91.5	0.77	0.57	0.72	0.77
Sep-99	11.3	9.5	11.0	11.1	12.1	10.1	11.7	11.9	91.2	84.8	86.4	91.8	0.78	0.61	0.72	0.77
Oct-99	11.7	10.2	11.5	11.4	12.0	10.5	11.8	11.8	90.8	84.4	85.4	91.0	0.81	0.65	0.75	0.79
Nov-99	11.8	10.0	11.7	11.5	11.8	10.0	11.7	11.6	90.8	82.1	84.1	91.1	0.81	0.62	0.74	0.79
Dec-99	11.9	10.6	11.4	11.3	11.6	10.4	11.1	11.1	91.1	83.4	83.2	91.8	0.82	0.67	0.72	0.79
Jan-00	11.7	10.8	11.4	11.3	11.3	10.4	11.0	11.0	89.9	79.8	79.3	90.5	0.79	0.65	0.69	0.78
Feb-00	12.3	11.4	12.0	12.0	12.2	11.3	11.9	12.0	90.7	85.4	84.9	90.5	0.84	0.74	0.77	0.82
Mar-00	12.0	11.2	11.9	11.7	12.1	11.3	11.9	11.8	90.0	83.2	82.7	89.3	0.82	0.71	0.75	0.80
Apr-00	12.1	11.3	12.0	11.8	12.5	11.7	12.3	12.3	90.5	86.2	85.7	89.3	0.83	0.74	0.78	0.80
May-00	11.8	10.9	11.6	11.7	12.5	11.7	12.4	12.5	90.8	87.2	86.9	89.7	0.81	0.72	0.77	0.79
Jun-00	11.8	10.9	11.7	11.2	12.5	11.4	12.5	12.0	90.8	86.8	86.7	89.5	0.81	0.72	0.77	0.76
Jul-00	11.9	11.3	11.7	11.7	12.4	11.6	12.3	12.3	90.7	85.1	84.9	89.2	0.81	0.73	0.75	0.79
Aug-00	11.8	11.3	11.7	11.6	12.6	11.9	12.6	12.5	91.1	87.7	87.4	90.2	0.82	0.75	0.78	0.79
Sep-00	11.9	11.2	11.7	11.1	12.5	11.8	12.3	11.7	91.1	85.7	85.2	90.2	0.82	0.73	0.76	0.76
Oct-00	12.1	11.5	11.7	10.9	12.3	11.8	11.9	11.2	91.1	85.3	84.5	90.6	0.84	0.74	0.75	0.75
Nov-00	11.9	11.2	11.7	10.7	11.8	11.1	11.6	10.7	90.4	80.6	80.6	90.5	0.82	0.68	0.72	0.74
Total	11.7	10.4	11.6	11.4	12.2	10.8	12.1	12.0	90.7	84.9	85.5	90.7	0.80	0.67	0.75	0.79

Table 6: Efficiency data obtained from table 5, an effective cell area of 0.72 m2 and a STC-power of 95 Wp per module

FIGURES

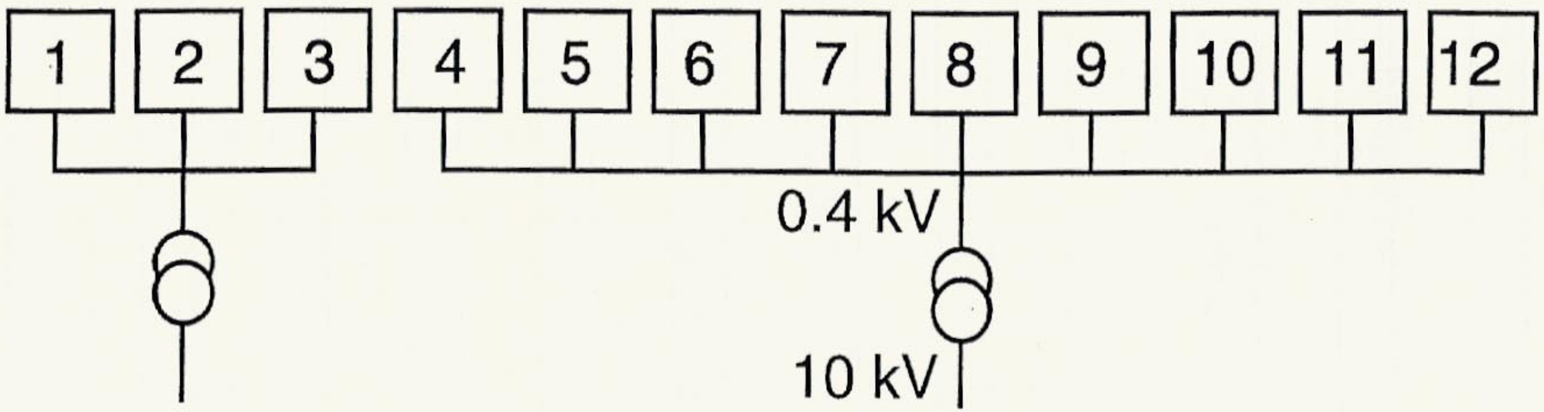

Figure 1: Connection of the 2160 AC-modules through 12 cabinets to the grid

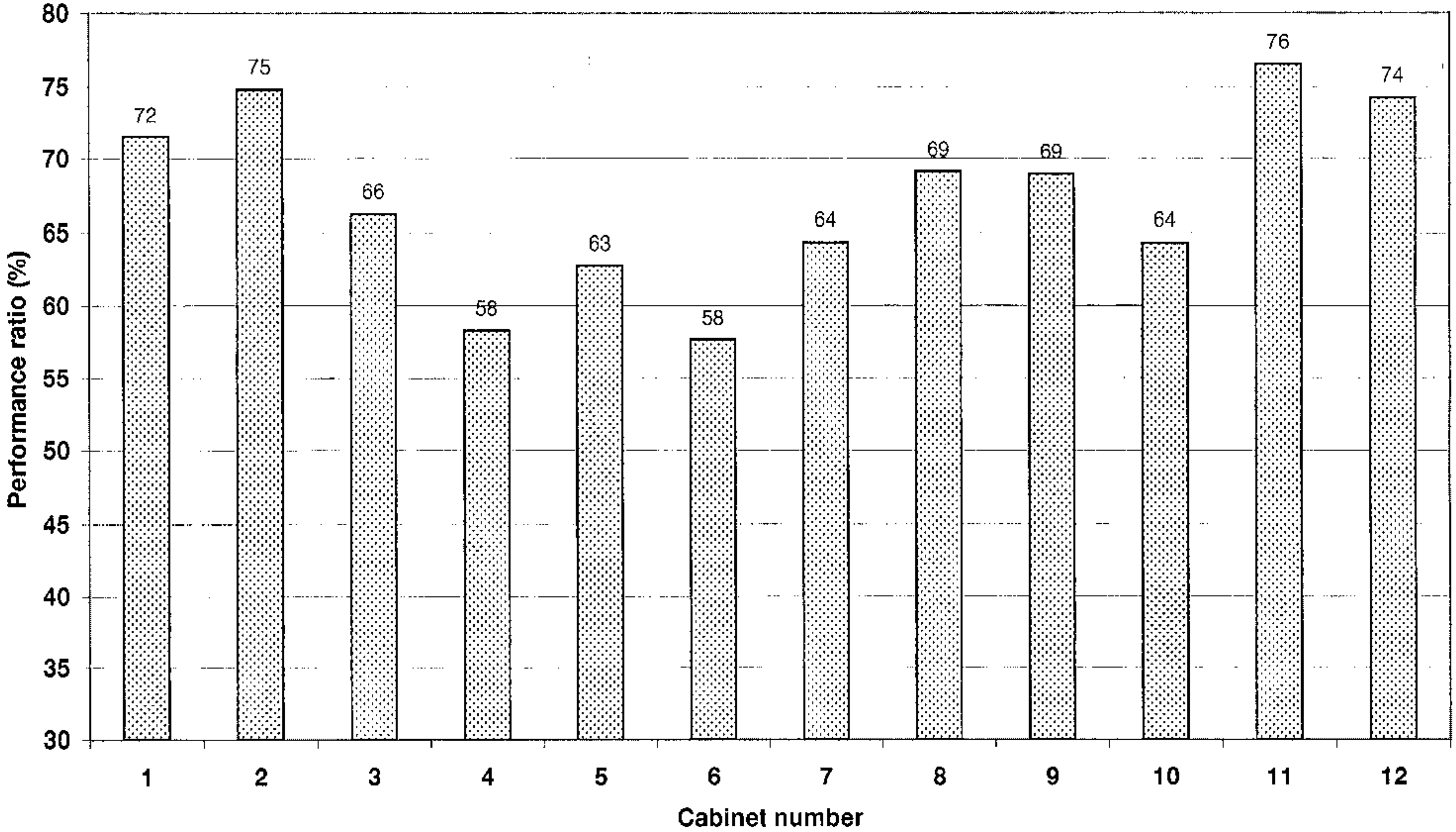

Figure 2: Performance ratio per cabinet over a 2-year period

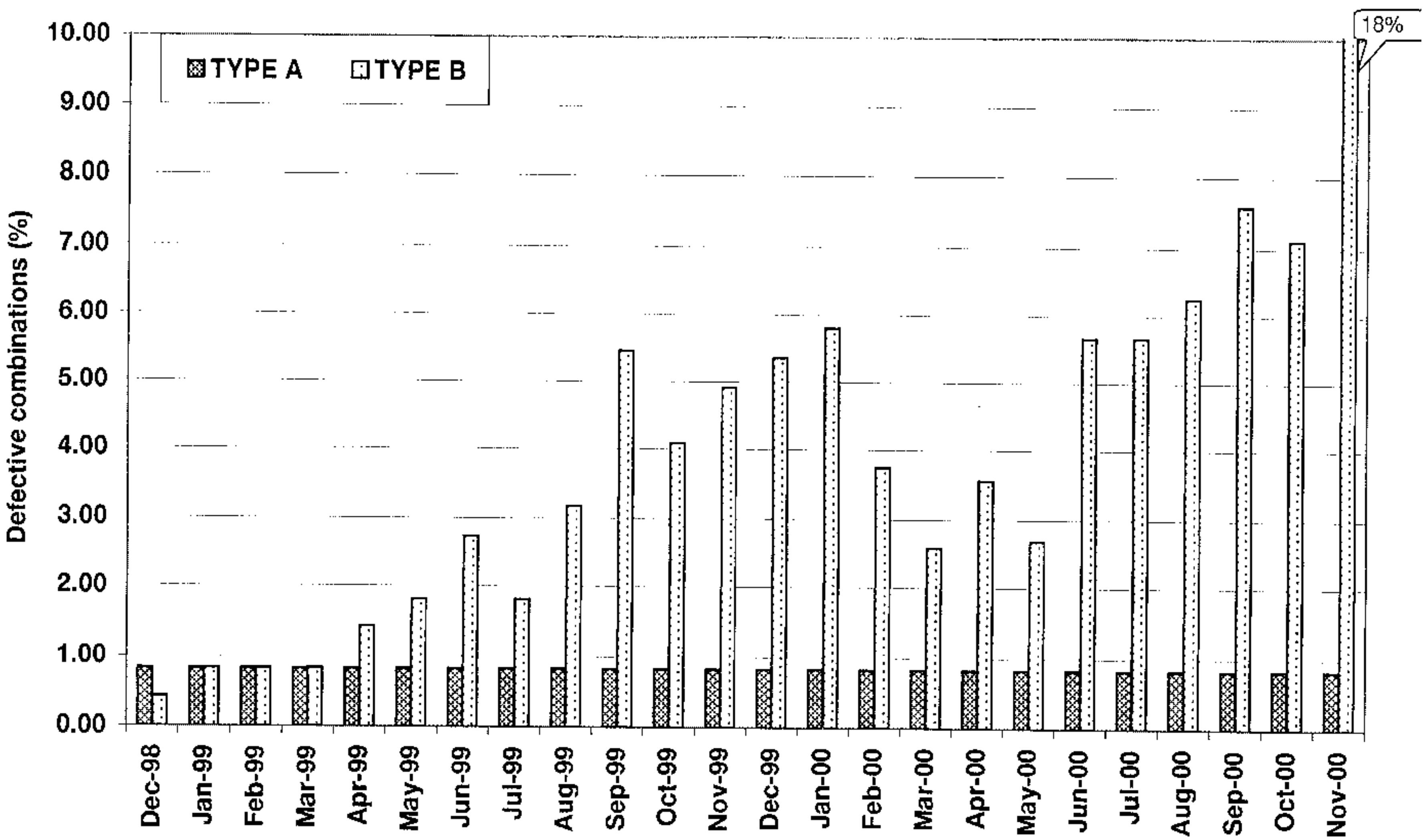

Figure 3: Percentage of defective combinations (module, inverter and monitoring device) per inverter type

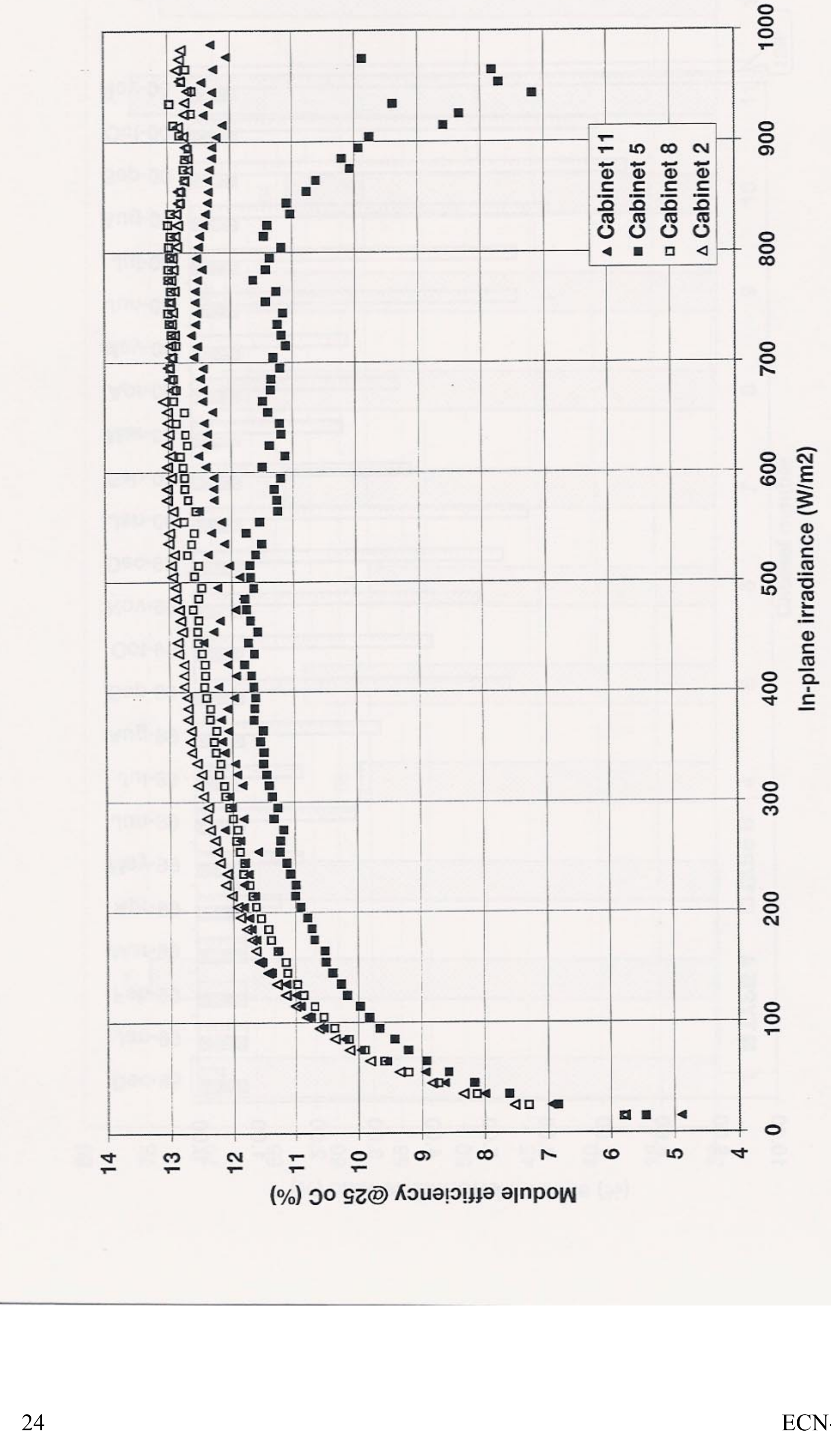

Figure 4: Module efficiency, corrected to a module temperature of 25 degr. C

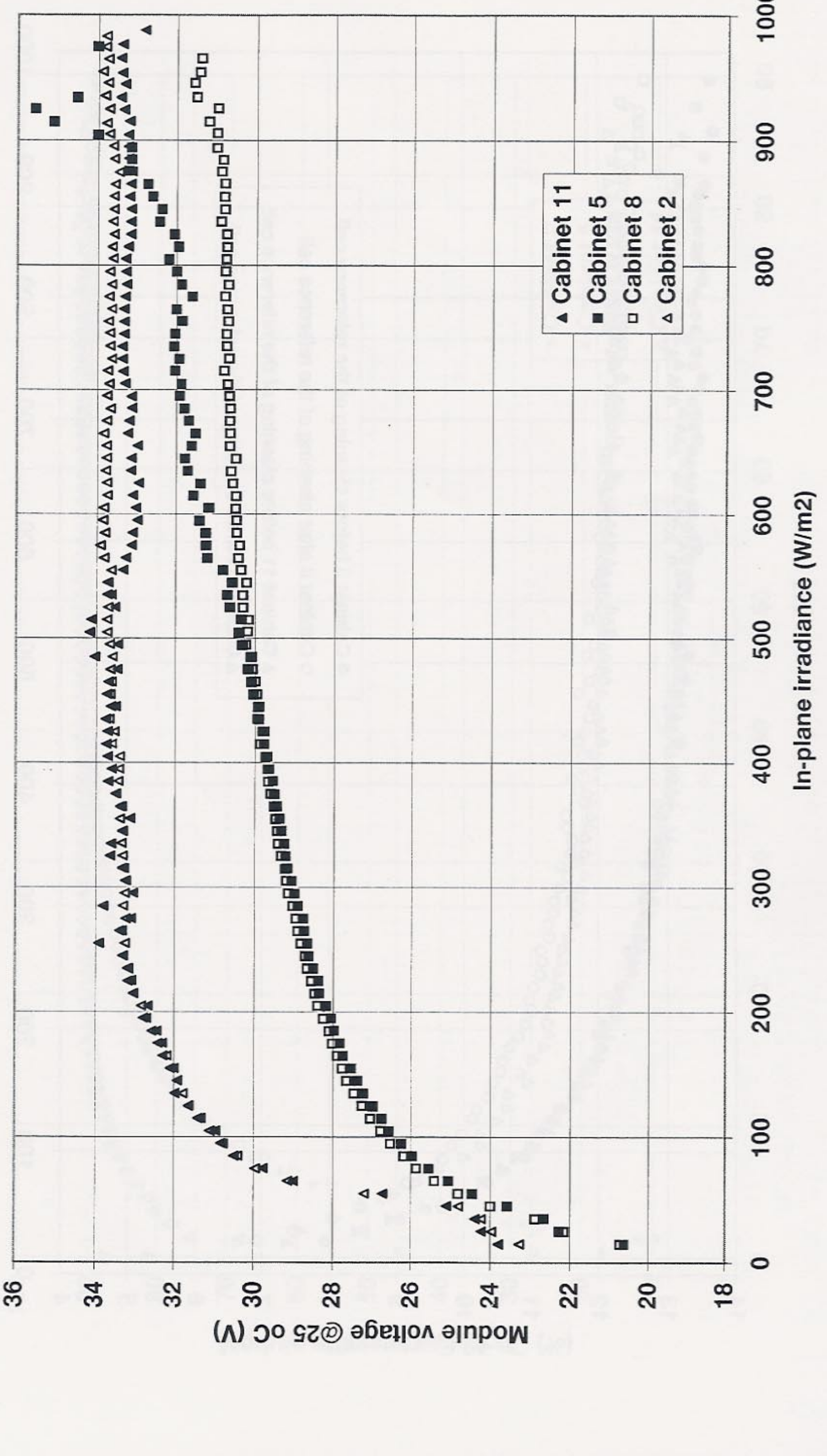

Figure 5: Module voltage, corrected to a module temperature of 25 degr. C

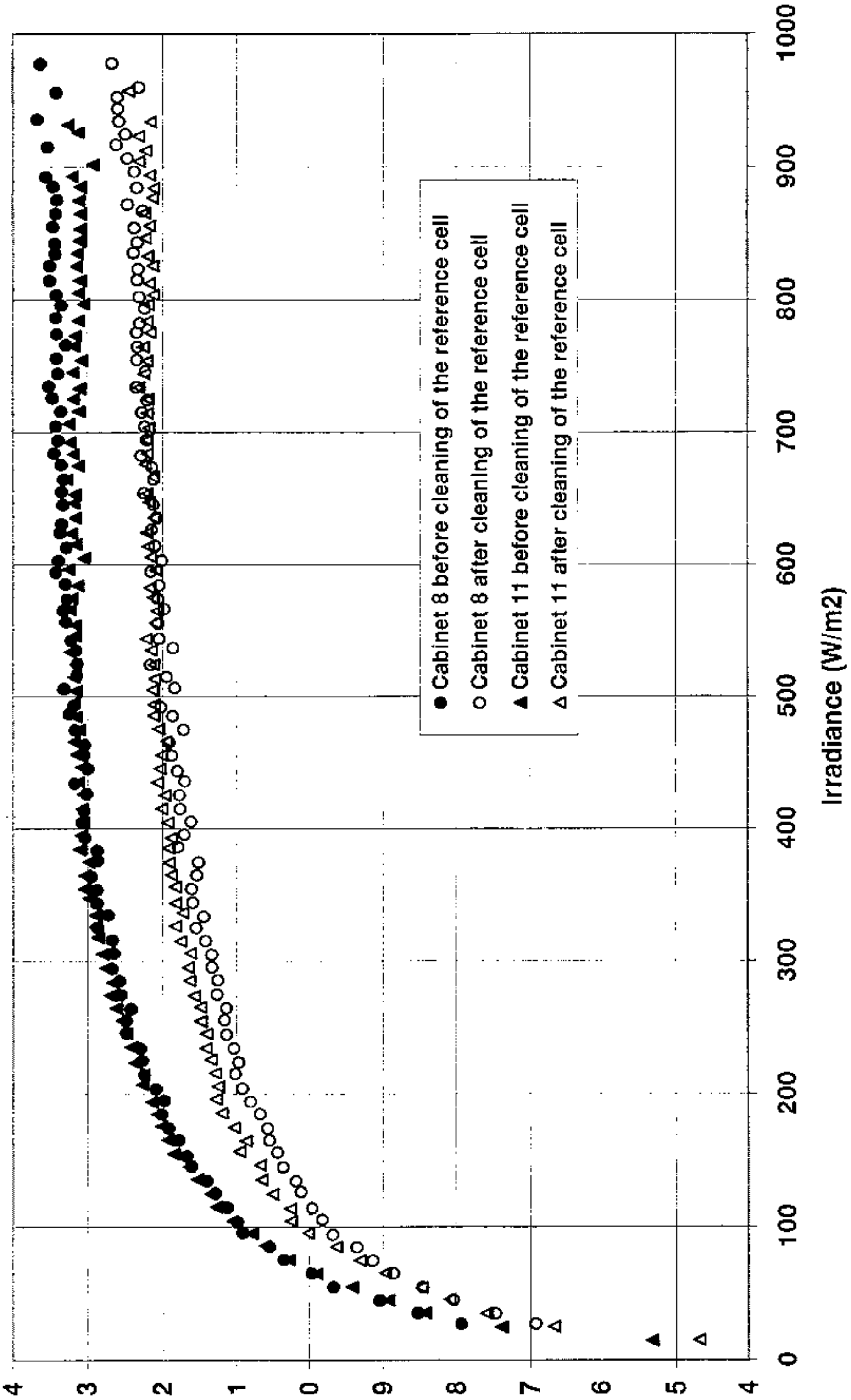

Figure 6: Effect of dust on the reference cells

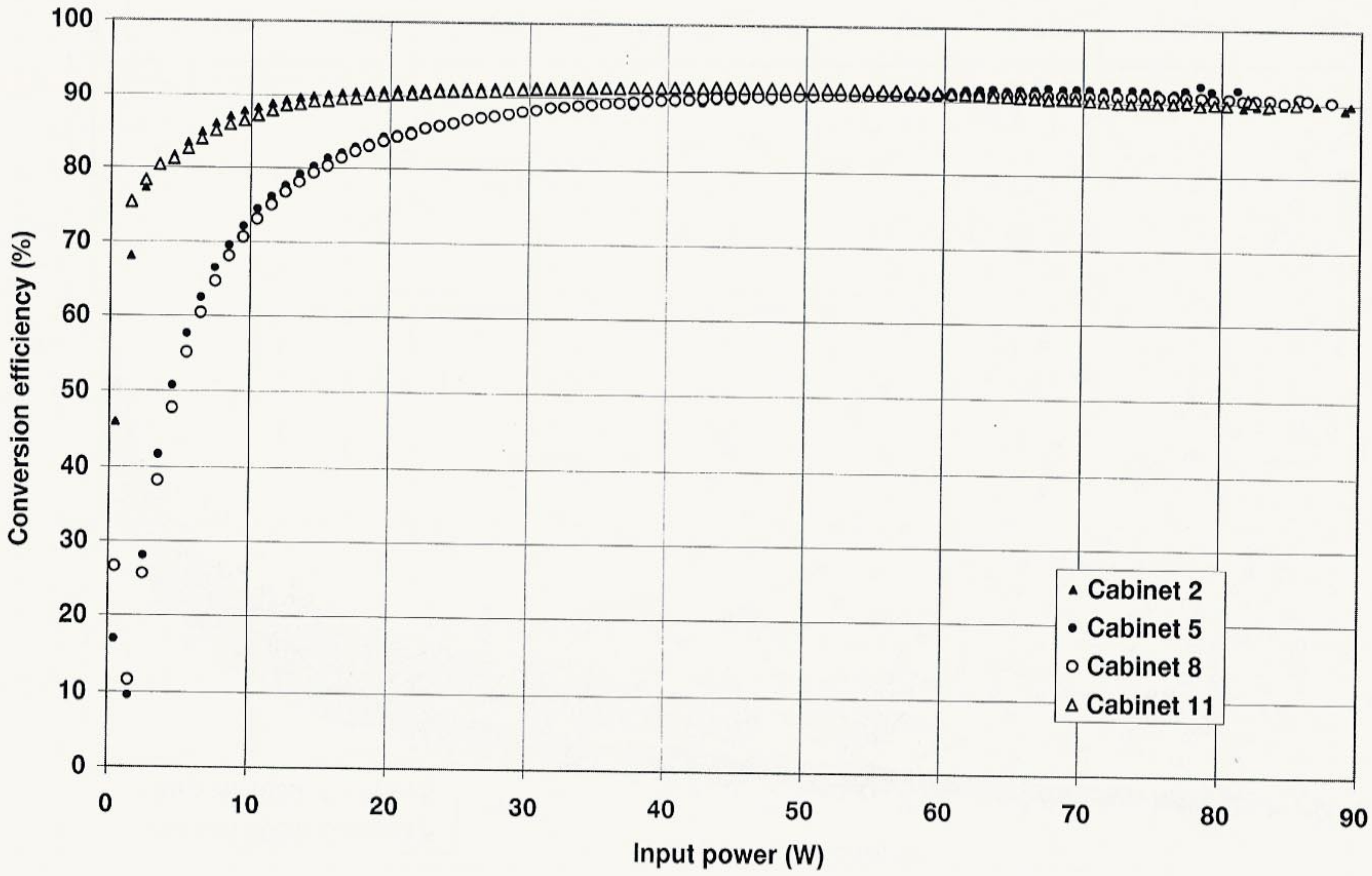

Figure 7: AC / DC conversion efficiency of the inverters

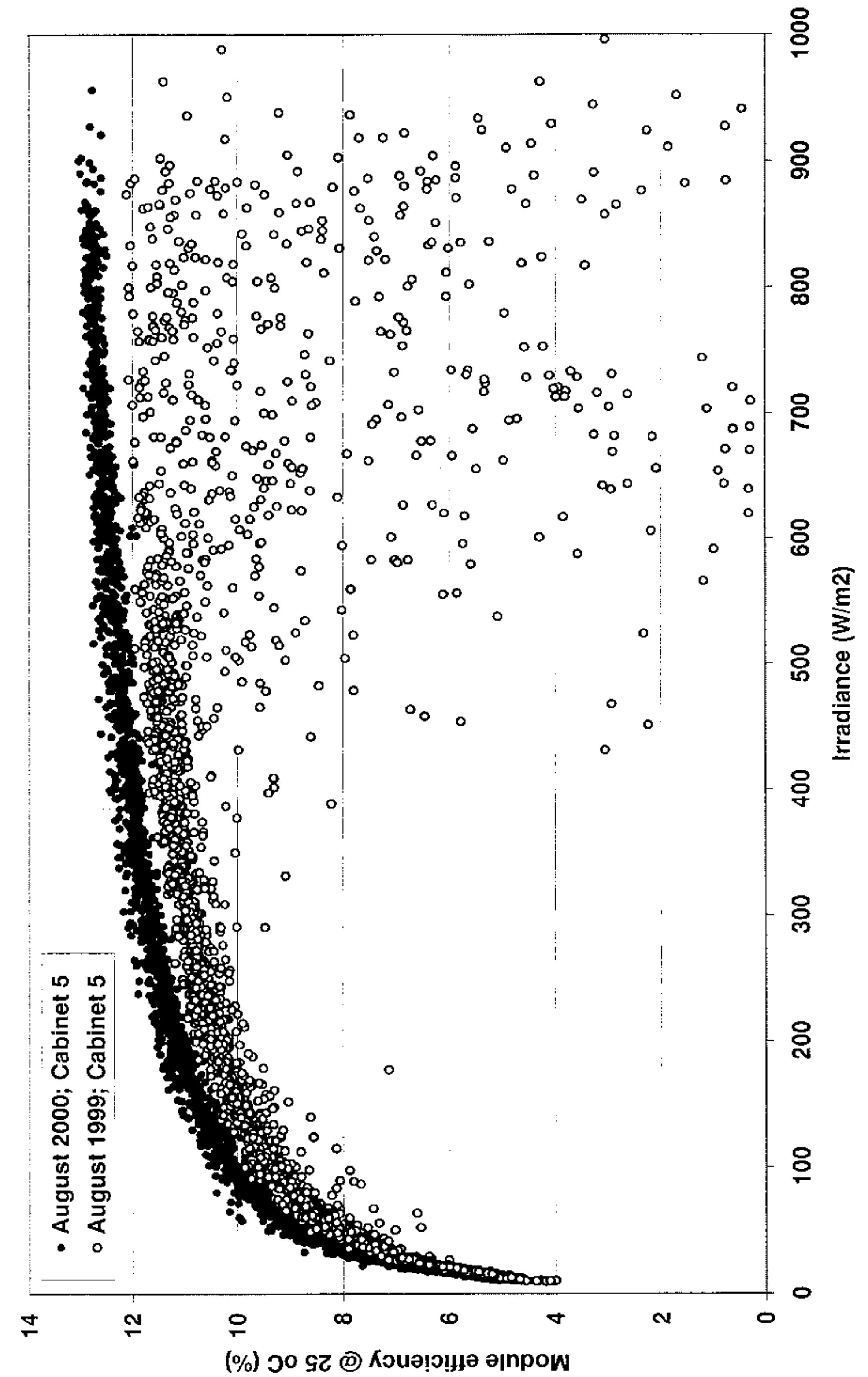

Figure 8: Illustration of dropouts due to grid interference

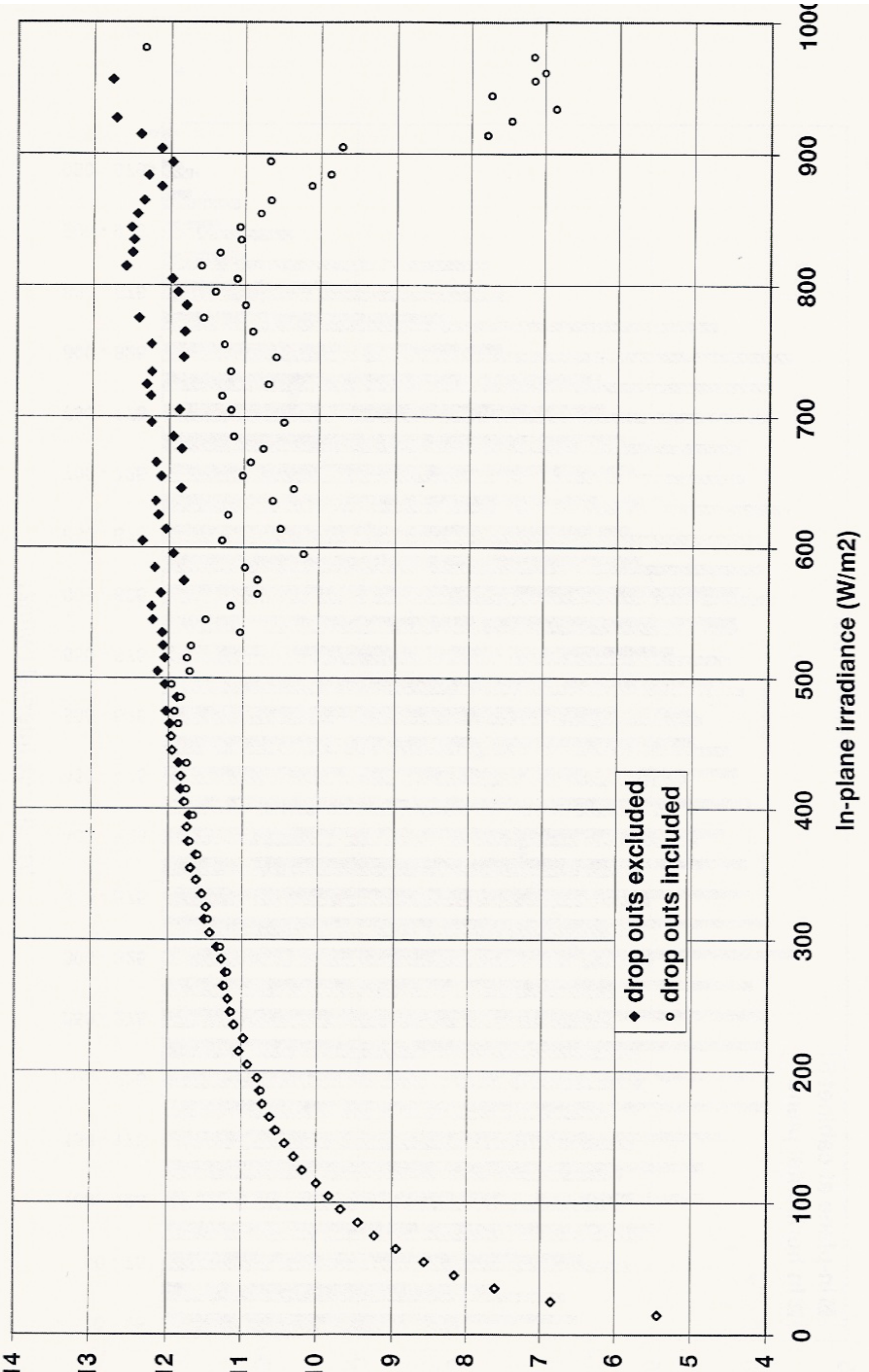

Figure 9: Effect of the grid interference on the module efficiency (cabinet 5)

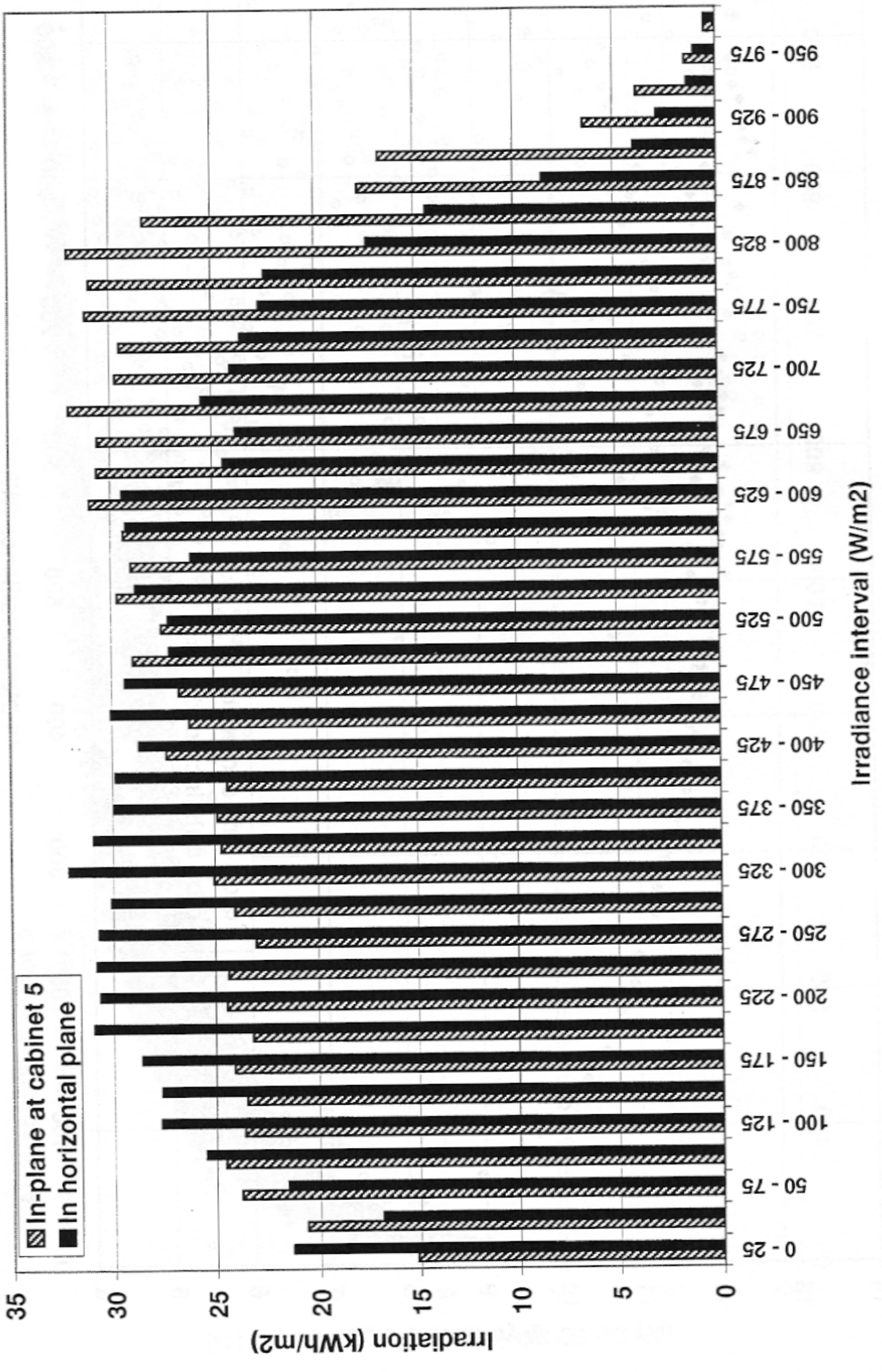

Figure 10: Annual distribution of irradiation

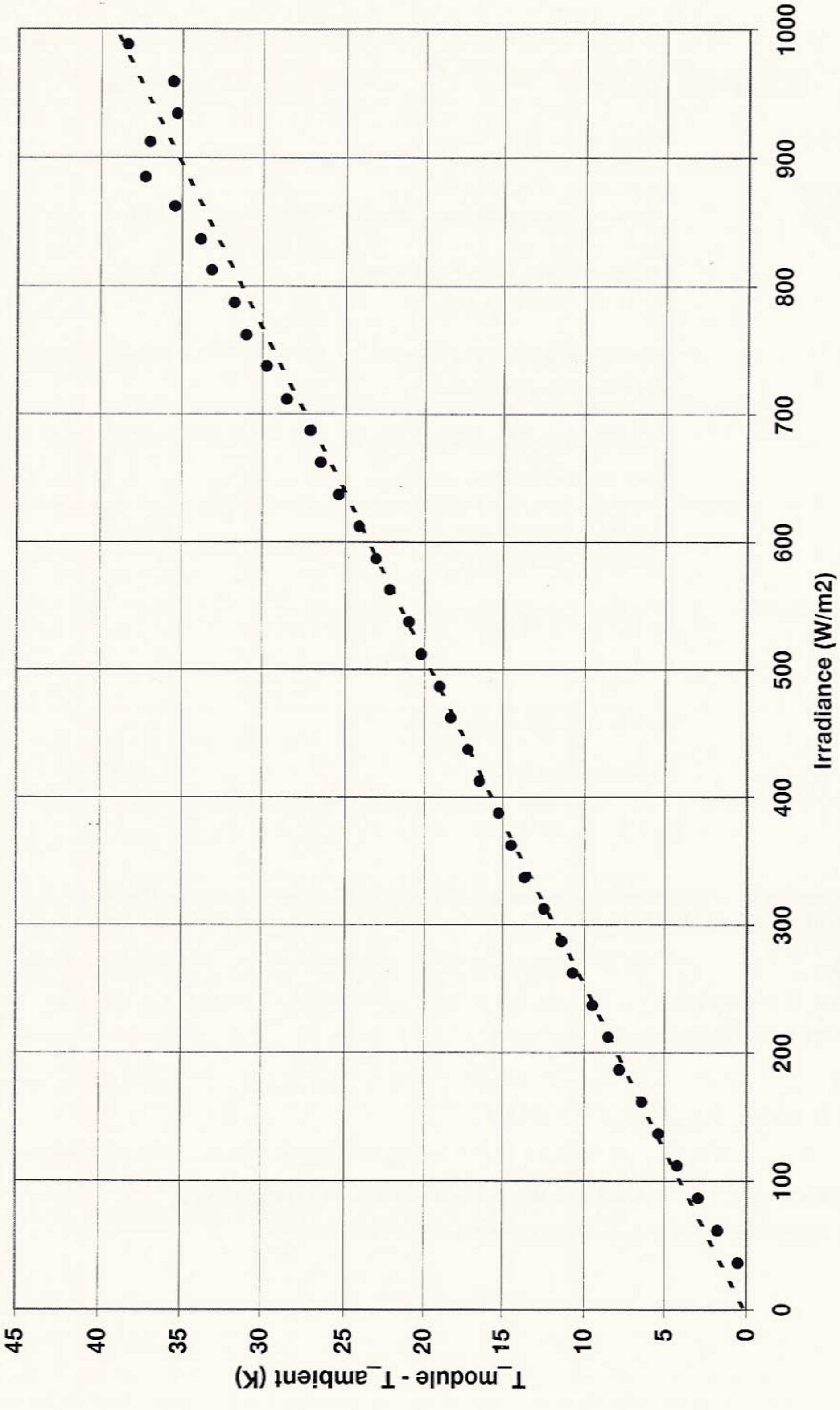

Figure 11: Influence of the irradiance on the module temperature

10. NOMENCLATURE

AC-energy	Output energy of the inverter	[Wh]
DC-energy (@ 25 ˚C)	Input energy of the inverter (corrected to a module temperature of 25 ˚C)	[Wh]
G_i	Irradiance in the plane of the module Measured with a reference cell	[W/m^2]
G_o	Irradiance in the horizontal plane Measured with a pyranometer	[W/m^2]
H_i	Irradiation in the plane of the module Measured with a reference cell	[Wh/m^2]
H_o	Irradiation in the horizontal plane Measured with a pyranometer	[Wh/m^2]
Module efficiency	DC-energy / (H_i * cell area) (see note 1)	[%]
P_{nom}	Module output power at STC & MPP (see note 2)	[W_p]
PR	Performance ratio (see note 3)	[%]
Y	Yield (see note 4)	[kWh/kWp]

Note 1
Following the Dutch recommended practices, the module efficiency is based on the cell area instead of the total module area.

Note 2
Standard Test Conditions (G_i = 1000 W/m^2, T_{module} = 25 ˚C; Air Mass 1.5 spectrum)
Maximum Power Point

Note 3
PR = (AC-energy / P_{nom}) / (H_i / 1000 W/m^2)

Note 4
AC-energy / P_{nom}, often defined for a period of a certain year or a reference year.

In The Netherlands a reference year corresponds to H_o = 1000 kWh/m^2.

11. APPENDIX

Appendix 1: Results of the supervision monitoring programme

! means defective combination of module, inverter and minitoring device; ? means no information

from	till	Cabinet	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
01-Dec-98	01-Jan-99	1								*!*																						
01-Dec-98	01-Jan-99	2																														
01-Dec-98	01-Jan-99	3																														
01-Dec-98	01-Jan-99	4																														
01-Dec-98	01-Jan-99	5																														
01-Dec-98	01-Jan-99	6																														
01-Dec-98	01-Jan-99	7																														
01-Dec-98	01-Jan-99	8																														
01-Dec-98	01-Jan-99	9																														
01-Dec-98	01-Jan-99	10									*!*																					
01-Dec-98	01-Jan-99	11																														
01-Dec-98	01-Jan-99	12																														

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
01-Jan-99	01-Feb-99	1								*!*																						
01-Jan-99	01-Feb-99	2																														
01-Jan-99	01-Feb-99	3																														
01-Jan-99	01-Feb-99	4																														
01-Jan-99	01-Feb-99	5																														
01-Jan-99	01-Feb-99	6																														
01-Jan-99	01-Feb-99	7																														
01-Jan-99	01-Feb-99	8																														
01-Jan-99	01-Feb-99	9													*!*																	
01-Jan-99	01-Feb-99	10									*!*																					
01-Jan-99	01-Feb-99	11																														
01-Jan-99	01-Feb-99	12																														

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
01-Feb-99	01-Mar-99	1								*!*																						
01-Feb-99	01-Mar-99	2																														
01-Feb-99	01-Mar-99	3																														
01-Feb-99	01-Mar-99	4																														
01-Feb-99	01-Mar-99	5																														
01-Feb-99	01-Mar-99	6																														
01-Feb-99	01-Mar-99	7																														
01-Feb-99	01-Mar-99	8																														
01-Feb-99	01-Mar-99	9					*!*																									
01-Feb-99	01-Mar-99	10									*!*																					
01-Feb-99	01-Mar-99	11																														
01-Feb-99	01-Mar-99	12																														

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
01-Mar-99	01-Apr-99	1								*!*																						
01-Mar-99	01-Apr-99	2																														
01-Mar-99	01-Apr-99	3															*!*															
01-Mar-99	01-Apr-99	4																				*!*										
01-Mar-99	01-Apr-99	5																														
01-Mar-99	01-Apr-99	6																														
01-Mar-99	01-Apr-99	7																														
01-Mar-99	01-Apr-99	8																														
01-Mar-99	01-Apr-99	9																														
01-Mar-99	01-Apr-99	10																														
01-Mar-99	01-Apr-99	11																														
01-Mar-99	01-Apr-99	12																														

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
01-Apr-99	01-May-99	1								*!*																						
01-Apr-99	01-May-99	2																														
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	Date: February 2001	**Number of report:** ECN-C--01-021

Title	Photovoltaic noise barrier at the A9-highway in the Netherlands Results of the monitoring programme
Authors:	N.J.C.M. van der Borg, M.J. Jansen
Principal(s)	NUON International/Duurzame Energie European Commission
ECN project number **Principal's order number**	7.4457 NUON: DE/EV/237 and DE/EV/300 EC: SE/068/97/NL/DE/CH
Programme(s)	NOZ-PV THERMIE

Abstract

A large photovoltaic energy system has been integrated into a noise barrier at the A9-highway near Ouderkerk aan de Amstel in The Netherlands. The PV-system consists of 720 AC-modules with inverters of type A and 1440 AC-modules with inverters of type B. The monitoring activities within the project are performed by ECN in co-operation with Fraunhofer ISE. This document describes the results of the monitoring programme during the first 2 years of operation. The main conclusions are:

- The AC-modules with type A inverters perform very well and have a low failure rate.
- The AC-modules with type B inverters perform less good and have a higher failure rate. The reasons of the lower performance are the lower inverter efficiency and the occurrence of grid interference. Modifications on the PV-system to prevent the grid interference are ongoing.
- Accumulated traffic dust on the modules causes significant energy losses.

The main recommendations are:

- Global monitoring should be continued for the assessment of the results of the modifications and for detecting possible failures in the future.
- Annual cleaning of the modules after the winter season should be considered.

Key words Photovoltaic, Noise barrier, Monitoring

Authorization	**Name**	**Signature**	**Date**
Checked	J.A. Eikelboom	[signature]	2-2-2001
Approved	J.A. Eikelboom	[signature]	2-2-2001
Authorized	W.C. Sinke	[signature]	12-2-2001