PERFORMANCE ASSESSMENT OF DIFFERENT PHOTOVOLTAIC SYSTEMS UNDER IDENTICAL FIELD CONDITIONS OF HIGH IRRADIATION

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***Abstract*— This paper presents the first year performance results and analysis of 14 grid connected photovoltaic (PV) systems under the weather conditions in Cyprus. The different PV technologies under test range from monocrystalline to multicrystalline and thin film technologies. As in all performance assessment practices of PV systems the results are provided according to their measured Performance Ratio (PR) and the Energy Yield (both dc and ac). Such evaluation of installed PV systems is very important in enhancing the efficiency in the quest for increased power production to be fed into the electricity grid. The use of these performance parameters further facilitates direct comparisons which are independent of geographic location of the installed systems. This is particularly important as in the scope of this project the same PV systems are installed in Germany and Egypt. Based on this background and by utilizing the acquired data from the sophisticated datalogging system installed, the performance ratio and energy yield of the installed systems has been evaluated and analyzed for the period of one year. The arrays under test have shown yearly energy yields (dc) between 1700 – 1800 kWh/kWp and energy yields (ac) between 1550 – 1650 kWh/kWp. Accordingly the PR (dc) was between 85% – 93% while the respective PR (ac) was between 77% - 85%.**

I. INTRODUCTION

The continuously increasing demand for energy and the high levels of dependence on fossil fuels impose high risks to humanity due to natural resource depletion and the obvious climate change. The concerns of generations and the widely accepted vision for a transition towards renewable and sustainable sources of energy have been attracting attention around the world. As a result, there is a growing interest and initiative towards the direction of stimulating the uptake of renewable technologies, with photovoltaics constituting a key technology especially in countries with high solar irradiation such as Cyprus. Solar irradiation in Cyprus is at the top for Europe. More than 300 days of the year provide good sunny weather and every square meter of Cyprus is estimated to collect around 1700 kWh/m^2 which is around 30% higher than the sunniest areas of the world's largest market, Germany.

The energy production of a photovoltaic system primarily depends on the weather conditions of the geographical location where the system is installed and on a number of other factors such as the orientation profile, and the power loss in wiring and inverters [1]. The possible PV potential, which is going to assist wider uptake of this technology, especially for countries of high solar irradiation can only be provided though the evaluation and detailed outdoor field analysis of the performance of different installed PV systems. Even though there have been a number of similar PV investigations worldwide [1-4] such a study is conducted for the first time in Cyprus and with such resolution. Parameters such as the energy yield and performance ratio have been used in order to enable comparisons to be made.

The annual PV system energy yield Y_F is defined as the total energy output E normalized to the nameplate dc power P_0, as provided by the manufacturer of each respective PV system. The value of energy can be either given as the energy of the dc or ac side. This parameter provides a very common way to compare the energy produced with respect to the installed system size from a number of systems of different size and the units characterizing this are hours or kWh/kWp [1].

$$Y_F = \frac{E}{P_0} \qquad (kWh / kW) \qquad (1)$$

Another useful parameter is the reference yield, Y_R, which represents the total in-plane irradiance H, normalized to the PV system's reference irradiance G. This parameter represents an equivalent number of hours of irradiation at the reference irradiance level which is given as 1kW/m^2 at Standard test Conditions (STC) of 25˚C, AM 1.5 and solar irradiation of 1kW/m^2. This is also defined as the number of peak sun hours or the solar radiation resource of the PV system. The reference yield is in general affected by the geographical location of the installation, the orientation of the array and the annual weather potential.

$$Y_R = \frac{H}{G} \qquad (hours) \tag{2}$$

In addition to the energy production by a PV system the performance of grid connected systems is further characterized by the performance ratio which is defined as the ratio of the measured system efficiency and the nominal efficiency of the PV modules. The performance ratio PR of a PV system is the value provided by dividing Y_F by the Y_R value. It is a useful way of quantifying the overall effect of losses due to the inverter, wiring, module mismatch and other losses such as PV module temperature, optical reflection, soiling and downtime failures.

$$PR = \frac{Y_F}{Y_R} \qquad (\text{dimensionless}) \tag{3}$$

Although the performance ratio gives a global idea of the system behaviour it is very difficult to use it as a tool to identify components that are not working properly and is thus provided on an annual basis. Large decreases in PR indicate events that significantly impact performance such as inverters not operating. Small decreases in PR indicate that a less severe problem exists.

The performance parameters considered in this work are described in Table 1.

TABLE I
IMPORTANT PERFORMANCE PARAMETERS

Abbreviation	Parameter Name	Unit	Range or Normalization
H	Irradiation Incident	kW/m^2	0 - 1.4
G	Irradiation (STC)	kW/m^2	1
T_{AM}	Ambient temperature	˚C	0 - 100
T_M	Module Temperature	˚C	0 - 100
WS	Wind speed	m/s	0 - 20
Y_R	Insolation of Ref yield	kWh/m^2	0 ~ 1.4/h
Y_A	DC yield	Wh/W_p	0 ~ 1.4/h
Y_F	AC yield	Wh/W_p	0 ~ 1.4/h
PR_{DC}	Performance Ratio (DC)	-	0 - 100%
PR_{AC}	Performance Ratio (AC)	-	0 - 100%

II. PV System Description and Measurement System

Below is the description of the PV systems installation and measurement system.

A. *PV Systems Description*

The PV Park, situated at the premises of the University of Cyprus, consists of 14 different PV technologies of 1 kWp peak power each. Twelve of the systems are fixed plate mounted, one is a two-axis tracking system and the last one is a new concentrator system by Concentrix. The PV park arrangement is shown in Fig 1. The total PV power capacity of the site is 15 kWp and the integration area is $101m^2$. Each system has its own inverter installed behind each respective system in close proximity. All inverters generate the sine wave required by converting the dc current generated by the PV modules to AC with the use of power electronics. The inverter inputs are connected to the respective DC bus of the PV arrays while the single phase outputs are uniformly distributed over the phases so as to feed a balanced three phase input to the utility electricity grid. The feed in point is located near the PV installation and total energy production monitoring is performed though a special installed meter box.

Fig. 1. Photovoltaic Park at the University of Cyprus.

The systems have been provided through the project PV-Yield, funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The same systems are installed in three different locations (Germany, Cyprus and Egypt). The technologies involved range from fixed system mono crystalline, multi crystalline silicon to amorphous thin film silicon, cadmium telluride (CdTe), $CuInGaSe_2$, HIT-cell and other solar cell technologies from a range of manufacturers such as BP Solar, Atersa, Sanyo, Solon, SunPower etc. A tracking system has also been installed as well as the latest GaAs concentrix technology covering the majority of the current and up coming PV technologies.

Before installation all modules have been tested and measured on a solar simulator at the *ipe* Stuttgart, however, normalization in the scope of this work is performed according to the manufacturer’s nameplate recommendations. Fig. 2 provides a description of the installation and measurement system layout.

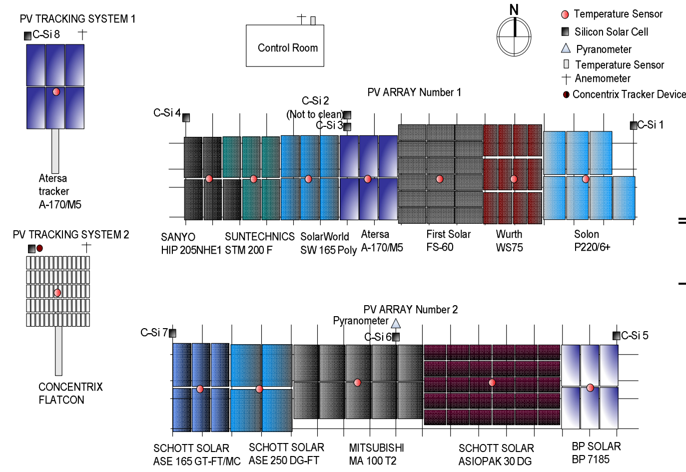

Fig. 2. Photovoltaic Park installation and measurement system layout plan.

The flat plate PV systems are installed at the optimum annual energy yield angle for Cyprus of 27.5° in an array configuration with most modules placed in series. The systems are installed in two arrays. In the first array there are five systems including the thin film technologies which occupy the largest area of the array while in the second row are seven PV technologies including the two high efficiency systems which require approximately $6m^2$ and only five modules to provide the same power output as the rest of the systems.

Fig. 3 shows the concentrating system at the University of Cyprus. The solar cell positioned exactly on the focal spot transforms the sunlight concentrated by the fresnel lens into electric power. By using tandem or triple solar cells a particularly high efficiency can be achieved [5].

Fig. 3. Concentrix Solar GmbH installed a concentrator demonstration installation in Cyprus in May 2006

Table 2 shows all the installed PV systems at the PV Park of the University of Cyprus including the manufacturer, module model, the technology and the installed power according to the respective manufacturer nameplate.

TABLE 2
PV SYSTEMS DESCRIPTION

Manufacturer	Model Name	Technology	Nameplate Installation Wp
Solon	P220/6+	Multi c-Si	1540
Sanyo	HIP-205NHE1	HIT	1025
Atersa	A-170M 24V	Mono c-Si	1020
Suntechnics	STM 200 FW	Mono c-Si	1000
Schott Solar	ASE-260-DG-FT	EFG	1000
BP Solar	BP7185S	Mono c-Si	1110
SolarWorld	SW165 poly	Multi c-Si	990
Schott Solar	ASE-165-GT-FT/MC	Multi c-Si Main	1020
Würth	WS 11007/75	CIS	900
First Solar	FS60	CdTe	1080
Mitsubishi	MA100T2	a-Si	1000
Schott Solar	ASIOPAK-30-SG	a-Si (tandem)	966
Atersa Tracker	A-170M 24V	Mono c-Si	1020
Concentrix	Flatcon	GaAs	898

B. PV Measurement system

In addition to the PV systems an advanced measurement platform is also installed to provide information of the performance of the modules. Measurements of power and energy can thus be obtained at the dc side which allows an insight of the operation of the PV modules. The electrical parameters of the PV systems are continuously monitored in accordance with the respective environmental conditions. The measurement system which comprises of a number of sensors and a central datalogging measurement system can acquire data at a sampling period of 1 second so that climatological and operational characteristics can be evaluated, stored and then analysed. The PV systems have been monitored for one full year starting from the 12th May 2006.

In this monitoring platform the following electrical and meteorological parameters are measured: dc voltage, dc current, dc and ac power, dc and ac energy yield. The meteorological measurement parameters include the Global Irradiation from a pyranometer, DNI (Direct Normal Irradiation) sensor and 8 c-Si solar cells, ambient temperature, module temperature, wind speed and wind direction. Data is collected in a large variety of formats and a database has been developed to convert and store the data in a common format for easy manipulation and comparison.

Primarily, information of the measurements is stored on the short term memory of the datalogging systems. Each night the data is then retrieved and records are further stored at a second's resolution and at fifteen minute's average values at two central database systems located both at the Institute of Physical Electronics and at the University of Cyprus. The data is further processed for validity on a daily basis.

Fig. 4. Monitoring System at Photovoltaic Park. Cables from all outdoor sensors are terminated at the central datalogging system which stores and sends the data to a central database both at the Institute of Physical Electronics in Stuttgart and the University of Cyprus.

Fig. 4 depicts the datalogging system utilized at the PV site. More specifically the data acquisition system installed (both sensors and datalogging equipment) is summarized in Table 3.

TABLE 3
DATA ACQUISITION AND INSTRUMENTATION

Variable Parameter	Sensor	Manufacturer	Model
Data Measurement	Datalogger	Delphin	TopMessage
Temperature Ambient	Temperature	Delta T	RHT2
Temperature Module	Temperature	PICO	PT-100
Global Irradiance	Pyranometer	Kipp Zonen	CMP 29
Direct Normal Irradiance	DNI Sensor	Kipp Zonen	CH 1
DC Voltage	DC Voltage	Potential Divider	Self Designed
DC Current	DC Current	Shunt Resistor	Self Designed

III. PV System Results

From previous work it is expected that the corresponding ac yields should roughly be 10% below the dc yields (8% that should be attributed to the inverter and the other 2% to cabling losses [4]). The conversion losses (dc to ac), are considered equal for all systems as they utilize the same type of inverters and the average conversion energy loss as found in this analysis was 157.75 kWh, approximately 8.77% of the total average energy yield of all modules.

Malfunctions or defects that had occurred during the one year period under investigation were carefully corrected with most of these problems attributed to inverter breakdown. Nevertheless, the inverter related problems during the one year period were minimal, highlighting the improvements in reliability over the years.

Outage events were carefully accounted for by applying corrections to the measurements of the affected systems always taking into consideration the weather conditions during the outage and the effect it had on the annual energy yield.

A. *PV Array Energy Yield*

Table 4 and Fig. 5 and 6 give the results of the annual energy output from the different systems. The energy yield for the concentrating system has not been included in this work.

TABLE 4
ANNUAL ENERGY YIELD

System Name		Size (Wp)	Y_F (dc) (kWh/kWp)	Y_F (ac) (kWh/kWp)
System 1	Solon	1540	1730	1582
System 2	Sanyo	1025	1810	1650
System 3	Atersa	1020	1768	1608
System 4	Suntechnics	1000	1880	1709
System 5	Schott Solar	1000	1736	1578
System 6	BP Solar	1110	1631	1482
System 7	SolarWorld	990	1701	1590
System 8	Schott Solar	1020	1767	1603
System 9	Würth	900	1845	1671
System 10	First Solar	1080	1774	1618
System 11	Mitsubishi	1000	1744	1600
System 12	Schott Solar	966	1705	1551
System 13	Atersa Tracker	1020	2268	2069
System 14	Concentrix	898	NM*	NM*

NM* Not Measured in the scope of this work

The ac energy distribution yield of the different PV systems for most systems is within the interval of 1600 and 1700 kWh/kWp. Only six systems fall below 1600 kWh/kWp. The ac average energy yield of all the systems is 1639 kWh/kW_p while at the dc side the average energy yield is 1796 kWh/kW_p.

The new PV systems which are specially manufactured to provide extra efficiency such as the Suntechnics with back contact, Sanyo HIT (Heterojunction Intrinsic Thin Film) technology, provide high energy yields. Thin film technologies with modules of Copper Indium Diselendide (CIS) and Cadmium Telluride (CdTe) have also shown high energy yields. It must also be stated that in the case of thin film technologies such as a-Si there is always a higher first year yield result until the material stabilizes.

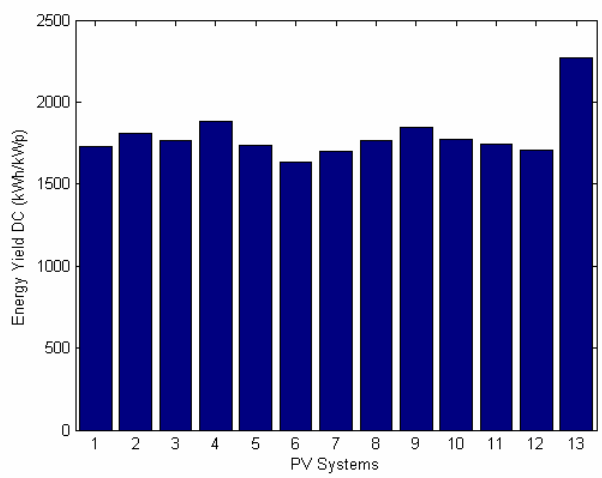

Fig. 5. DC energy yield measured for each system.

At the same period the tracker has shown an energy yield 26% higher than the average energy yield of all modules.

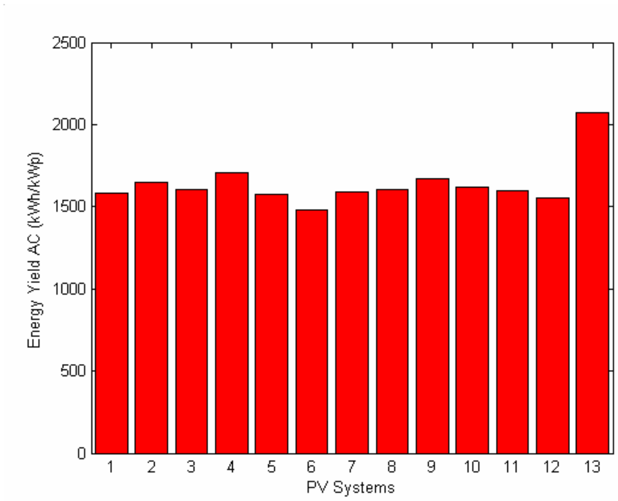

Fig. 6. AC energy yield measured fro each system.

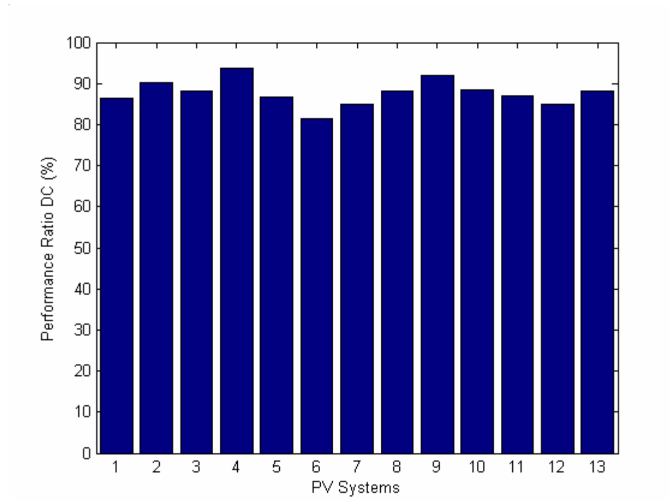

Fig. 7. DC performance ratio measured for each system.

B. PV Array Performance Ratio

Since all PV systems are optimized for maximum annual yield at an inclination angle of 27.5˚ (except from the tracking systems) the comparison between performance and energy yield can be directly undertaken. Fifteen minute averages of data measured at a resolution of a second are used for this analysis to provide the total irradiance at the plane of array as registered using the pyranometer. The total irradiation at the angle of 27.5˚ was measured to be 2005 kWh/m^2. Furthermore the measured total irradiation from the silicon solar cell installed on the tracker was 2569 kWh/m^2.

Performance ratio both dc and ac and system yield are summarized in Table 5 and Fig. 7 and 8.

TABLE 5
PERFORMANCE RATIO (DC AND AC)

System Name		Size (Wp)	PR (DC)	PR (AC)
System 1	Solon	1540	86%	79%
System 2	Sanyo	1025	90%	82%
System 3	Atersa	1020	88%	80%
System 4	Suntechnics	1000	94%	85%
System 5	Schott Solar	1000	87%	79%
System 6	BP Solar	1110	81%	74%
System 7	SolarWorld	990	85%	79%
System 8	Schott Solar	1020	88%	80%
System 9	Würth	900	92%	83%
System 10	First Solar	1080	88%	81%
System 11	Mitsubishi	1000	87%	80%
System 12	Schott Solar	966	85%	77%
System 13	Atersa Tracker	1020	88%	81%
System 14	Concentrix	898	NM	NM

A direct comparison between the Performance Ratio of all systems shows that the PR for most systems is within the range of 85% - 93%. In this particular comparison it is obvious that the PV systems which provided the highest energy yield also had the highest PR values.

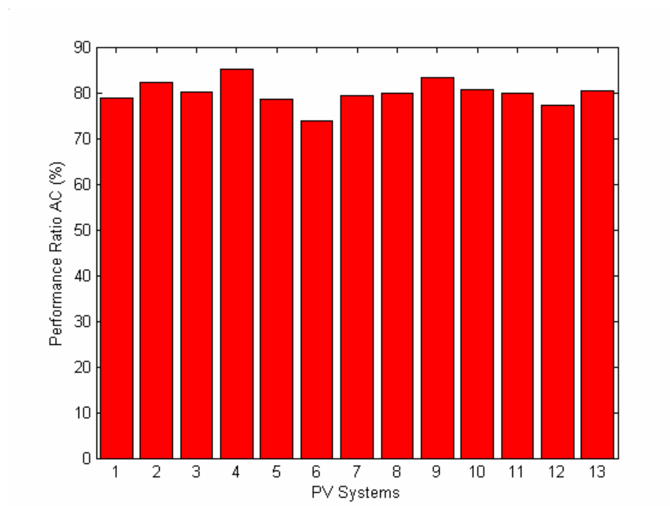

Fig. 8. AC performance ratio measured for each system

Within the scope of the comparison between the systems it is very important to emphasise that a consumer must also consider the size (surface area) and price of each system so as to decide which is more suitable. Information on the size of each 1 kWp system and their respective efficiencies is summarized in Table 6.

TABLE 6
PV SYSTEMS INFORMATION FOR 1 KWP

PV System	Number Modules	Size (m^2)	Efficiency Nameplate	Technology
Solon	7	11.50	13.39%	multi c-Si
Sanyo	5	6.26	16.36%	HIT
Atersa	6	7.90	12.91%	mono c-Si
Suntechnics	5	6.22	16.09%	mono c-Si
Schott Solar	4	8.58	11.66%	EFG
BP Solar	6	7.52	14.77%	mono Saturn
SolarWorld	6	7.82	12.65%	poly c-Si
Schott Solar	6	7.87	12.96%	multi-Si MAIN
Würth	12	8.75	10.29%	CIS
First Solar	18	12.96	8.33%	CdTe
Mitsubishi	10	15.74	6.35%	a-Si
Schott Solar	30	18.00	5.37%	a-Si (tandem)
Atersa Tracker	6	7.90	13.39%	mono c-Si
Concentrix	70	6.30	23.5%	Concentrating

It is worth noting that the PR as such does not represent the amount of energy produced because a system with a low PR in a high solar resource location might produce more energy than a system with a high PR in a low solar resource location.

In addition, the increased module temperature that is observed in Cyprus is an important loss mechanism. Fig 9 below shows a typical daily measurement in August. It is clearly shown that the module temperature increases, especially near midday reaching temperatures in excess of 60˚C.

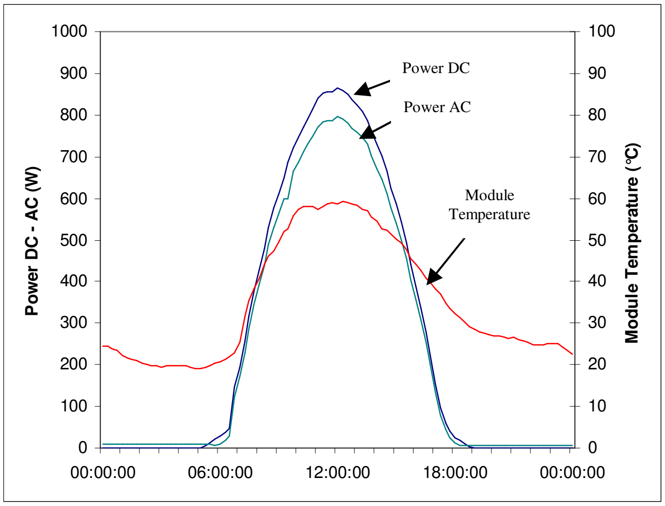

Fig. 9. DC-power, AC power and module backside temperature over the course of a sunny day in Cyprus (10th of August 2006) for PV System 2 (Sanyo).

Better performance and energy yield can also be registered with a combination of regular maintenance (immediate cleaning of soiling). In the above measurements the modules were cleaned at a six month period.

It is estimated that in the near future crystalline PV modules will continue to dominate this market segment due to the fact that in most installation cases there is a limited roof area which accordingly necessitates modules with high efficiency. However once the first thin film modules with efficiencies up to 10% become available which is expected by 2008 then many monocrystalline modules with low efficiency will come under pressure maintaining their market share [6].

IV. Conclusion

Grid connected PV systems and monitoring systems are installed at the University of Cyprus and their performance is analysed and evaluated.

The results of this investigation of the first year results clearly show that solar irradiation in Cyprus is easily transformed into high energy yields and the average yield under the climatological conditions in Cyprus was between 1600 to 1700 kWh/kWp.

The work is expected to reveal the best performing technologies for the particular conditions in Cyprus and thus it will enable improved efficiencies to be obtained. Finally in order to further encourage activities within this field and provide a complete picture of the performance of the installed PV systems, future work will include additional measurements for verification of the several loss parameter factors, and identification of areas of improvement of system performance.

Acknowledgment

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Jürgen H. Werner is currently the Director of the Institute of Physical Electronics (*ipe*) at the University of Stuttgart and widely accepted as a pioneer in the field of PV. He earned his diploma degree in 1979 from the University of Tübingen and received his Ph.D. from the University of Stuttgart in 1983. His PhD thesis work on grain boundaries in silicon at the Max-Planck-Institute for Solid State Research, received the Otto-Hahn-Medal of the Max-Planck-Society, in recognition for the quality of his work. Between 1985-1987 he spent two years in the United States as a guest scientist at the IBM T. J. Watson Research Center and AT&T Bell Laboratories, Murry Hill, working on Schottky diodes. In 1987 he was offered a position as a permanent scientist at the Max-Planck-Society and in 1991 he received the habilitation from the University of Munich. During these years, his research concentrated on semiconductor interfaces. In 1996 he became the director and full professor of the Institute for Physical Electronics. Prof. Werner is author and co-author of over 230 publications, the editor of nine books and has more than 30 invited papers at prestigious international conferences.