Zonneweide performance study

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1 Introduction

1.1 The Zonneweide

The Zonneweide is a test field for various PV technologies and is part of the ACRRES research facility of the Wageningen UR. The solar test field consists of eleven different systems, ranging from fixed tilt systems, adjustable systems and trackers. Furthermore, three different PV technologies a-Si, c-Si and CIS are included and their performance is investigated. A top view of the systems is visualized in figure 1. Details about each system are given in table 1:

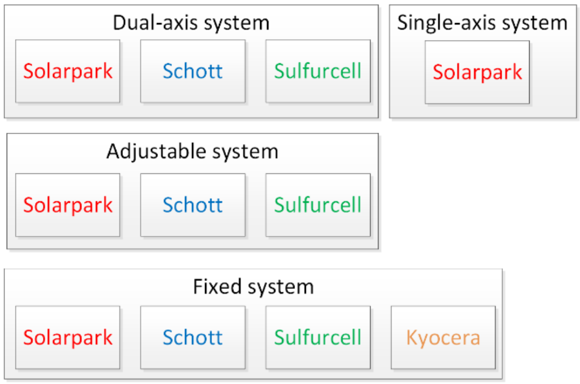

Fig. 1 Top view of the Zonneweide Systems

Table 1 *Details of the Zonneweide Systems*

System number	System type	Tilt	PV module	Nameplate margins	PV techno-logy	PV temp P coef. (%/K)	Installed capacity (Wp)	Inverter type
1.	Fixed	36	Schott-ASI 97	+3% / -0%	a-Si	-0.2 %	1164	Sunny Boy 1200
2.	Fixed	36	Sulfurcell SCG 55-HV-F	+5% / -5 %	CIS	-0.3 %	1430	Sunny Boy 1200
3.	Fixed	36	Solarpark SPP 230	+2 % / - 0%	c-Si	-0.45 %	3320	Sunny Boy 3300TL HC
4.	Fixed	36	Kyocera KD240 GH-2PB	+5 % / - 3%	c-Si	-0.46 %	3360	Sunny Boy 3300TL HC
5.	Adjustable	-	Schott-ASI 97	3% / -0%	a-Si	-0.2 %	1164	Sunny Boy 1200
6	Adjustable	-	Sulfurcell SCG 55-HV-F	+5% / -5 %	CIS	-0.3 %	1430	Sunny Boy 1200
7.	Adjustable	-	Solarpark SPP 230	+2 % / - 0%	c-Si	-0.45 %	3320	Sunny Boy 3300TL HC
8.	Single-axis tracker	-	Solarpark SPP 230	+2 % / - 0%	c-Si	-0.45 %	3320	Sunny Boy 3300TL HC
9.	Dual-axis tracker	-	Schott-ASI 97	3% / -0%	a-Si	-0.2 %	1164	Sunny Boy 1200
10.	Dual-axis tracker	-	Sulfurcell SCG 55-HV-F	+5% / -5 %	CIS	-0.3 %	1430	Sunny Boy 1200
11.	Dual-axis tracker	-	Solarpark SPP 230	+2 % / - 0%	c-Si	-0.45 %	3320	Sunny Boy 3300TL HC

For the adjustable system, the PV is tilted depending on the month. Table 2 shows the months of the year and the tilt angle applied for the adjustable system.

Table 2 *Tilt angles for the adjustable system*

Month	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Tilt	60	50	40	30	20	10	10	20	40	50	60	60

The single-axis tracker follows the elevation of the sun and the dual-axis tracker uses an irradiance sensor to determine the optimum angle.

1.2 Goal of this study

In the previous reports from the ACRRES the performance of the various PV systems and PV technologies was given in kWh/kWp [1]. From these results, it was not clear why certain PV technologies performed different than other technologies. Especially the effect of shadow on the systems and the difference in performance between the c-Si technologies and the thin film technologies was unclear. Therefore, the goal of the research is to investigate the performance losses of the different PV technologies and architectures. Consequently, a deeper understanding of the system losses and system optimization is acquired and can be used for future system design optimization.

This report starts with an overview of the data available for the study and the methods used to identify performance losses. Next, an overview of the individual losses of the system is presented and analysed. Then, the differences between the PV systems are estimated and discussed. Finally, from these findings a conclusion is drawn and recommendations are given.

This study is performed by SEAC in cooperation with ACRRES. The authors would like to thank ACRRES for the provided data.

2 Methodology

This chapter gives an overview of the data availability and the performance analysis conducted.

2.1 Data quality and availability

The Zonneweide test field went operational in August 2011 and is still operating. The AC data is monitored using SMA internal inverter monitoring and is sent towards the SMA sunny portal. The DC data is available from 20-07-2014, and is stored in a memory card. An overview of the available data for this research is shown in table 3:

Table 3 *Data availability of the ACRRES Zonneweide*

Period	Data available
11-08-2011 till 12-03-2012	15 minutes AC KWh energy from all systems except the Kyocera fixed
13-03-2012 till 07-04-2013	15 minutes AC KWh energy from all systems
07-04-2013 till 17-05-2013	15 minutes AC KWh energy from all systems except the Schott adjustable
18-05-2013 till 15-11-2013	15 minutes AC KWh energy from all systems
16-11-2013 till 26-11-2013	No data available
27-11-2013 till 22-06-2014	15 minutes AC KWh energy from all systems
23-06-2014 till 5-10-2014	15 minutes AC KWh energy from all systems except the Kyocera fixed
20-07-2014 till 5-10-2014	15 minutes DC data from all systems except the Kyocera fixed and the Solarpark single-axis system

The quality of the irradiance data was assessed by a comparison with the KNMI station in Lelystad (station number 269), data was retrieved from the KNMI website [2]. Figure 2 shows on the left graph the KNMI and ACRRES data for the period 2011- 2014 and on the right graph the correlation.

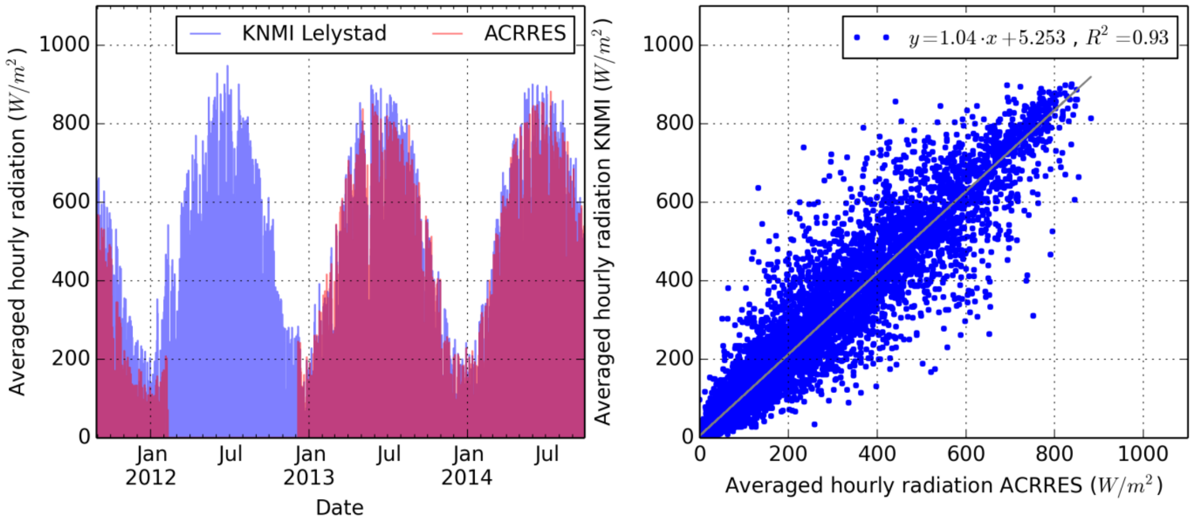

Fig. 2 *Data availability (left) and correlation (right) of the radiation data between KNMI and ACRRES*

Clearly visible is the missing ACRRES irradiance data in 2012. Moreover, the correlation between the measurements shows a small offset of 5 W/m2, a slope of 1.04 and a R2 of 0.93. Pyranometer soiling or albedo effects are possible explanations for the reported deviations seen. Therefore, hourly radiation values of the KNMI station will be used within this research.

The plane of array radiation values are calculated from the radiation values using the Evseev and Kudish revised Olmo model [3].

2.2 Performance analysis

Various loss factors are possible within a PV system. These losses are individually estimated.

Rating the performance

Rating the performance of the PV systems is performed by the so called performance ratio (PR). The performance ratio is a commonly agreed standard to analyse the quality of PV systems and it is specified as the ratio of the final PV system yield to the reference yield [4] and given in equation 1.

$$\text{Performance ratio} = \frac{E_{\text{feed-in}}}{P_{\text{STC}}} \cdot \frac{G_{\text{STC}}}{G_{\text{POA}}} \cdot 100\%$$

Eq. 1

Where $E_{\text{feed-in}}$ is the power fed into the grid, P_{STC} the rated STC power of the system, G_{STC} the irradiance under STC conditions (1000 W/m2) and G_{POA} the measured irradiance under plane of array. Performance of systems can also be compared using the specific yield in kWh/kWp. Within this study both the specific yield and the performance ratio are used.

Inverter losses

The inverters used at the systems are analysed based on their efficiency and operating points. Furthermore, the saturation of the inverters is investigated. The inverter efficiency is the ratio of AC output power to DC input power. Available DC data is used for this analysis.

Irradiance and temperature losses

The low light performance and temperature of the PV systems is investigated. To investigate the temperature losses, the ambient temperature measured by the KNMI station in Lelystad is used. For this study DC data are used to filter out the effect of the inverter.

Shading losses

A 'shade free' time period is determined by measurements performed with the Solmetric SunEye. This device measures the obstacles between the path of the sun and the PV modules. By placing the device upon the PV module, the time periods of shade casting the module can be determined. Figure 3 shows the SunEye measurement from the right side of the adjustable fixed Schott modules. Clearly visible is the shading from the neighboured threes early in the morning and the shading from the fixed Schott system before afternoon in the winter months. The histograms below show the monthly solar access. From these histograms it is understandable that the adjustable Schott modules are shaded for around 50 % during the months December and January. From the shading measurements a 'shadow free time period' is calculated and consequently the impact of the shading is estimated.

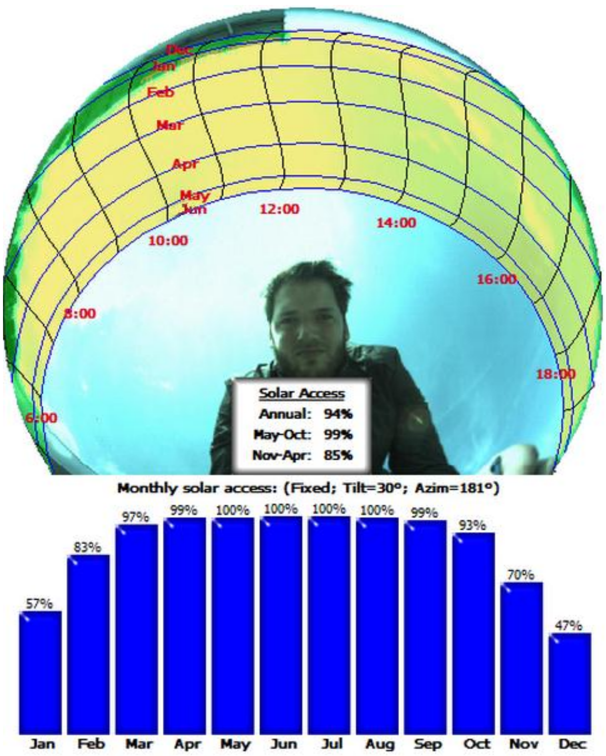

Fig. 3 *SunEye measurements (top) and calculated monthly solar access (bottom)*

3 Results

In this chapter, various PV technologies and system architectures are compared to each other.

3.1 DC comparison for clear days

First, a comparison of the DC data is performed using the data of two clear days. Therefore, differences between PV systems and potential losses become clearly visible. These two days are the 23rd of July and the 3rd of October 2014. For these days the DC current (left axis, solid lines) and DC voltage (right axis, dotted lines) are plotted for the PV technologies and systems, and shown in figure 4. Furthermore, the elevation angle is given as well in the bottom graph. Note that the three different systems (Schott, Sulfurcell and Solarpark) have different installed capacity.

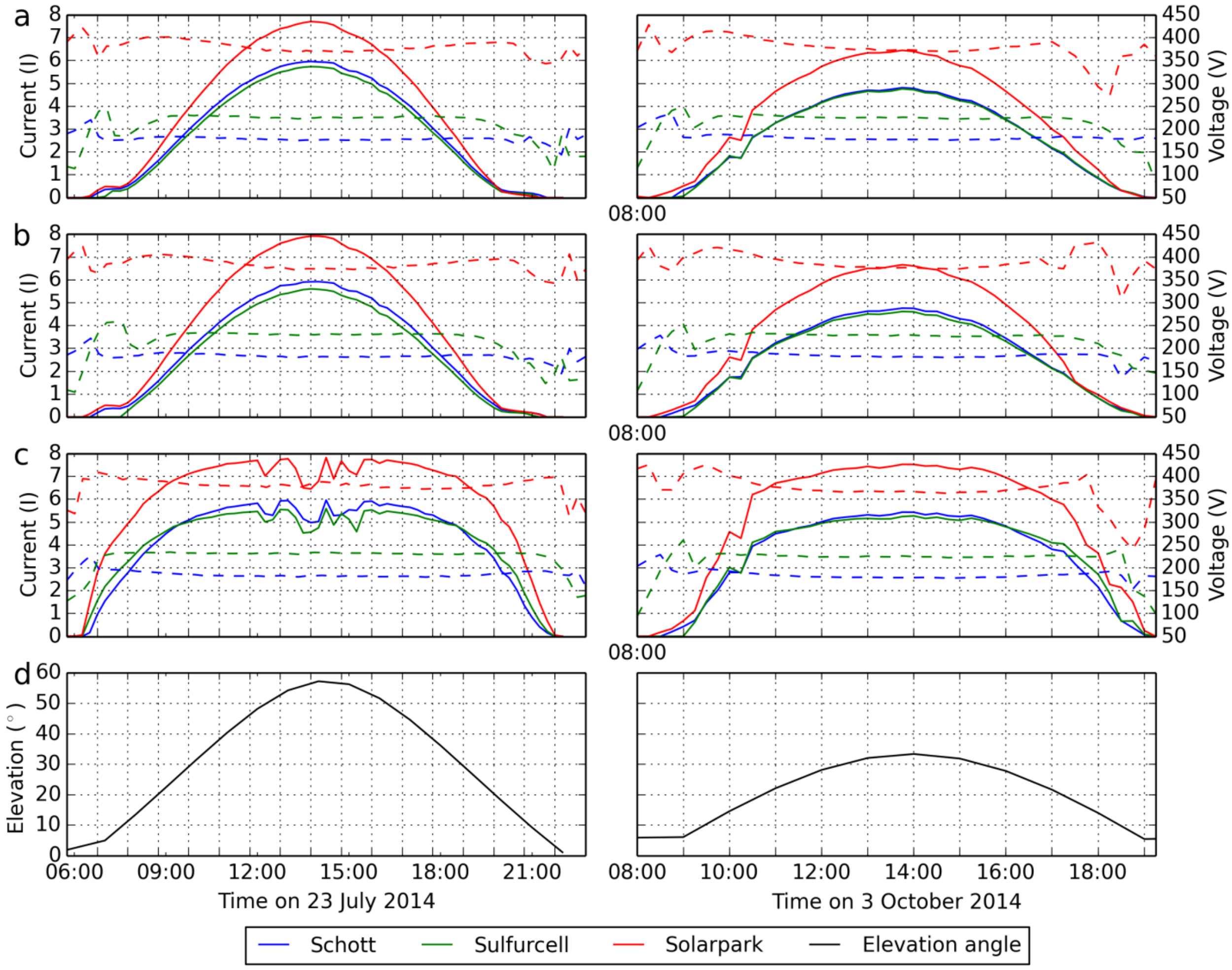

Fig. 4 *DC characteristics for two clear days in 2014 (left 23rd of July and right 3rd of October 2014). From top to bottom: a) Fixed systems, b) Adjustable systems, c) Dual-axis tracker systems, d) Solar elevation angle*

The figure visualizes the following points:

- The Schott and Sulfurcell (thin film) systems are operating at a lower voltage and current levels compared to the Solarpark (c-Si) systems. This is related to the difference in system design, installed capacity, module characteristics and string lengths.
- For 23rd of July between 06:00 and 08:00, the fixed and adjustable Sulfurcell systems are showing a lower current and a peak in voltage. This indicates that they are heavily shaded. Also the Solarpark and Schott fixed and adjustable systems a partly shaded before 07:00. However, the impact of the shade is less visible and consequently has a lower impact on the energy production. The dual-axis tracker systems do not show shade impact for this day.

- The voltage of the Solarpark system bends more over the day, compared to the Schott and the Sulfurcell system, which stay quite constant. This is related to the differences of temperature coefficients of the modules.
- The dual-axis systems are not working correctly when the solar elevation angle is high. On the 23rd of July the dual-axis systems show a fluctuation in current between 12:00 and 16:00. These electric currents should behave like the currents shown on 3rd of October. The time period of the fluctuating currents correlate to an elevation angle higher than 40°. Also on other days it is visible that the tracker is not working correctly at higher solar elevation angles.
- The differences between the current of the Schott and the Sulfurcell are larger on 23rd of July, compared to the 3rd of October. In addition, at higher elevation angles the Schott modules have a higher current compared with the Sulfurcell for the dual-axis systems. These effects could be related to differences in spectra. At higher elevation angles, the spectral irradiances are shifted towards the blue, resulting in a positive spectral effect for a-Si technologies [5].

3.2 Fixed vs dual-axis systems

The next part in this study consists of the comparison between the fixed system and the dual axis system, to investigate the angular effects. Especially in the early morning and the late afternoon, the solar elevation angle is low, resulting in higher angles of incidence for the fixed systems. For this study the ratio of the fixed system power to the dual-axis system power is analysed and visualized in figure 5.

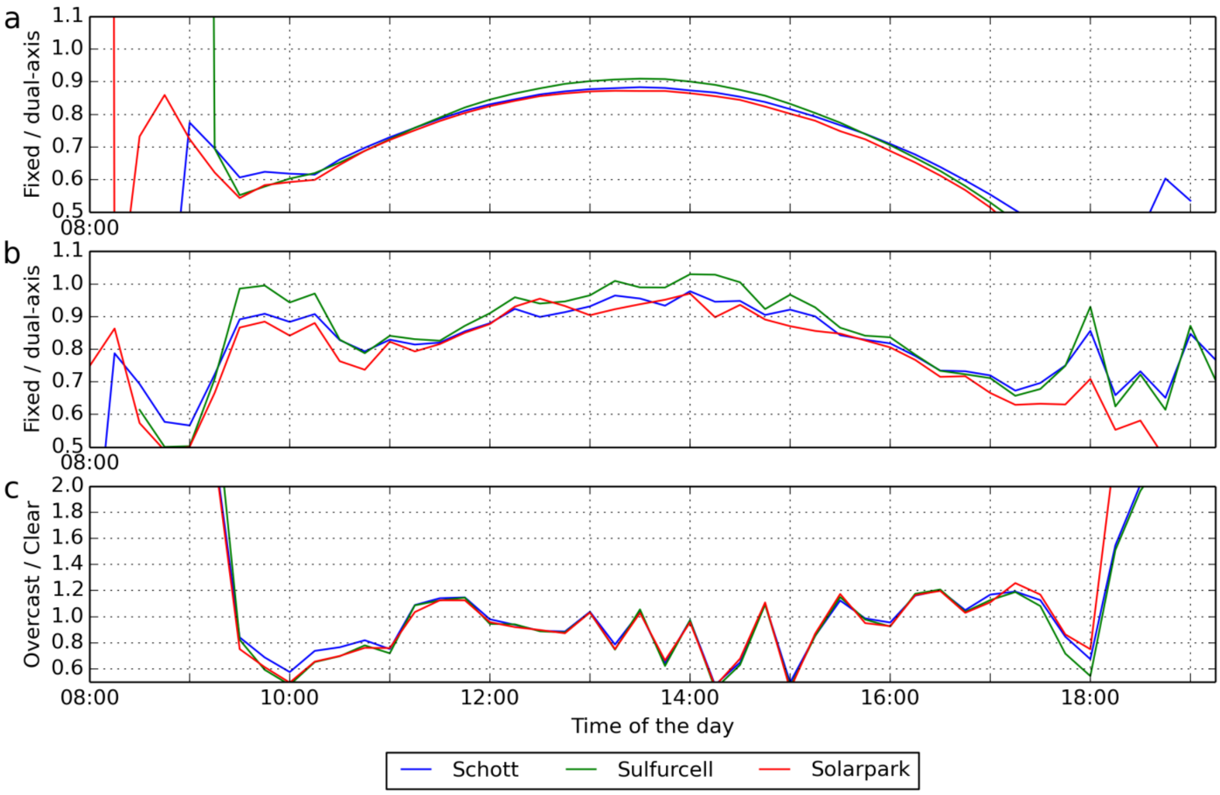

Fig. 5 *Comparison of fixed systems with dual-axis systems for clear and overcast days. From top to bottom: a) Clear day at 3rd of October, b) Overcast day at 7th of September , c) Overcast day / clear day for the fixed systems*

The top graph shows the fixed to dual-axis ratio for a clear day (3rd of October). This shows clearly that the dual-axis systems generate, except for the early morning, more power than the fixed systems. In the early morning (08:00 till 09:00) the fixed Sulfurcell and Solarpark systems produce more power compared to the dual-axis system, probably because of shading.

At solar noon the difference between the systems is the smallest for the Sulfurcell panels and the largest for the Solarpark panels. This difference could be related to the difference in temperature coefficients between the technologies. The differences between the c-Si and thin film technologies are not considerable increasing in the early morning and late afternoon. Therefore, the influence of the angle of incidence on the thin film technologies compared to the c-Si technologies is not clearly visible. The data do not show that thin film PV performs relatively better under small angle of incidence compared to crystalline Si, as is sometimes stated.

The middle graph of figure 5 shows the fixed to dual-axis ratio for an overcast day (7th of September). It is clearly visible that the fixed to dual axis ratios are higher on the overcast day compared to the clear day. In an overcast day, light is mainly diffuse and is scattered on the PV panel from different directions. Consequently, the tilt angle of a PV module has a lower influence. Subsequently, the performance gain of a tracker is lower on an overcast day compared to a clear day.

The bottom graph shows the ratio between the fixed systems of the overcast day (7th of September) divided by the fixed systems of the clear day (3rd of October). Because the overcast day was in the beginning of September, more daylight hours were available compared to the clear day from October. Consequently, more energy was produced by the overcast day compared to the clear day in the early morning and late afternoon. Also the data do not show higher performance of the thin film technologies compared to c-Si under diffuse irradiance.

3.3 Irradiance and temperature effects on DC yield

The effect of temperature and low light conditions on DC systems performance is analysed and shown in figure 6.

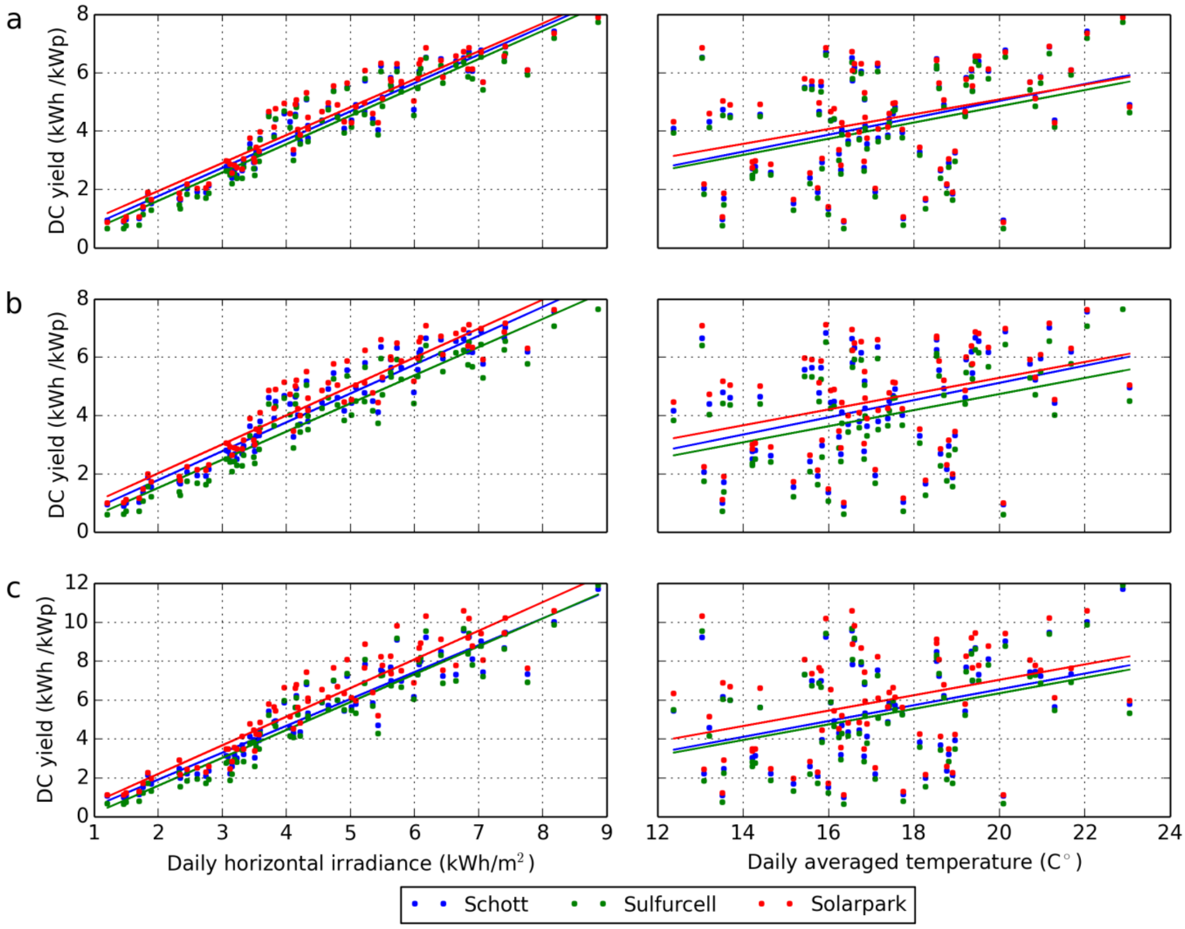

Fig. 6 *Irradiance (left) and ambient temperature (right) vs daily DC yield. (Data from 20-07-2014 till 5-10-2014). From top to bottom: a) Fixed system, b) Adjustable systems, c) Dual-axis tracker system*

The graphs on the left show no significant difference between the PV technologies on low irradiance days compared to the high irradiance days for all three systems. The Solarpark modules generate more energy than the Schott and Sulfurcell modules. The difference between the yield of the Solarpark modules and the Schott modules could be related to the DC cable losses, but also spectral effects have some influences.

The difference between the Schott modules and the Sulfurcell modules is probably related to the difference in rated STC power. In table 1 it is stated that the STC power rating of Sulfurcell modules is in the range of +5% / -5 %, whereas for the Schott modules it is in the range of +3% / -0%.

The effect of the ambient temperature on the PV technologies is visible. The Schott modules have an increased yield on warm days compared to the Solarpark and Sulfurcell modules, due to the lower temperature coefficient of the a-Si modules. This is especially visible at the fixed and adjustable systems. Consequently, this could indicate that the dual-axis modules are colder than the modules in the other systems, probably related to more wind cooling of the dual-axis systems.

3.4 Inverter losses

The inverter efficiency is depending on the PV panel technology and the system size. In the ACRRES test field there are four configurations, shown in table 4. Furthermore, the averaged inverter efficiency is given for the time period that DC data was available (20-07-2014 till 5-10-2014).

Table 4 *Overview of PV Panel - Inverter configurations and averaged inverter efficiency*

PV Panel	PV technology	Inverter type	Max. DC input inverter	System size (Wp)	Avg. η (%)
Schott	a-Si	SMA Sunny Boy 1200	1320	1430	89.95 %
Sulfurcell	CIS	SMA Sunny Boy 1200	1320	1164	89.83%
Solarpark	c-Si	SMA Sunny Boy 3300 TL	3440	3320	95.54 %
Kyocera	c-Si	SMA Sunny Boy 3300 TL	3440	3360	-

The table shows that the thin film modules are connected to a Sunny Boy SMA 1200, and the c-Si modules to a Sunny Boy 3300TL HC. The difference in averaged efficiency between the two inverters is around 5 %.

The Kyocera system was not analysed due to missing data. However it can be assumed that it will have similar inverter operation conditions as the Solarpark. Figure 7 shows the inverter efficiencies curves of the different systems.

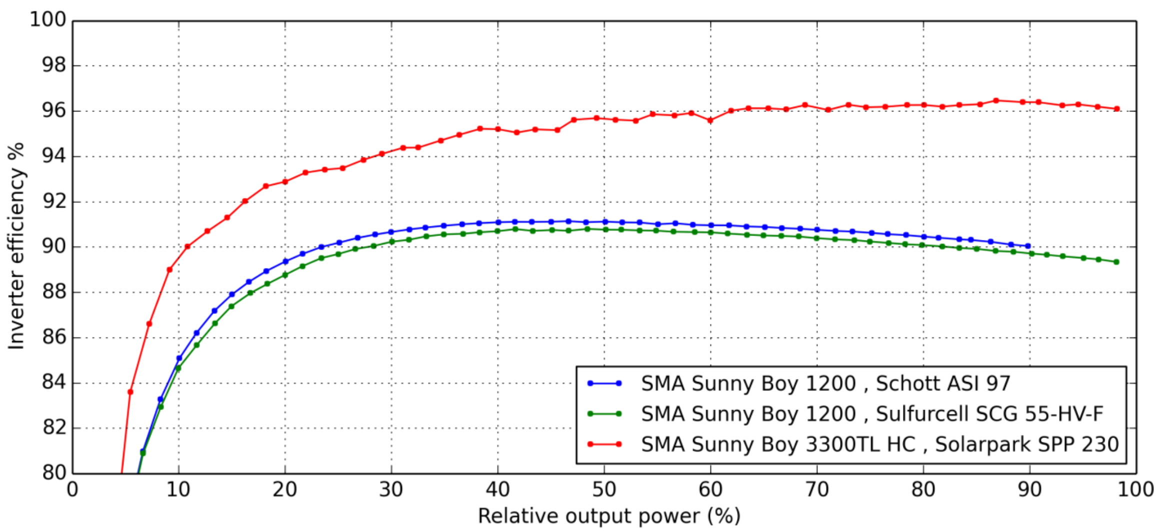

Fig. 7 *Inverter efficiencies for the different inverters connected to modules of different PV technologies*.

Clearly visible is the lower inverter efficiency of the Sunny Boy 1200 compared to the Sunny Boy 3300TL HC. Especially at higher relative output power the Sunny Boy 3300 shows up to 6 % higher efficiency compared to the Sunny Boy 1200. The main difference between the two inverters is the use of a transformer in the Sunny Boy 1200, resulting in additional losses.

The Sunny boy 1200 is required to effectively ground the thin film modules and to prevent TCO corrosion. The combination of leakage currents, humid environment and the sodium traces in the PV glass, results in TCO layer corrosion of the thin film modules especially at the edges of the modules. Therefore, most thin film manufacturers suggest to ground the negative pole of the system. This can be achieved by using an inverter with galvanic isolation (transformer topology). Consequently, the thin film systems used in the Zonneweide have a lower yield and therefore decreased performance compared to the c-Si systems.

Furthermore, the inverters connected to the Schott modules show a bit lower inverter efficiency compared to the Sulfurcell. This is related to the lower DC voltage of Schott modules compared to the Sulfurcell. The efficiency of the Sunny Boy 1200 is increasing with decreasing input voltage. Also it can be seen that the Schott connected inverter had a maximum relative output of 90 % due to the lower installed capacity compared with the Sulfurcell modules.

In addition, the inverter saturation where analysed, but no saturation effects where found. This is probably related due to the 15 minutes of data. Therefore this impact is not significant.

3.5 Differences in shading losses.

The losses related to shade for the fixed and adjustable systems were determined. The shade losses for the dual-axis systems where not determined because the tilt angles of the trackers were not recorded. The yield of the systems under conditions without shade was calculated and compared with the total yield. The differences were calculated according to Equation 2. This number is an indication of how much of the total yield was produced while the system was shaded. A relative high difference is related to a higher yield under shade.

$$\text{Relative difference} = \frac{\text{Total yield} - \text{Yield of period without shade}}{\text{Total yield}}$$

Eq. 2

Table 5 shows an overview of the relative differences in percentage for the three time periods of one year.

Table 5 *Relative difference in percentage between shadow free yield and total yield*

Sys number	1	2	3	4	5	6	7
System type	Fixed				Adjustable		
PV panel	Schott	Sulfurcell	Solarpark	Kyocera	Schott	Sulfurcell	Solarpark
11-8-2011 till 10-8-2012	5.63	5.19	6.64	4.29[1]	13.22	13.81	8.91
11-8-2012 till 10-8-2013	5.33	4.86	6.37	5.96	12.54	11.44	8.61
11-8-2013 till 10-8-2014	5.34	4.92	6.51	7.75	10.81	11.18	7.70
Yearly averaged difference	5.43	4.99	6.51	6.86[1]	12.19	12.14	8.41

[1]Yield difference for Kyocera was taken from 13-03-2012 therefore; the first year is not taken into account for the average

The fixed systems show a clear difference between the thin film modules (Schott and Sulfurcell) and the c-Si modules (Solarpark and Kyocera). The c-Si modules produced an increased amount of energy under shade than the thin film modules of roughly 1.5 %. This is related to the position of the fixed thin film system on the test field. These modules are located at the middle of the system and therefore receive more shade.

The adjustable systems consist of two rows of modules. The front row of modules is shading the back row of modules, especially in the winter months when the modules are at 60 degrees. Consequently, the impact of the shade on the adjustable systems is larger than on the fixed systems.

For the adjustable system the shade on the c-Si modules is having the highest impact. This is around 4 % compared to the Schott and Sulfurcell modules. This difference is related to the design of the modules. The thin film modules consist of strings with multiple strip shaped cells. These substrings are connected in parallel. The c-Si modules consist of 60 cells connected in series. Therefore, the thin film modules have a higher shade tolerance. Especially in portrait position, a small shade of a few cells can reduce the power of the c-Si modules by 80 %.

3.6 Yearly AC performance ratios for the fixed systems

For the AC side of the systems the yearly performance ratios were calculated for the fixed systems. The other systems (adjustable, single-axis tracker and dual-axis tracker) have not well known tilt angles for the measured data periods. Therefore, the performance ratios for these systems were not calculated. Figure 8 shows the performance ratios for three time periods.

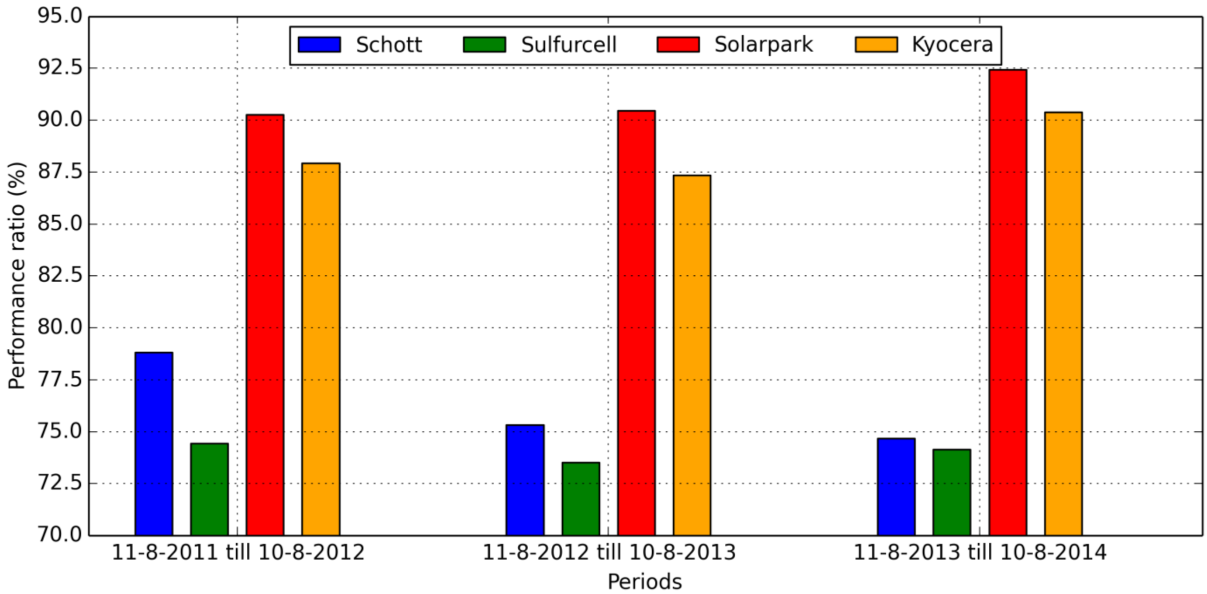

Fig. 8 *Performance ratios for the fixed systems (for the Kyocera system the first time periods is 13-03-2012 till 10-8-2013, and the third on 11-08-2014 till 22-06-2014)*

The figure shows that the performance ratios of the fixed Solarpark and Kyocera systems are very good for the three years analysed, ranging between 87 and 93 %. The difference between the two c-Si systems is around 3 % and could be related to name plated rating or small differences in module temperature.

The thin film modules give lower performance ratios compared with the c-Si technologies. These lower performance ratios are mainly caused by the use of different inverters. Besides, the fixed Schott system is showing a higher performance ratio in the first year compared to the Sulfurcell PR. However, in the third year the differences are almost negligible. A possible explanation of this difference is the faster degradation (around 1% annually) of a-Si modules [6]. An in-depth explanation of the yield difference between systems is given in the discussion in paragraph 4.

3.7 Yearly AC specific yield for all systems

The specific yield in kWh/kWp is presented for the systems in this section. Figure 9 shows an overview of the total system yields of all systems for the last three years.

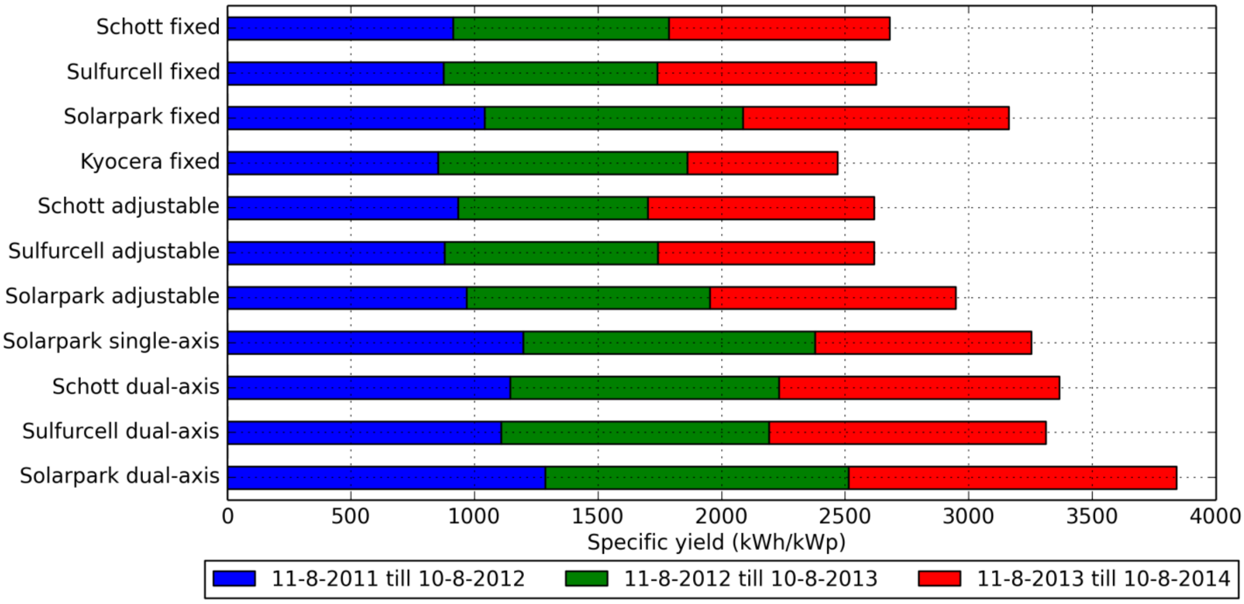

Fig. 9 *Energy yield of the various systems for the last three years.*

The graph shows the highest yield for the solarpark dual-axis system and the lowest for the Kyocera system. However, due to missing data of the Kyocera system, this cannot be directly compared for the time periods given in the figure. Furthermore, other systems also miss data for certain time periods. Consequenly a time period of 1 year was defined in which all systems had the same amount of data available. This time period is from 21-03-2012 till 20-03-2013. The yield in kWh/kWp is given for each of the four seasons within this period and visualized in figure 10.

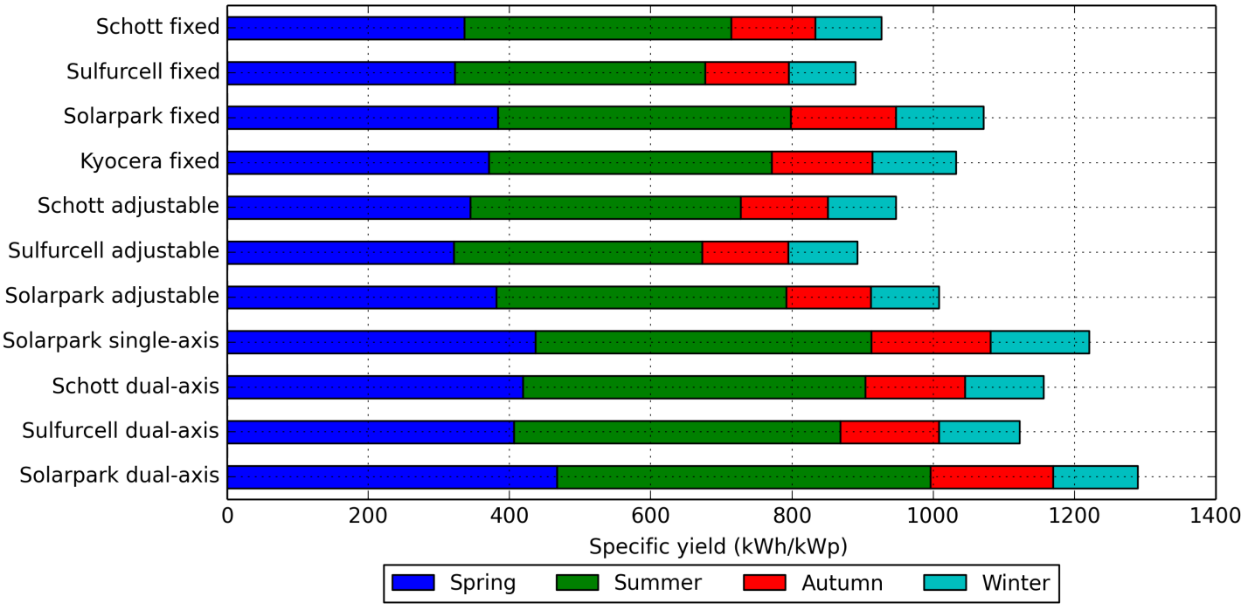

Fig. 10 *Energy yield of the various systems for each of the seasons between 21 march 2012 and 20 march 2013*

Figure 10 shows that the systems have a yearly specific energy yield between 890 and 1300 kWh/kWp. Furthermore, around 80 % of the energy is generated in the spring and the summer. Also the difference between the fixed system and the adjustable systems is very small. Additionally, the solar park dual-axis system produces less power than the Solarpark fixed system in the winter months. This could be related to shade on the tracker system, or due to an error in the algorithm of the tracker. Additional DC data is required to analyse these effects in-depth.

4 Discussion

In the discussion chapter of this report the differences between the PV technologies for each system topology are elaborated and discussed.

4.1 Observed yield loss differences

The performance loss difference between the PV systems is given for the DC data and the AC data. An overview of the relative differences in percentage of the DC data (from 20-07-2014 till 5-10-2014) between the systems is given in table 6. The Kyocera fixed system is not included, as well the Solarpark single-axis system due to missing data.

Table 6 *Relative difference of the 11 weeks of DC yield between the various systems of the Zonneweide*

		Reference systems numbers								
		1	2	3	5	6	7	9	10	11
Systems	**kWh/kWp**	**296.36**	**285.54**	**307.25**	**301.42**	**278.17**	**318.40**	**379.63**	**366.76**	**416.50**
1. Schott fixed	**296.36**	-	3.8%	-3.5%	-1.7%	6.5%	-6.9%	-21.9%	-19.2%	-28.8%
2. Sulfurcell fixed	**285.54**	-3.7%	-	-7.1%	-5.3%	2.7%	-10.3%	-24.8%	-22.1%	-31.4%
3. Solarpark fixed	**307.25**	3.7%	7.6%	-	1.9%	10.5%	-3.5%	-19.1%	-16.2%	-26.2%
5. Schott adjustable	**301.42**	1.7%	5.6%	-1.9%	-	8.4%	-5.3%	-20.6%	-17.8%	-27.6%
6. Sulfurcell adjustable	**278.17**	-6.1%	-2.6%	-9.5%	-7.7%	-	-12.6%	-26.7%	-24.2%	-33.2%
7. Solarpark adjustable	**318.40**	7.4%	11.5%	3.6%	5.6%	14.5%	-	-16.1%	-13.2%	-23.6%
9. Schott dual-axis	**379.63**	28.1%	32.9%	23.6%	25.9%	36.5%	19.2%	-	3.5%	-8.9%
10. Sulfurcell dual-axis	**366.76**	23.8%	28.4%	19.4%	21.7%	31.8%	15.2%	-3.4%	-	-11.9%
11. Solarpark dual-axis	**416.50**	40.5%	45.9%	35.6%	38.2%	49.7%	30.8%	9.7%	13.6%	-

The differences between the individual fixed systems, the adjustable systems and the dual-axis systems are visible in the blue squares and are colour-scaled. Also for the AC side, an overview between the relative differences was generated. The AC yield of a one year period (21-03-2012 till 20-04-2013) was used for these calculations and shown in table 7.

Table 7 *Relative difference of 1 year AC energy yield between the various systems of the Zonneweide*

		Reference systems numbers										
		1	2	3	4	5	6	7	8	9	10	11
Systems	**kWh/kWp**	**933.08**	**896.08**	**1079.41**	**1039.96**	**953.87**	**898.99**	**1015.56**	**1229.05**	**1164.91**	**1130.16**	**1299.58**
1. Schott fixed	**933.08**	-	4.1%	-13.6%	-10.3%	-2.2%	3.8%	-8.1%	-24.1%	-19.9%	-17.4%	-28.2%
2. Sulfurcell fixed	**896.08**	-4.0%	-	-17.0%	-13.8%	-6.1%	-0.3%	-11.8%	-27.1%	-23.1%	-20.7%	-31.0%
3. Solarpark fixed	**1079.41**	15.7%	20.5%	-	3.8%	13.2%	20.1%	6.3%	-12.2%	-7.3%	-4.5%	-16.9%
4. Kyocera fixed	**1039.96**	11.5%	16.1%	-3.7%	-	9.0%	15.7%	2.4%	-15.4%	-10.7%	-8.0%	-20.0%
5. Schott adjustable	**953.87**	2.2%	6.4%	-11.6%	-8.3%	-	6.1%	-6.1%	-22.4%	-18.1%	-15.6%	-26.6%
6. Sulfurcell adjustable	**898.99**	-3.7%	0.3%	-16.7%	-13.6%	-5.8%	-	-11.5%	-26.9%	-22.8%	-20.5%	-30.8%
7. Solarpark adjustable	**1015.56**	8.8%	13.3%	-5.9%	-2.3%	6.5%	13.0%	-	-17.4%	-12.8%	-10.1%	-21.9%
8. Solarpark single-axis	**1229.05**	31.7%	37.2%	13.9%	18.2%	28.8%	36.7%	21.0%		5.5%	8.7%	-5.4%
9. Schott dual-axis	**1164.91**	24.8%	30.0%	7.9%	12.0%	22.1%	29.6%	14.7%	-5.2%	-	3.1%	-10.4%
10. Sulfurcell dual-axis	**1130.16**	21.1%	26.1%	4.7%	8.7%	18.5%	25.7%	11.3%	-8.0%	-3.0%	-	-13.0%
11. Solarpark dual-axis	**1299.58**	39.3%	45.0%	20.4%	25.0%	36.2%	44.6%	28.0%	5.7%	11.6%	15.0%	-

The difference between the fixed systems, the adjustable systems and the dual-axis systems will be explained individually in the next chapters.

4.2 Differences between the fixed systems

The fixed systems show that the Solarpark is producing 15.7 %, 20.5 % and 3.8 % more AC energy than the Schott, Sulfurcell and the Kyocera modules respectively. From the DC side an extra yield of 3.7 % and 7.6 % of the Schott and Sulfurcell modules is shown respectively.

The difference in AC yield between the two c-Si modules, Solarpark and Kyocera of around 4 % could be due to the following reasons:

- Difference in nameplate rating vs real power rating. Solarpark modules give a +2% / -0% rating and Kyocera +5%/-3%. Consequently, this difference can also occur in the test field.
- Small difference in additional shade loss for the Kyocera modules, estimated to be 0.3 % (see table 5) The Kyocera modules are located at the far right side of the test field and therefore have the most shade in the morning due to neighbouring trees.

The differences between the Solarpark modules and the Schott modules are around 15 % according to the one year AC data and around 3.7 % according to the 11 weeks DC data. This could be explained by the following reasons:

- At least 5 % higher yield due to the higher inverter efficiency of the SMA 3300 TL compared to the Sunny Boy 1200 as explained in section 3.3. However, this could be even higher because the difference is increasing during winter months.
- The difference of 3.7 % in DC performance could be related to difference in name plating or due to degradation of the modules.
- Especially during the winter months the atmospheric spectrum is shifting towards the red side, therefore resulting in lower energy yield of the a-Si modules compared to c-Si modules. This adds additional losses in the winter months which are currently not investigated due to non-available DC data.

The difference between the two thin film technologies is around 4 %, in favour for the Schott modules. This is also visible from the DC data. However, this difference is expected to decrease due to the degradation of the Schott modules, as explained in section 3.5. This difference could be caused by three foremost reasons:

- Small effect due to higher efficiency of the inverters connected to the Schott modules as a result of the lower input voltage of the Schott modules compared to the Sulfurcell modules.
- Lower temperature coefficient of the Schott modules compared to the Sulfurcell modules
- Higher nameplate rating compared to the real power rating of the Sulfurcell modules.

4.3 Differences between the adjustable systems

Also for the adjustable systems the Solarpark modules are performing better than the thin film modules. The differences from the AC data are 6.5% and 13 % more energy, compared to the Schott and the Sulfurcell modules respectively. From the DC data these differences are 5.6 % and 14.5 %.

The reasons of the difference observed between the PV technologies are similar as the fixed systems, explained in the section 4.2. However, the AC differences are around 6 % smaller compared to the fixed system (6.5% and 13 % vs 15.7 % and 20.5 %). This difference could be due to the following reason:

- The effect of shade is larger on the adjustable system compared to the fixed system. This is related to the system design, which consists of two rows of modules. The front row is shading the back row, especially during winter months. The thin film modules are more shade resistant compared to the c-Si modules. The extra yield under shade for the thin film modules is estimated to be 4 %, according to table 5.

Larger differences between the fixed system and the adjustable systems are shown with the comparison of the DC data. Comparing the DC data of the fixed system with the adjustable system shows a larger difference in DC data (3.7% and 7.6 % vs 5.6 % and 14.5 %). This is also visible in figure 6, where the lines of the systems are more distant from each other. This could be related to the following reasons:

- Morning shade of two hours (visible in figure 6 b) from the Sulfurcell system results in a lower power output during the days.
- Larger differences in nameplate rating vs real power rating between the modules installed in the adjustable systems.

4.4 Differences between the dual-axis systems

For the dual-axis tracker systems, the Solarpark modules yield 11.6 % and 15 % more energy compared to the Schott and the Sulfurcell modules respectively. These differences are very similar to the fixed system. The reasons for these differences are also similar, and explained in section 4.2

For the DC data the differences observed are 9.7 % and 13.6 % for the Schott and Sulfurcell modules respectively. The reasons for this difference could be related to:

- Differences in tracker position among the systems. Especially in the DC data period some strange behaviour is observed for all trackers (visible on figure 6 c) at higher solar elevation angles. Therefore, the difference in power production is fluctuating more between the dual-axis systems compared to the fixed and adjustable systems.
- The trackers have a better wind cooling, therefore reducing the temperature of the modules. The thin film modules have a lower temperature coefficient compared to the c-Si modules. A lower temperature of modules attached on the tracker, compared to the fixed and adjustable systems, results in a larger yield difference between the thin film modules and the Solarpark modules.

5 Conclusions & Recommendations

This study investigated the differences in performance of the Zonneweide test field of ACRRES. This test field consists of four PV system topologies (fixed, adjustable, single-axis and dual-axis tracker) and three PV technologies (c-Si, a-Si and CIS). AC kWh data for the period of Augustus 2011 till October 2014 and DC data for 11 weeks (20-07-2014 till 5-10-2014) were analysed. Irradiation and temperature data from the KNMI Lelystad weather station was used.

The data analysis shows that a dual axis tracker gives 20-26% more energy yield compared to the fixed set-up. The single-axis solar tracker gives 14% more energy yield compared to the fixed set-up.

One of the focus points of this report is the analysis of differences between the thin film technology (a-Si and CIS) panels and the crystalline Silicon (c-Si) panels. We conclude that the largest difference of at least 5 %, between the thin film technologies and the c-Si, is related to a difference in inverters. The thin film modules are connected to an inverter using a transformer and the c-Si modules are connected to a transformerless inverter. The transformer is required for the thin film technologies, resulting in extra conversion losses and lower final energy yield.

The second largest factor is probably related to the margins in nameplate rating in relation with the actual power rating (as would be measured by a flash test). Performance ratio's are defined relative to the rating on the nameplate. Manufacturers apply different tactics for the nameplate ratings, as shown in table 1. Manufacturers of a-Si panels (like Schott) usually anticipate on degradation and therefore give a lower rating than actually measured, with a positive margin. The Sulfurcell and Kyocera modules give large margins on the nameplate rating. This means that any measured differences that are smaller than these margins could be originating from these margins. A way to get around this, is to apply a flash test to the modules before installing them in the test field.

We found that some shadow effects are present in the test field, however the effect is small. For the adjustable systems the shadow results in approximately 4 % less power production for the c-Si modules, in comparison with the thin film modules. Especially in the winter, when the solar elevation is low, a small shading can decrease the power of the portrait c-Si modules severely.

Another clear effect is that the Schott systems are degrading faster compared to the other systems.

Furthermore, an error in the dual-axis tracker was found at high solar elevation angles. The error could be related to the tracker software because similar errors were observed for all the three dual-axis trackers. Also, no significant influence of the angle of incidence on the performance of the different PV technologies was found.

Overall the performance ratio of the c-Si panels (fixed set-up) is very good (87% - 92%). The performance ratio of the thin film panels (fixed set-up) ranges from 74% to 78%. It must be noted however that the yearly specific yield (see figure 10) for the fixed systems of Schott (933 kWh/kWp) and Sulfurcell (898 kWh/kWp) are both higher than the 875 kWh/kWp, known as the averaged specific yield for the Netherlands.

Based on the results of this study, we recommend the following:

(1) Inspection of the tracking software of the dual-axis.
(2) Continue the DC data collection and determine the actual inverter losses for a period of at least 1 year. Also the DC data provides extra information on the effect of shading between the PV systems.
(3) Installation of temperature sensors on the PV modules in order to determine the temperature losses more accurately.
(4) Installation of a pyranometer at the tilt of the fixed systems, and one pyranometer on top of the dual-axis tracker. Consequently, accurate irradiance data for the various tilt angles will become available.
(5) Also an option is to automatically store the direction and tilt angle of the dual-axis trackers in a data logger. Then it will be possible to analyse in-depth the angle of incidence effects.
(6) For new installations we recommend to do a flash test on the panel before installations. This will enable to exclude the effects of the name plate tactics of the manufacturers.

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