# TEMPERATURE AND INTENSITY DEPENDENCE OF TWELVE PHOTOVOLTAIC TECHNOLOGIES

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ABSTRACT: In close cooperation with the University of Cyprus, the Universität Stuttgart operates two identical sets of similar photovoltaic (PV) systems of different technologies at the locations Stuttgart (Germany) and Nicosia (Cyprus) since 2006. This paper analyzes the temperature and irradiance dependence of the twelve installed PV technologies. Performance data of the year 2007 are normalized and fitted to determine the temperature and irradiance coefficients at the maximum power point (mpp) of the PV generators. At high temperature as well as under low light conditions, the two thin film technologies of amorphous silicon and CdTe present the best relative performance. Crystalline silicon technologies exhibit almost similar coefficients of their temperature ($\gamma_{Pmpp}$ = ~-0.5 %/K) and irradiance dependence. The total energy yield of the PV systems during the year 2007, however, shows no discernible effect of temperature and irradiance coefficients of the different technologies.
Keywords: Energy Performance, Thermal Performance, Irradiance Performance

## 1 INTRODUCTION

Photovoltaics (PV) offers a high potential of contributing to the power supply of the world. At present, many different PV technologies share the market, or attempt to enter it. Especially investors want to know how much energy each of the PV technologies produces, and which is the best technology for a specific application and location. This paper determines the dependence of each PV technology on temperature and irradiance under different climatic conditions, especially in Southern countries with much higher insolation than in Middle Europe. One of our objectives is to check, if thin film technologies perform better in southern climates, due to their lower temperature coefficient and their better low light behavior.

## 2 THE PV SYSTEMS

Since June 2006, the Institut für Physikalische Elektronik (*ipe*) of the Universität Stuttgart operates twelve fixed mounted photovoltaic systems of different technologies (monocrystalline, multicrystalline, amorphous silicon, CdTe, $Cu(InGa)Se_2$) in Stuttgart, Germany and in Nicosia, Cyprus. Figure 1 shows photographs of the PV systems. Table I lists the PV technologies and manufacturers. Each system has a size of approximately 1 $kW_p$ and is equipped with the same type of inverter to exclude the effect of different maximum power point (MPP) tracking methods on the DC yield.

**Figure 1:** PV systems on top of the university building in Stuttgart (left), and at the university campus in Nicosia (right).

**Table I:** PV technologies examined in this paper.

| manufacturer | module type | technology |
|---|---|---|
| **monocrystalline** | | |
| Atersa | A-170M 24V | monocrystalline silicon |
| BP Solar | BP7185S | monocrystalline silicon (saturn-cell) |
| Sanyo | HIP-205NHE1 | monocrystalline silicon (HIT-cell) |
| Suntechnics | STM 200 FW | Sunpower monocrystalline silicon (back contact-cell) |
| **multicrystalline** | | |
| Schott Solar | ASE-165-GT-FT/MC 170 | multicrystalline silicon (MAIN-cell) |
| Schott Solar | ASE-260-DG-FT 250 | multicrystalline EFG silicon |
| SolarWorld | SW165 poly | multicrystalline silicon |
| Solon | P220/6+ | multicrystalline silicon |
| **thin film** | | |
| Mitsubishi | MA100T2 | amorphous silicon (single-cell) |
| Schott Solar | ASIOPAK-30-SG | amorphous silicon (tandem-cell) |
| First Solar | FS60 | cadmium telluride (CdTe) |
| Würth | WS 11007/75 | cooper-indium-gallium-diselenide (CIGS) |

A system for extensive data acquisition logs all relevant PV system and weather data. All data are recorded every second with a high accuracy to allow later analyses with a high temporal resolution. Nevertheless, this investigation relies on 15-minute averages of the acquired data. A previous paper presented details of the PV systems and the data acquisition setup [1].

## 3 CLIMATIC CONDITIONS

The most important factor for the energy yield of a PV system is the amount of solar irradiation, of course. The second important parameter is the module operating temperature. Figures 2 and 3 show the distribution of the irradiated energy $H = \Sigma G$ of the sun as a function of the irradiance $G$ and of the resulting module temperature $T_{mod}$. As expected, the distribution of $H$ in dependence on $G$ and $T_{mod}$ are shifted to higher levels in Nicosia.

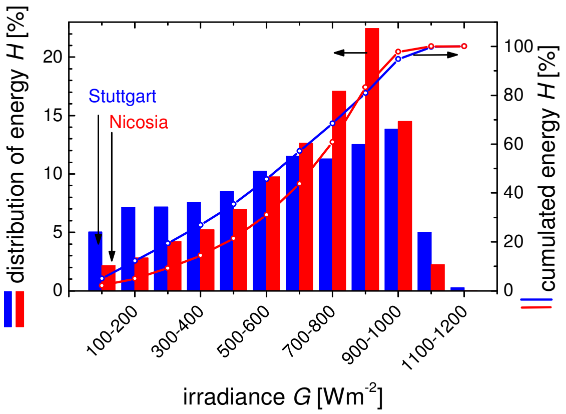


**Figure 2:** Bar chart shows the percentage of the annual (year 2007) irradiated energy $H$, harvested in the plane of modules over $G$ in intervals of 100 Wm$^{-2}$. At both locations most of the energy is received at high irradiation levels. About 50 % of the annual irradiation $H$ in Stuttgart is received for irradiance $G > 640$ Wm$^{-2}$, and in Nicosia for $G > 740$ Wm$^{-2}$. In Stuttgart the low light fraction is much higher than in Nicosia.

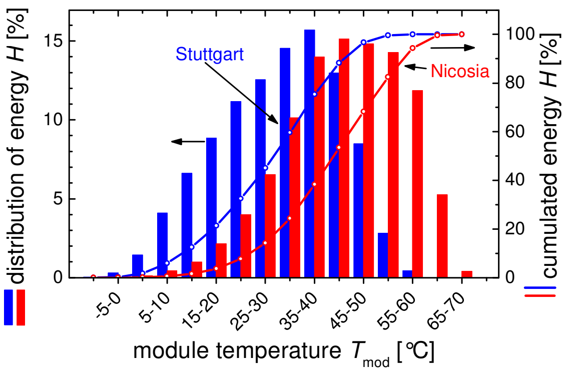


**Figure 3:** Bar chart shows the percentage of the annual (year 2007) irradiated energy $H$, harvested in the plane of modules over $T_{mod}$ in intervals of 5 K. At both locations, most of the energy is received for $T_{mod} > 25$ °C. In Cyprus, the module temperature is approximately 12 K higher than in Germany.

## 4 COUPLED DEPENDENCIES

The electrical power

$$P = G\,A\,\eta(T_{mod}, G) \tag{1}$$

of a PV module can be calculated with the efficiency η, the area $A$, and the irradiance $G$. In general, the efficiency η depends on the module temperature $T_{mod}$ and on the irradiance $G$. In field operation, many different combinations of $T_{mod}$ and $G$ occur, whereas the Standard Test Conditions (STC: $G$ = 1000 Wm$^{-2}$, $T_{mod}$ = 25 °C, $AM$ = 1.5) are very rare and not sufficient to predict the annual energy yield of a PV system. To get a better idea of the performance of the PV systems, we must investigate the temperature and irradiance effects on the energy yield.

## 5 TEMPERATURE DEPENDENCE

Most of the temperature dependence of $P$ is due to linear voltage drop at higher temperature. The temperature effect on the current $I$ is one order of magnitude lower and neglected. King et al. revealed [2], that a difference in irradiance between 100 and 1000 Wm$^{-2}$ will change the temperature coefficient γ by less than 5 %. Whitaker et al. [3] found out, that the temperature coefficient becomes lower and could also change its sign at low irradiation. This paper determines the temperature coefficient γ at $G$ = 1000 Wm$^{-2}$ as it is done for the data sheets of PV modules.

Since the output power $P$ is directly proportional to the irradiation $G$, the first step of our analysis is a linear normalization of the power values to $G$ = 1000 Wm$^{-2}$. As the temperature coefficient $\gamma_{Pmpp}$ also depends on irradiance [2, 3], we only use data points within 950 Wm$^{-2}$ < $G$ < 1050 Wm$^{-2}$ to determine the temperature coefficient. Figure 4 shows these data plotted and fitted for extracting the coefficient. Figure 5 compares the different PV technologies in Nicosia, whereas Table II presents all results for Stuttgart and Nicosia.

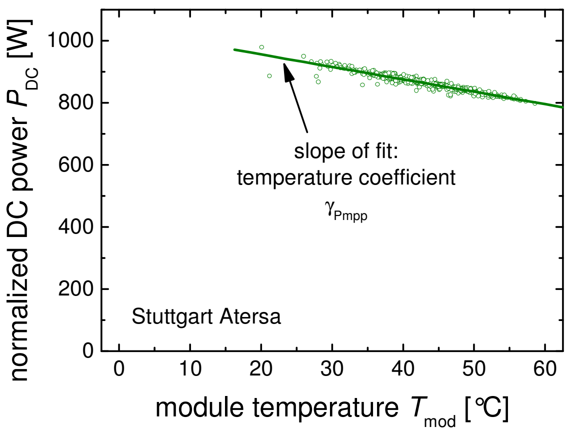


**Figure 4:** DC power output of the Atersa monocrystalline Si system in Stuttgart. Only data within 950 Wm$^{-2}$ < $G$ < 1050 Wm$^{-2}$ are plotted here. A linear fit to this data set yields the temperature coefficent $\gamma_{Pmpp}$ = -0.4 % K$^{-1}$.

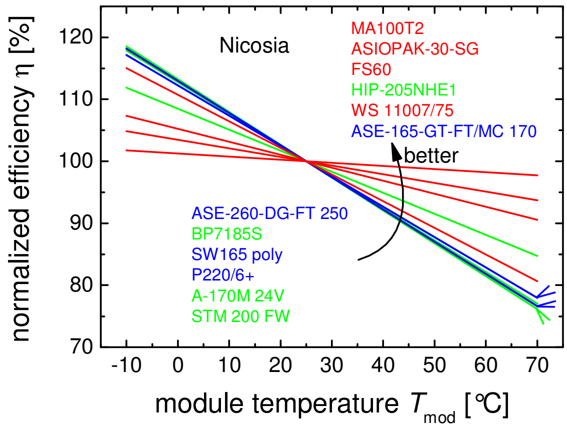


**Figure 5:** Comparison of the temperature coefficients in Nicosia. Some of the lines lie on each other. Thin film technologies perform better at high temperatures. Most crystalline Si modules have almost the same temperature coefficent ($\gamma_{Pmpp}$ = ~-0.5 %/K).

**Table II:** Temperature coefficients γ and irradiance coefficients δ of the output power of the PV systems. The values are evaluated from one year (2007) field operation. The numbers in *italics* have an uncertainty due to temporary measurement faults.

| module type | temperature coefficient $\gamma_{Pmpp}$ [%/K] Stuttgart | temperature coefficient $\gamma_{Pmpp}$ [%/K] Nicosia | irradiance coefficient δ [W(Wm$^{-2}$)$^{-1}$] Stuttgart | irradiance coefficient δ [W(Wm$^{-2}$)$^{-1}$] Nicosia |
|---|---|---|---|---|
| **monocrystalline** | | | | |
| A-170M 24V | -0.40 | -0.53 | 0.034 | 0.031 |
| BP7185S | -0.40 | -0.51 | -0.003 | 0.021 |
| HIP-205NHE1 | -0.25 | -0.34 | -0.038 | -0.044 |
| STM 200 FW | -0.40 | -0.53 | 0.015 | 0.040 |
| **multicrystalline** | | | | |
| ASE-165-GT-FT/MC 170 | -0.39 | -0.49 | 0.004 | 0.019 |
| ASE-260-DG-FT 250 | *-0.36* | -0.49 | *0.064* | 0.068 |
| SW165 poly | -0.42 | -0.52 | 0.028 | 0.060 |
| P220/6+ | *-0.39* | -0.52 | *0.015* | 0.009 |
| **thin film** | | | | |
| MA100T2 | -0.02 | -0.05 | -0.072 | -0.095 |
| ASIOPAK-30-SG | *-0.07* | -0.14 | *-0.151* | -0.345 |
| FS60 | -0.04 | -0.21 | -0.163 | -0.129 |
| WS 11007/75 | -0.35 | -0.43 | 0.158 | 0.162 |

Remarkable is that the temperature coefficients are generally lower in Stuttgart than in Nicosia. In Nicosia, the coefficients from field data compare well with data sheet values and with an evaluation by Makrides [4]. Figure 5 shows that the thin film modules exhibit a favorable temperature dependence.

## 6 IRRADIANCE EFFECT

The efficiency of the PV modules depends on the irradiation level, too, due to several reasons: The operating voltage has a logarithmic dependence on irradiance. Parallel resistance losses are almost constant as the voltage is approximately constant, but the relative effect can be significantly different. The losses $P_{loss}$ at the series resistance $R_S$ increase quadratically ($P_{loss} = R_S I^2$) with the current $I$, which is linearly dependent on $G$. In amorphous silicon, the recombination dependence on irradiance, which reflects in the fill factor, is sligthly sublinear.

This paper, however, employs a simple linear approximation of all effects of the irradiation on efficiency. Figure 6 shows the DC power normalized to an irradiance of $G$ = 1000 Wm$^{-2}$ during the year 2007. As temperature is the second most important parameter, figure 7 shows the same data normalized to $T_{mod}$ = 25 °C in addition, using the field temperature coefficients from table II. Thereby the scatter plot clearly narrows.

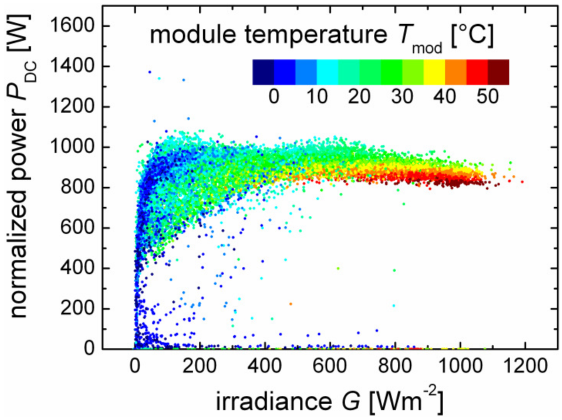


**Figure 6:** DC power output of the Atersa monocrystalline Si system in Stuttgart normalized to $G$ = 1000 Wm$^{-2}$. Power decreases at high irradiation due to elevated module temperature. At low irradiation levels, the change in Air Mass and the reflectance of the module cover glass decrease power output.

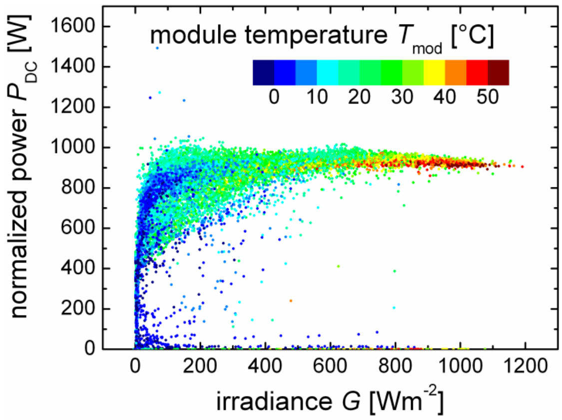


**Figure 7:** DC power output of the Atersa monocrystalline Si system in Stuttgart normalized to $G$ = 1000 Wm$^{-2}$ and to $T_{mod}$ = 25 °C. By taking the thermal effects into account, the scatter of the field data significantly drops, in contrast to the uncorrected data of Fig. 6.

Figure 8 shows the same data as Fig. 7 but only in the module temperature range around STC (20 < $T_{mod}$ < 30 °C). Furthermore, data at flat incidence angles are cut off to exclude the effect of transmission losses in the front glass. Krauter [5] calculated the transmittance of the glass of a solar module in dependence of the angle of incidence. For angles θ measured to the normal of the glass, with θ < 45° the transmittance is > 99 %. Between θ = 60° and 90° the transmittance goes down to 0 % very fast. A linear fit to the data gives the irradiance coefficient δ. Table II shows the results for all systems and Figure 9 shows them graphically for Nicosia.

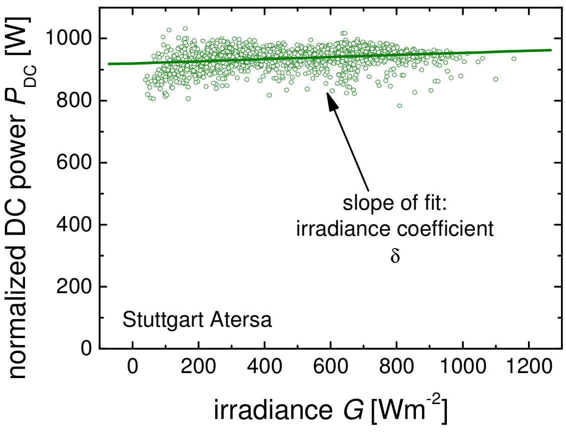


**Figure 8:** DC output power of the Atersa monocrystalline Si system in Stuttgart normalized to $G$ = 1000 Wm$^{-2}$ and $T_{mod}$ = 25 °C. Data filtered to 20 °C < $T_{mod}$ < 30 °C, angle of incidence θ < 45°. The linear fit gives an irradiance coefficient of δ = 0.034 W(Wm$^{-2}$)$^{-1}$.

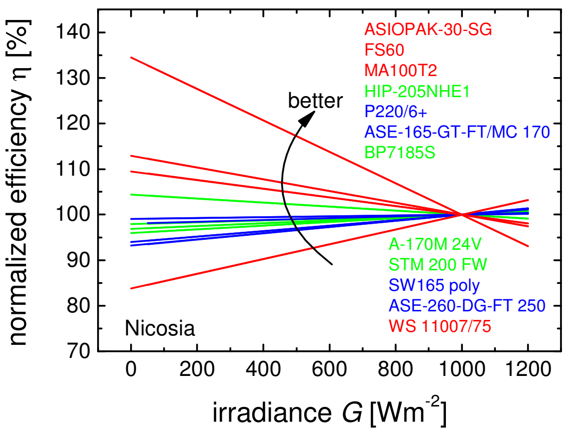


**Figure 9:** Comparison of the irradiance dependence in Nicosia. Amorphous silicon and CdTe modules have higher relative efficiencies at low light.

## 7 EFFECT ON ANNUAL YIELD

Figure 10 shows the annual yield for each PV system. The general opinion would expect that modules with low temperature coefficients perform well in the hotter Nicosia and modules with good low light behavior perform well in the cloudier Stuttgart.

Surprisingly this is not true in many cases. The CIGS module is the weakest in irradiance dependence, but presents the best yield in Stuttgart. Even its temperature behavior is not the best, but it has a good yield in Nicosia. The amorphous Si and CdTe thin film modules exhibit the best temperature behavior, but their annual yield is not over average in Nicosia. The back contact cell from Sunpower has the weakest temperature and low light performance of the monocrystalline Si, but it demonstrates the best yield in Nicosia. The HIT cell from Sanyo presents the best temperature and low light behavior of all crystalline Si cells and an over average yield in Nicosia. Therefore, the HIT cell supports the general opinion, but the others do not.

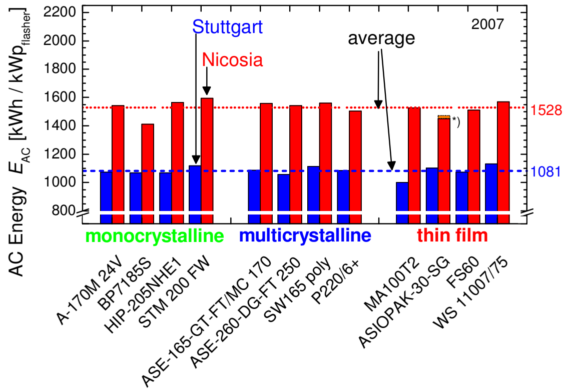


**Figure 10:** AC energy yield of the 12 fixed systems in Stuttgart and Nicosia in 2007. The values are normalized to [kW$_p$] using the flasher data of the manufacturer. *) At this system a module was damaged, after mathematic correction the yield lies in the orange box.

## 9 CONCLUSION

This paper has analyzed the temperature and irradiance dependence of twelve different PV technologies. It shows that the annual energy yield does not significantly correlate with the temperature coefficient $\gamma_{Pmpp}$ determined at $G$ = 1000 Wm$^{-2}$ and the irradiance coefficient δ determined at $T_{mod}$ = 25 °C. Effects like the dependence of the temperature coefficient on irradiance, and the dependence of the irradiance coefficient on temperature, or spectrum changes also affect the annual energy yield and need further detailed investigation.

## 10 ACKNOWLEDGMENTS

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