Evaluating the Impact of PV Module Orientation on Grid Operation

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***Abstract*— A large number of photovoltaic (PV) systems in the power system can cause a variety of different problems in grid operation. As PV modules can have different orientation, the influence on the grid operation, such as power gradients, voltage issues or overloading of assets, is also different. In order to evaluate the impact of PV module orientation on these issues various characteristics of seven differently orientated PV systems have been investigated: seasonal capacity factor, power gradients, peak power, area utilization, and correlation between generation and consumption. The capacity factor decreases for systems with a suboptimal orientation, but on the other hand the generated peak power is also lower. This is beneficial in case of voltage problems and asset overloading. Power gradients are lower and the energy production therefore smoother which leads to a reduced need for conventional power plants or other flexibility options to follow the gradients. East/West oriented PV systems achieve higher area utilization and yield per surface area and may negate the effect of peak power reduction. The correlation of production and consumption of PV systems not facing south is worse while a south orientated façade system has the best correlation.**

Keywords-PV; capacity factor; power gradient; peak power; area utilization; correlation

I. INTRODUCTION

The current strategic objective of Europe’s energy policy is to reduce greenhouse gas emissions by 60-80 % by 2050 compared to 1990 [1]. This involves a commitment to achieve 20 % reduction by 2020 through the improvement of energy efficiency by 20 % and increasing the share of renewable energies to 20 % [2]. This commitment has stimulated the growth of distributed energy resources and especially PV systems.

The integration of renewable energy sources into the already existing infrastructure is a challenging task. Wind and solar power do not necessarily follow energy demand, but rather produce energy when their respective resource is available. A high penetration of renewable energy may lead to less correlation of a large proportion of energy production to demand. Since energy production and consumption within an electricity network always need to be balanced, a higher correlation is desired in order to lessen the needed controlling power range. A lower correlation of production and consumption at the lower voltage level also leads to over voltage problems and a power flow into the higher voltage level.

The problem of over voltage stems from the peak power generation of PV systems during midday. A lower peak power would be beneficial in counteracting the issue, but decreases the yield of the PV system. A different orientation, instead of the much preferred south orientation, may be beneficial in this case. Ideally the energy production in the morning and evening could be higher, while the peak at midday is reduced. This potential behavior shall be investigated by exploring the change in key characteristics of PV energy production. The identified key characteristics are the capacity factor, power gradients, peak power, yield per surface area and correlation of production and consumption. Since the capacity factor corresponds to the yield per year and is a key indicator of profitability and likelihood of occurrence, it is considered first. Power gradients and peak power are relevant for grid operation and influence the system as a whole as well as at their respective connection point. The yield per surface area has an impact on system sizes and therefore influences potential peak power and yield. Since the balance of electrical generation and consumption always needs to be maintained in the grid, the correlation of these two is relevant for stability and difficulty of operation.

II. PV SYSTEM SETUPS

Seven PV system setups with different orientations were investigated. Their output was modeled for the city of Aachen in Germany (50°46'23" North 6°6'7" East). An overview of the setups can be found in Table I.

TABLE I. SETUP OF PV-SYSTEMS

PV System No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Orientation	South		East/West				Tracking
Inclination	35°	90°	0°	15°	35°	90°	Tracking

The first PV-system is the reference system since it is usually the first choice when installing new PV modules. The second PV-system is a façade installation orientated to the south. The third PV-system is a horizontal system, which has been included for comparison reasons. These systems are normally not installed, as they tend to lose their performance very fast due to dirt, which cannot be washed away by rain. The fourth and fifth systems are east/west configuration with different inclination angles. The orientation east/west means half of the installed system faces east while the other half faces west. This is also true for PV-system No. 6, which is also a façade system. Finally the tracking system is supposed to indicate the maximum possible energy yield at the chosen position. These seven PV-systems cover the whole range of reasonable PV orientations and should therefore be sufficient to get a good picture of the impact of PV module orientation on grid operation.

III. Irradiation Data

In order to obtain irradiation data for the different orientations and inclinations the "Photovoltaic Geographical Information System" (PVGIS) [3] was used. With the given position, orientation and inclination, the system compiled a data set for a day of a specified month. These data sets contained typical daily irradiation values on a fixed plane or on a tracking plane. The obtained values were subdivided into average irradiation and clear-sky irradiation on a 15 minute scale. Clear-sky irradiation was used to determine maximum ramp rates and peak power values over the course of one year. The energy output of the PV-modules was derived through evaluation of the average irradiation. Figure 1 displays the average power generation of a day in April for all considered PV-setups.

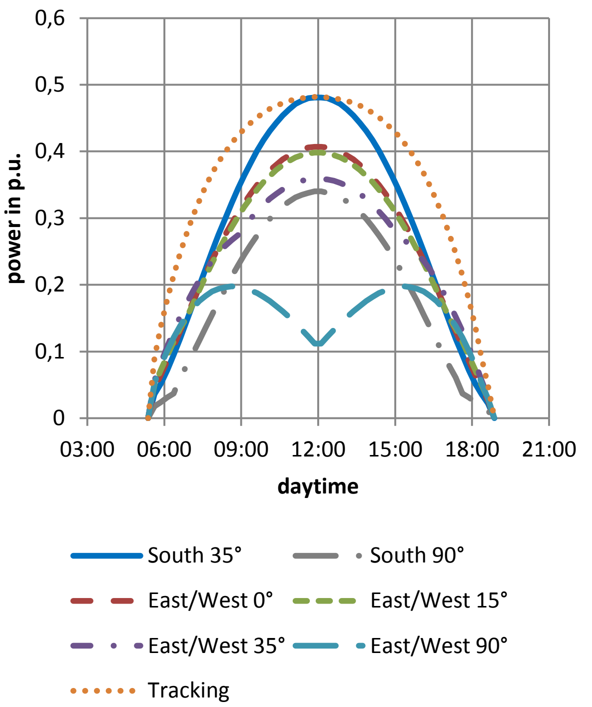


Figure 1. Average power generation of a day in April for all considered PV-setups

IV. Results

A. Capacity Factor

A PV system is intended to produce energy that can be sold or consumed by the owner. Therefore it is important to evaluate the impact of different orientations and inclinations on the energy yield. The orientation and inclination of PV modules determines the average daily irradiation on the system. The irradiation is directly linked with the power generation through size and efficiency of the PV-system.

The capacity factor of the production is the ratio of yearly energy yield to theoretical generation capability per year (nominal power times 8760 h/a). When multiplying the capacity factor with 8760 h the number of full load hours can be determined. Figure 2 gives an overview of the capacity factor of all investigated setups.

The highest energy yield can be achieved with a tracking system; it is roughly 20 % higher than the south orientated system. East/West orientated systems are only slightlyworse than south orientated; 10 to 20% less yield has to be taken into account as long as the inclination of the roof is not too high. A PV system on an easterly and westerly façade (PV system No. 5: East/West 90°) would produce 35% less energy than a south orientated façade system and 50% less than a south orientated system with optimal inclination. Such a system would be from an economic point of view not recommendable.

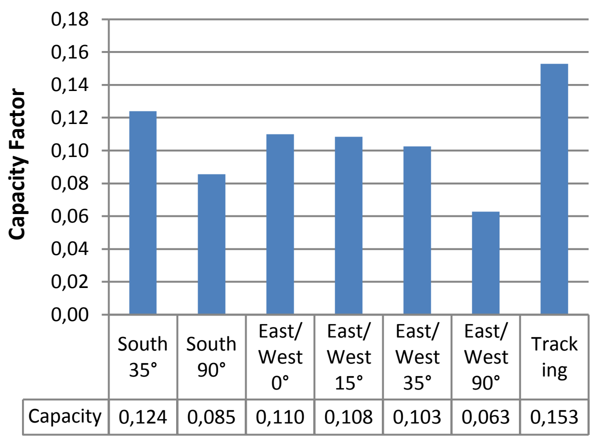


Figure 2. Capacity Factor

The load profile of residential customers in Germany is called the "H0-Profile". It predicts the energy consumption of an average household and is normalized to a yearly consumption of 1000 kWh/a. When considering the standardized H0-Profile, there is a higher demand for electric power in winter (see Figure 4). Therefore it is reasonable to consider power generation per month. Figure 3 depicts the capacity factor of each PV setup per month.

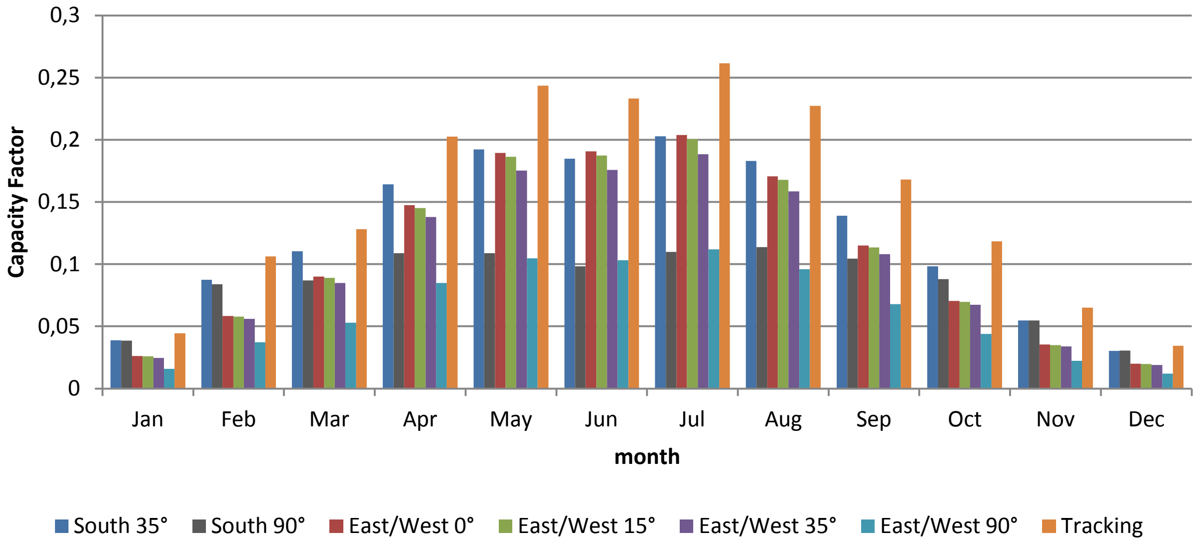


Figure 3. Monthely Capacity Factor

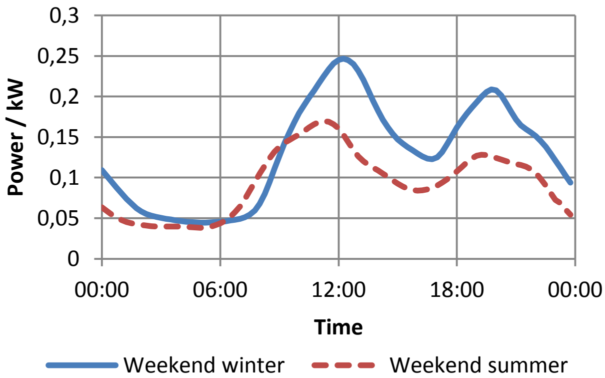
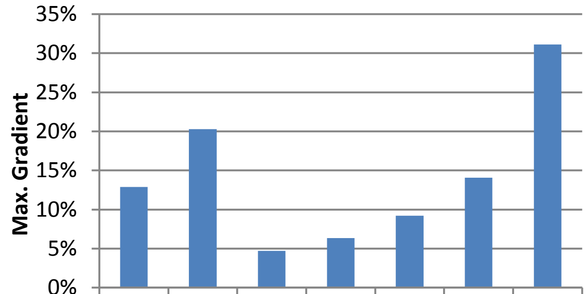


Figure 4. Typical residential customer load profile (H0-Profile)



	South 35°	South 90°	East/ West 0°	East/ West 15°	East/ West 35°	East/ West 90°	Tracking
Gradient	12,9%	20,3%	4,7%	6,4%	9,2%	14,1%	31,1%

Figure 5. Maximal absolute gradient rated to nominal power within 15 minutes

Due to the course of the sun in summer (i.e. sunrise in the north-east and sunset in the north-west and the sun being higher in the sky) the capacity factor in June and July of an east/west orientated PV system is higher than the one of a south facing system. However when the power is really needed in the wintertime, the capacity factor of an east and west oriented PV-system is lower. A south orientated façade system provides a good capacity factor in the wintertime, while yielding slightly less in the summertime. With respect to the capacity factor, the east/west orientated system is therefore inferior to the south oriented systems.

B. Power Gradients

The energy production of solar power plants in Germany has priority dispatch and must be distributed by the grid [4]. Other power plants need to be able to follow the combined gradients of solar power generation and consumption. This is especially critical in the evening, when the sun sets and consumption grows. Hence a lower gradient for PV-systems is more desirable. Otherwise, more conventional power plants would need to be in reserve in order to match generation and consumption [5].

The values for maximum gradients within 15 minutes are shown in Figure 5.

These gradients are based on the clear-sky irradiation due to the course of the sun, especially at sunrise and sunset. Of course the ramp rates of individual PV systems can be much higher e.g. when a cloud is passing through, however this would be of stochastic nature and the correlation between various PV systems is in this case very low, whereas on a clear-sky the correlation between PV installations is very high, thus the gradients due to the course of the sun are the overall highest gradients to be expected.

When comparing the PV systems in Figure 5 the highest gradients can be found for tracking systems closely followed by a south façade. The lowest gradients exist for low inclination combined with an east/west orientation. Here the energy production is smoothed compared to a south oriented system. From grid operation point of view, east/west systems are therefore advantageous in terms of gradients versus south orientated or tracking systems. However this is only true for unrestricted operation. In case gradients do really produce a grid operational problem, the gradients of the PV system can be limited using the (maximum) power point tracker of the inverter as depicted in Figure 6. This is particular true for positive gradients, but also negative gradients can be limited to a certain extent, as the clear sky power production curve can be very well predicted. The reduction in yield depends on the chosen maximum power gradient.

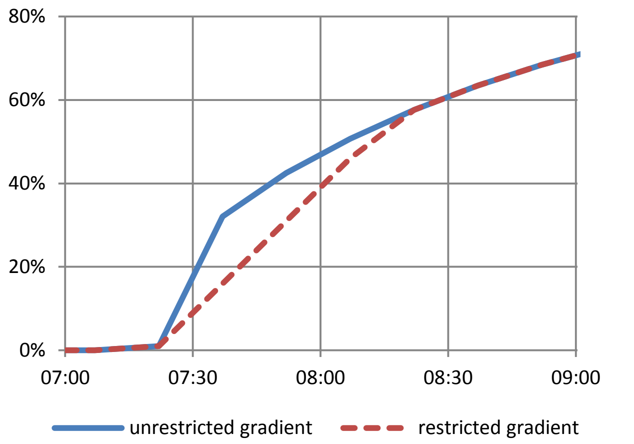


Figure 6. Example of limitation of the maximum power gradient of PV System No. 7 (Tracking)

C. *Peak Power*

Depending on the size of the solar power plant it will either be connected to the low-voltage grid or the medium-voltage grid. Especially in the low-voltage grid the maximum peak power generation of a PV-system determines the voltage level at the connection point and loading of transformer and cables. A high peak power and high penetration of PV may cause a breach of the allowed voltage or overloading of utilities. This could lead to costly extensions of the low-voltage grid.

As shown in Figure 7 an east/west orientation reduces the maximum peak power in relation to a south oriented PV-module. A higher inclination is beneficial in further reducing the maximal peak of east/west oriented systems.

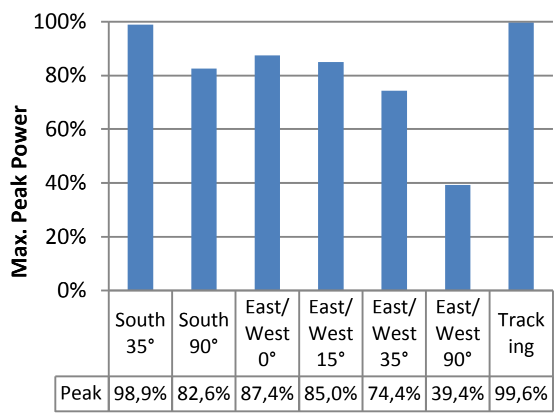


Figure 7. Maximal peak power rated to nominal power

The peak power reduction and the reduced yield compared to PV system No.1 is shown in Figure 8. Peak shaving refers to using PV system No.1 and cutting its power output at 70% of its nominal power. This results in a reduction in the yield of about 5% [6].

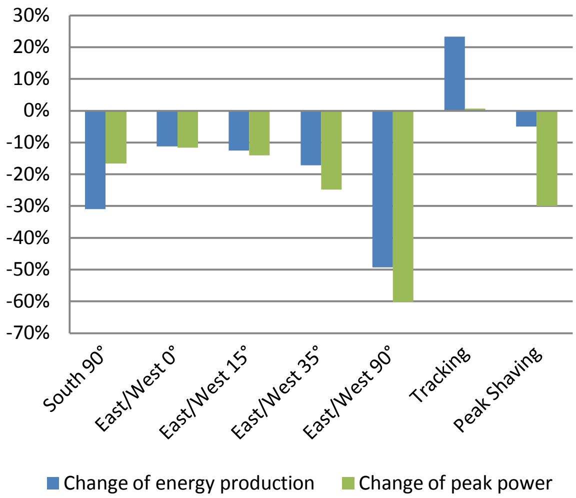


Figure 8. All PV Setups compared to PV System No. 1: South 35°

The result for a south façade system is very unfavorable, as the reduced yield is twice as high as the favorable peak reduction. For east/west orientated PV systems at a low inclination the reduction of peak power and of the yield is almost equal at a low inclination. A higher inclination (East/west 35° and 90°) pulls the individual peaks of the east and west orientated modules in relation to daytime further apart. Therefore the reduction in peak power is higher than that of the yield compared to a south oriented system. A tracking system provides higher yield without an increase of peak power. Peak shaving on the other hand provides a significant reduction of peak power while the reduction in yield is less severe.

Figure 9 displays an example of the lower peak power and lower gradients of an east and west oriented PV system in comparison to a south oriented system. The conditions are clear-sky on a day in May.

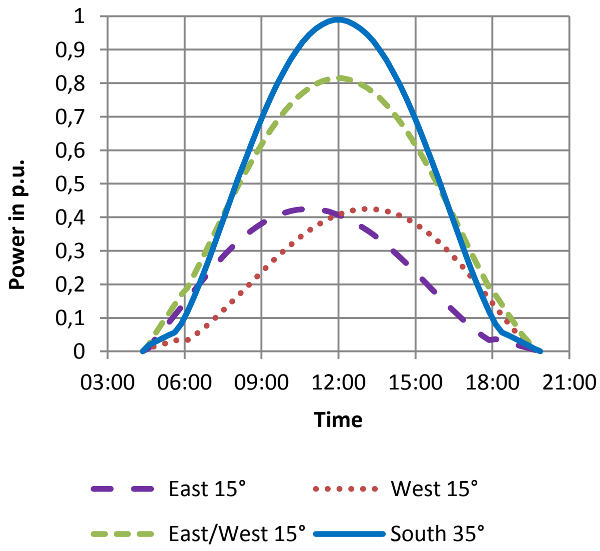


Figure 9. Comparison of the PV production on a clear day in May

D. Yield per surface area

An advantage of east/west oriented PV modules on rooftops or on an open field is the different arrangement of the system. On rooftops it may be possible to use double the amount of space compared to a south facing system, if both sides of the roof can be filled with PV modules. In an open field an area utilization of 35-40% for south oriented modules can be achieved, while an east and west oriented system has an area utilization of 70% [7]. The low area utilization of south oriented modules is given by the need to avoid shadowing.

While better area utilization is beneficial for the owner, it also compensates the lower peak power at midday due to bigger possible system sizes. This counteracts the potential of lower load and over voltage within the low voltage level. Considering an open field and filling it with PV modules would result in a 75% higher installed capacity for an east/west oriented system compared to a south oriented system. Figure 10 displays the increase of peak power and the gain of energy production compared to PV System No.1. Since façade systems would not be feasible on an open field and horizontal systems would be difficult to keep clean they have not been considered. The previously observed benefit of reduced peak power has changed to a significant increase, however the energy yield has increased even more.

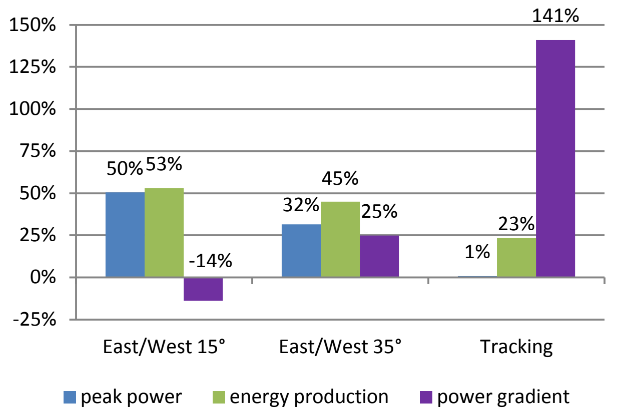
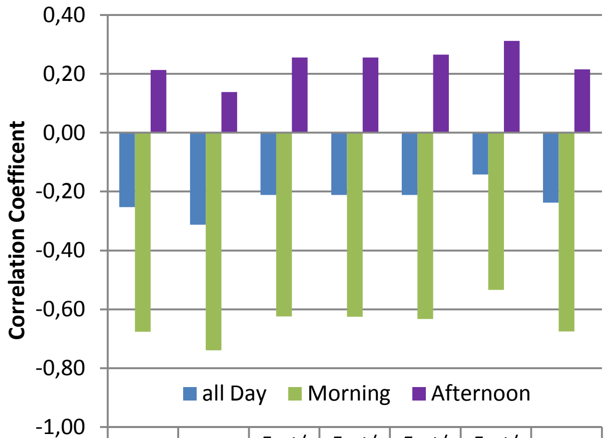


Figure 10. Effects of open field area utilization compared to PV System No.1: South 35°

E. Correlation between Production and Consumption

Assessing the matching of generation and consumption can be done through evaluation of the correlation coefficient. A correlation coefficient with respect to consumption can be within the range of minus one and plus one. A value near minus one implies a high correlation between generation and consumption whereas a value near zero means no correlation and a value near plus one indicates an anti correlation [8]. The standardized H0-Profile was used to represent the consumption, because most of the decentralized PV production should be consumed within the low voltage grid by households in order to minimize grid load. Since the average production of a PV system is in principle axially symmetric either side of midday, it has positive and negative gradients which can be more closely evaluated. Therefore the correlation coefficient over the course of one year has been calculated for the whole day, in the morning from 0 am to 12 am and in the afternoon from 0 pm to 12 pm.

The results depicted in Figure 11 indicate a worse correlation between production and consumption when PV-modules are not facing south. A higher inclination of PV-modules oriented to the east and west even worsens the relationship. The higher positive values for the latter half of the day are implying that the production decreases at the same time as the load increases. The best correlation can be observed when using south oriented façade systems.



	South 35°	South 90°	East/ West 0°	East/ West 15°	East/ West 35°	East/ West 90°	Tracking
all Day	-0,25	-0,31	-0,21	-0,21	-0,21	-0,14	-0,24
Morning	-0,68	-0,74	-0,62	-0,63	-0,63	-0,53	-0,68
Afternoon	0,21	0,14	0,26	0,26	0,27	0,31	0,22

Figure 11. Correlation coefficient between PV production and load

V. CONCLUSION

This paper investigates the difference between south oriented and east/west oriented PV modules with respect to grid related characteristics. Table II gives a rated overview of all key characteristics related to PV energy production. As a benchmark of the rating, the seven PV systems are compared among each other and not against other technologies like conventional power plants.

When analyzing this table, there is no obvious optimal orientation for grid operation. Every PV setup has its pros and cons.

System No. 1 facing south with an optimal inclination performs well when looking at the energy yield, especially also in winter time. The power gradients and the peak power are pretty high, inducing some problems for grid operation. However, by limiting the peak to 70 % and also restricting the gradients, this system can achieve the same good characteristic as the east/west orientated systems. The results for energy yield on an equivalent area do show an inferior characteristic compared to east/west. The correlation between production and consumption is remarkably good.

System No. 2, the south façade, performs especially well in energy yield during winter time and the correlation with consumption. Otherwise the overall yield is fairly bad.

System No. 3, the horizontal modules, is naturally good in terms of power gradients, however it has only an average correlation characteristic and a small energy yield during winter time.

TABLE II. CONCLUSION OVERVIEW

PV System No.			**1**	**2**	**3**	**4**	**5**	**6**	**7**
Orientation			***South***		***East/West***				***Tracking***
Inclination			***35°***	***90°***	***0°***	***15°***	***35°***	***90°***	***Tracking***
Equivalent rated power	Yield	overall	good	bad	o.k.	o.k.	o.k.	very bad	very good
		winter	good	good	bad	bad	bad	very bad	very good
		summer	good	very bad	good	good	good	very bad	very good
	Power Gradients		o.k.	bad	very good	very good	good	o.k.	very bad
	Peak Power		bad	o.k.	o.k.	o.k.	o.k.	very good	bad
Equivalent area	Yield	overall	bad	n/a	n/a	very good	good	n/a	o.k.
		winter	o.k.	n/a	n/a	good	good	n/a	good
		summer	bad	n/a	n/a	very good	good	n/a	o.k.
	Power Gradients		good	n/a	n/a	very good	o.k.	n/a	very bad
	Peak Power		good	n/a	n/a	bad	o.k.	n/a	good
Correlation between production and consumption			good	very good	o.k.	o.k.	o.k.	bad	good

System No. 4, east/west orientation with a small inclination, has a very good natural power gradient for an equivalent rated power. However the main advantage of such a system is the usage of space. This system is particular good in overall energy yield when looking at an equivalent area. However in this case the peak power might induce some grid operational issues.

System No. 5, east/west with a higher inclination, is very similar but in many cases not as good as system No.4.

System No. 6, east/west façade, is probably the worst system. The only advantage is a fairly low power gradient and very low peak power.

System No. 7, tracking, could probably emulate all other systems. Due to its ability to capture as much energy as possible it has the highest yield but also produces, if not restricted, the highest power gradients and peaks.

All results have been determined based on calculations of a location in Germany and are therefore quite specific for Germany's latitude. For other latitudes the results will be slightly different, i.e. further to the north (e.g. Sweden) the south facing system will be more advantage and further to the south (e.g. Portugal) the advantages of East/West might be more pronounced.

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