Study on the possible yield gain by inverters with multi-MPPT compared to single-MPPT inverters for different solar system configurations and locations

This analysis is a summary of a study conducted by the Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, on behalf of KACO new energy GmbH. To obtain the complete version of the study, please contact KACO new energy at sales@kaco-newenergy.de.

Single-MPPT inverters may generate more yield than multi-MPPT inverters, provided the solar PV system is homogeneous with low shading and symmetrical string design. This can be read from a study conducted by Fraunhofer ISE. Single-MPPT inverters have, in general, a higher efficiency than multi-MPPT inverters. This higher efficiency can outweigh slight mismatch losses of single-MPPT inverters.

Solar modules are generally operated at their maximum power point (MPP) in order to maximize their yield. Since the maximum system voltage today is usually 1500 VDC, modules are first connected in series to utilize the voltage range for power scaling of the systems. For further scaling, the module strings are then connected in parallel to an inverter.

There are currently two different concepts for string inverters on the market. In single-stage inverters (Figure 1a) with single MPP tracking, all module strings connected to the inverter are connected in parallel. In this case, the inverter tracks the voltage to the point of maximum power resulting from the entire PV generator.

The second concept pursued on the market consists of a two-stage concept (Figure 1b), in which the first stage consists of several parallel DC-DC-stages. Up to 2 strings can be connected in parallel at each DC input in conventional designs. Each DC input can then independently adjust the input voltage, allowing for more small-scale MPP tracking. This approach can minimize voltage-related mismatch losses between module strings. The following analysis argues, however, that due to their lower efficiencies, possible yield gains of multi-MPPT inverters can be neglected in most cases.

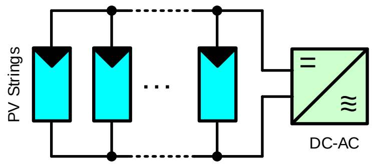


Figure 1a: Block diagram of string inverters with single-MPPT

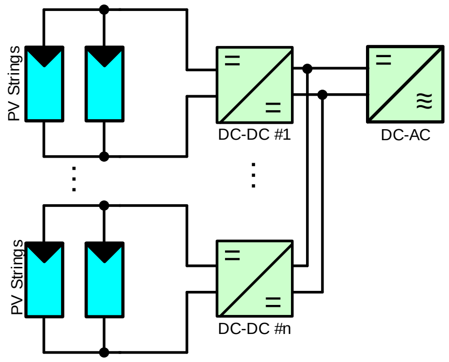


Figure 1b: Block diagram of string inverters with multi-MPPT

OBJECTIVE OF STUDY

The question of whether and when the use of an inverter with multiple independent DC inputs is beneficial is analyzed based on comparing the yield or better said kWh per year produced at the DC side under various scenarios and then obviously the higher losses of multi-MPPT are taken into account to come to an overall estimation under the scenarios. In other words, the focus of the study is on mismatch losses occurring between module strings. The investigations are based on yield simulations with the PVSyst© software, provided that the corresponding effect can be reasonably represented in the software. For some of the effects, PVSyst© only allows a constant percentage loss calculation. In this case, own analytic and numeric calculations were performed to evaluate the effect.

STRUCTURE OF STUDY

This study is structured to reflect typical PV plants where single and multi-MPPT inverters are used. It begins with inverter and module selection, through location selection to string combinations. This allows for the comparison of yields and mismatch losses of the selected inverters considering various orientations, tilts, near shading for rooftops and ground mounted installations and draws necessary conclusions for the consideration of the reader.

COMPONENTS USED IN THIS STUDY

The study was carried out with real single-MPPT inverter parameters and synthetic models of multi-MPPT inverters based on single-MPPT inverters from KACO new energy GmbH as listed below:

- blueplanet 60.0 TL3 M1 (single-MPPT)
- blueplanet 165 TL3 M1 (single-MPPT)
- blueplanet 60.0 TL3 M6 (Synthetic model inverter with 6 MPPT)
- blueplanet 165 TL3 M9 (Synthetic model inverter with 9 MPPT)

The synthetically generated multi-MPPT inverters have the same efficiencies and other performance parameters as the single-MPPT inverters, as the study is solely concerned with determining the effects of multiple MPP trackers (MPPT) versus single-MPPT. The module CS3W-410P 1000V/1500V from Canadian Solar with the specification given in table 1 is used in the study.

Parameter		Value
Open Circuit Voltage	V_{OC}	47,6 V
Short Circuit Current	I_{SC}	11,06 A
MPP Voltage	V_{MPP}	39,1 V
MPP Current	I_{MPPP}	10,49 A
Nominal Power	P	410 W

Table 1: Specifications of CS3W-410P 1500V according to PAN File

LOCATION AND INSTALLATION TYPES

For the investigations, two basic types of plants were distinguished and modeled. Scenario A is designed as a rooftop system with an inverter size of 60 kVA. Scenario B is a design for ground-mounted systems based on a string inverter with 165 kVA. Two representative locations were chosen: Arkona, Germany (AK) and Abu Dhabi, United Arab Emirates (AD). The following table summarizes the basic framework conditions.

Parameter	Scenario A	Scenario B
Plant Type	Rooftop	Ground-mounted
Inverter Power	60 kVA	165 kVA
Inverter	KACO blueplanet 60	KACO blueplanet 165
P_{DC}/P_{AC} ratio	1	1
Number of MPPTs	1 (6)	1 (9)
PV Module	CS3W-410P 1000V/1500V	
Max. PV Generator voltage	1000 V	1500 V

Number of Modules per String	18	AK: 28 AD: 29
Number of Strings	8	15 (16)
Orientation	South	
Optimal Tilt	AK: 40° AD: 22°	
Tracker System	-	(Single Axis NS)

Table 2: Framework for Scenario A and B

STRING LAYOUT CONFIGURATION

In most cases, only strings with the same number of modules are connected in parallel during system planning. However, to investigate mismatch losses occurring between module strings especially for smaller systems, it can make sense to combine different string lengths. For this purpose, different combinations of strings with 18 and 19 modules in series were considered in each case as shown in table 3.

String configuration	V_{OC}	V_{MPP}	I_{SC}	I_{MPPP}
1: 8x 18 + 0x 19	47.600	39.261	11.060	10.448
2: 7x 18 + 1x 19	47.879	39.436	11.058	10.443
3: 6x 18 + 2x 19	48.173	39.631	11.057	10.438
4: 5x 18 + 3x 19	48.482	39.847	11.056	10.434
5: 4x 18 + 4x 19	48.806	40.095	11.056	10.430
6: 3x 18 + 5x 19	49.145	40.375	11.056	10.429
7: 2x 18 + 6x 19	49.498	40.686	11.057	10.431
8: 1x 18 + 7x 19	49.865	41.040	11.058	10.437
9: 0x 18 + 8x 19	50.244	41.441	11.060	10.449

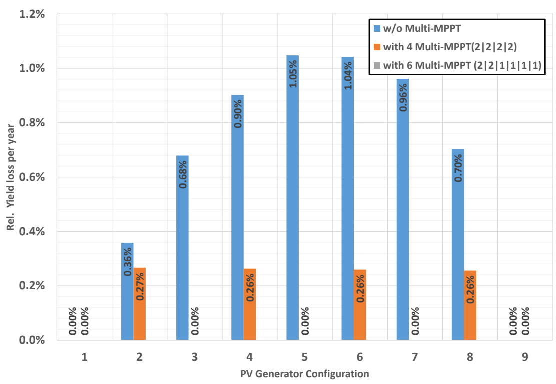
Table 3: Different module string configurations

YIELD RESULTS

Yield simulations for scenario A in Arkona were then carried out in PVSyst©. This was done for each case with single-MPPT, with 4 MPPTs and 6 MPPTs. The largest mismatch losses occur with a 50/50 asymmetrical configuration of the PV generator (variant 5 in table 3) amounting to 1.05% for single-MPPT. For other configurations, the mismatch decreases. For the case of an inverter with 4 MPPTs, mismatch occurs for odd ratios between the string lengths, since in this case one string with 18 and one string with 19 modules are always connected in parallel at one of the MPPTs. The mismatch here is ~0.26% in each case.

The results show that the yield losses are still relatively low with single-MPPT. Higher efficiency of single-MPPT inverters reduces this yield gains eventually.

A corresponding simulation for scenario B was not carried out since the results can be transferred accordingly.



DIFFERENT MODULE ORIENTATIONS

Particularly at locations in Germany, it has nowadays become attractive not to design systems facing south, but to plan a PV generator in which strings with an east and west orientation are combined in order to minimize the curtailment losses at outputs greater than 70% of the nominal module power.

For scenario A, Various string layout configurations were simulated using PVSyst© to calculate how much additional yield can be achieved by using a multi-MPPT inverter. The simulations were made for the Arkona site and for Abu Dhabi. The tilt angle for the east-west orientation was chosen to be 20° in both cases.

YIELD RESULTS

Orientation	String Layout	P_{DC}/P_{AC}	Location	Yield Gain
East-West	E: 5 / W: 5	1.2	AR	0.07%
East-West	E: 5 / W: 5	1.2	AD	0.07%
East-West	E: 4 / W: 4	1	AR	0.07%
East-West	E: 4 / W: 4	1	AD	0.07 %
East-West	E: 1 / W: 9	1.2	AR	0.01 %
East-West	E: 1 / W: 9	1.2	AD	0.02 %
S: +2° / -2°	+2°: 5 / -2°: 5	1	AR	0.00 %
S: +10° / -10°	+10°: 5 / -10°: 5	1	AR	0.01 %

Table 3: Simulated yield gains from multi-MPPT for different PV generator configurations for Scenario A.

As shown in table 3 above, for all configurations, the additional yield is less than 0.1%. The location has a slight influence on the mismatch. In locations with more direct sunlight (Abu Dhabi) the mismatch is marginally more noticeable. The additional yield here would be +0.02% points compared to a plant in Arkona.

A steeper installation angle leads to slightly larger mismatch losses. However, simulations have shown that even at an angle of 40°, the yield gains of multi-MPPT inverter increase on average by only about 0.01 percentage points.

In order to consider the influence of deviation from the optimal south orientation, simulations were performed with deviations of 2° and 10° with 50-50 splitting of the generator in each case. In these cases, the mismatch in the simulation is zero. With the generally higher efficiency of single-MPPT inverters, the overall yield could be higher for single-MPPT inverters in all the above cases.

DIFFERENT MODULE TILTS

Since in reality the tilt of different rows is not exactly identical, this effect was also represented in the simulation environment for scenario A. The orientation of the PV generator in this case was to the south for both locations. However, the strings in the generator were each subjected to different deviations in the 50-50 distribution. In this case, even extreme deviations of 20° only result in possible yield gains of max. 0.01%. As stated earlier, considering real efficiency of inverters, single-MPPT inverters could have generally higher yield in the below cases. The table 4 below summarizes the results:

Tilt	String Layout	P_{DC}/P_{AC}	Location	Yield Gain
35° / 45°	35°: 4 / 45°: 4	1	AR	0.00%
20° / 30°	20°: 4 / 30°: 4	1	AD	0.01%
20° / 40°	20°: 4 / 40°: 4	1	AR	0.01%
15° / 35°	15°: 4 / 35°: 4	1	AD	0.01%

Table 2: Simulated yield gains at the DC side for multi-MPPT string topologies versus single-MPPT string topologies for different PV generator configurations for Scenario A with variation of tilts within the generator.

ROOFTOP NEAR SHADING LOSSES

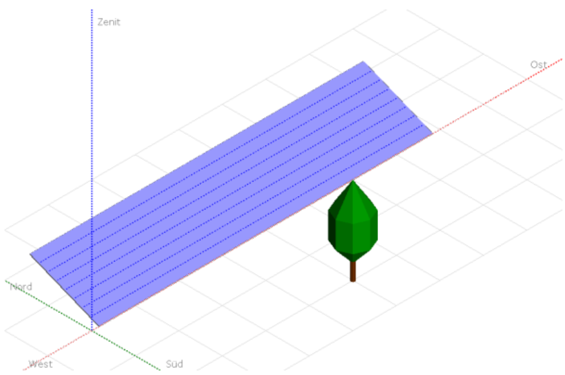


Figure 3: Shading scene with a tree for scenario A

To consider this effect, a representative shading scenario was defined in PVSyst©. For this purpose, the generator was defined as a coherent surface on a rooftop with a fixed installation angle of 40° (AK) or 22° (AD), so that the only shading that occurs is caused by the tree or another comparable obstacle directly blocking the generator from the south in this case. The scenario was simulated with single and multi-MPPT inverters. At the Arkona site, the additional yield through multi-MPPT amounts to 1.0%, the same value was found for Abu Dhabi and the results are as given in table 5 below. Higher efficiency of single-MPPT inverters reduces this yield gains eventually.

Location	**Yield with Single MPPT *MWh/year***	**Yield with Multi MPPT *MWh/year***	**Relative Yield Gain**
AK	68.853	69.560	1.0%
AD	108.400	109.470	1.0%

Table 3: Simulated yield gains from multi-MPPT for the shading scenario by a tree outlined above.

GROUND MOUNTED NEAR SHADING LOSSES

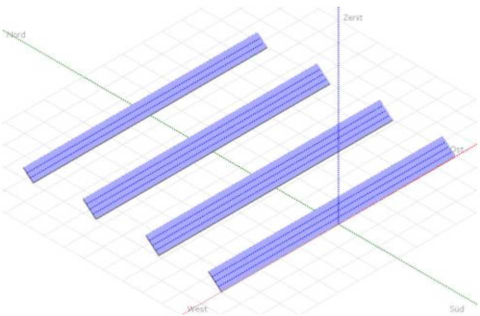


Figure 1: Shading scene row shadowing for Arkona (16 m)

In ground-mounted systems such as in figure 4, the tilt of the module rows inevitably leads to shading for certain sun angles. To analyze this effect, different configurations were defined based on scenario B and the additional yield was determined by multi-MPPT. The PV generator design was based on PV tables with 4 horizontal rows of 28 modules each (collector height per table: 4.2m). The last table has only 3 module rows due to the total number of strings. The installation angle and orientation were chosen to be optimal for both orientations.

Simulations with two different values for the row spacing were then performed for both locations and the potential additional yield was determined for multi-MPPT. The optimal row spacing was specified so that just no shading of the rows among each other occurs at noon on the shortest day of the year. In the second variant, the determined distance was halved.

Location	**Optimal row spacing**	**Reduced row spacing**
AK	16 m	8 m
AD	6 m	5 m

Table 6: Optimized and reduced row spacing for both locations.

YIELD RESULTS

The following graph also shows that only a very small part of the losses caused by the additional shading are compensated by multi-MPPT. These gains are lost when taking into consideration the real efficiency of the inverters. Single-MPPT inverters could have higher overall yield in all cases.

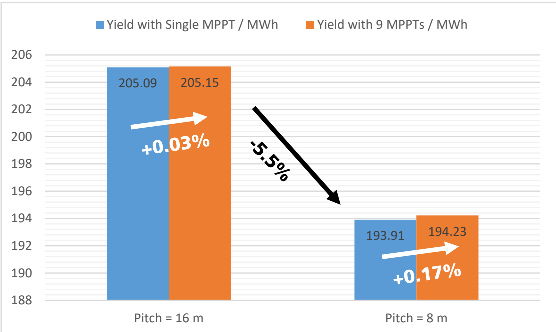


Figure 2: Simulation results with variation of row spacing for Arkona.

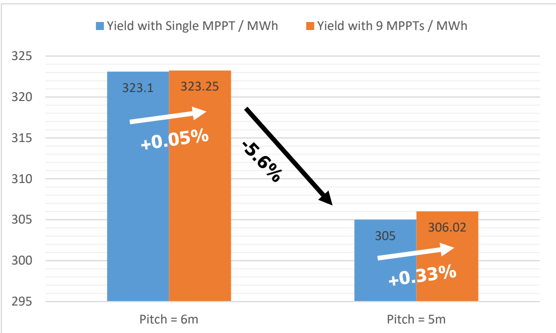


Figure 3: Simulation results with variation of row spacing for Abu Dhabi.

NEAR SHADING BY MODULE TABLES WITH SINGLE AXIS TRACKER (N-S)

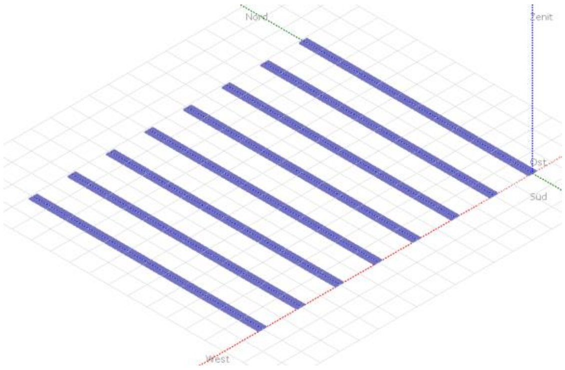


Figure 4: Shading scene tracker system (10 m pitch between tracker)

The same considerations were made for PV generators with single axis tracking. The tracker system was defined as a single-axis tracking along the north-south axis. For each tracker, 2 module rows with 28 modules each were designed. For symmetry reasons, the number of strings was increased from 15 to 16, resulting in 8 identical trackers. To evaluate the shading effect, different distances were simulated for both locations. The basic scenario for a distance of 10 m is shown in the following figure 7.

YIELD RESULTS

The picture is the same for all cases analyzed: only a very small part of the yield losses due to shading can be compensated by multi-MPPT at string level. Even with a spacing of up to 5m between the trackers, multi-MPPT only results in an additional yield of 0.19% in Arkona and 0.24% in Abu Dhabi.

For plants optimized for yield per kW_p with larger row spacing, the additional yield can be neglected. Even with narrower row spacing with optimization in terms of yield per area, the additional yield is less than 0.25% points, which can be more than compensated by the higher efficiency of single-MPPT inverters.

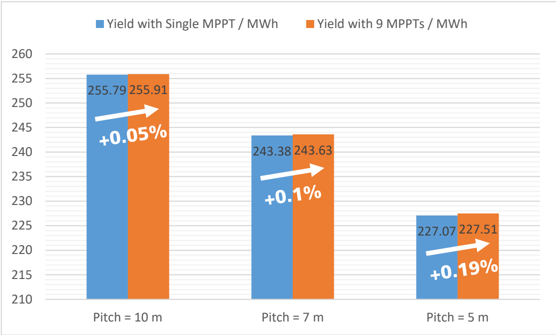


Figure 5: Simulation results with variation of the distance between the trackers for Arkona

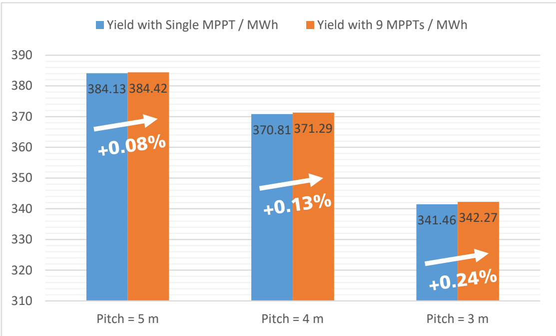


Figure 6: Simulation results with variation of the distance between the trackers for Abu Dhabi

RELIABILITY OF EFFICIENCY DATA

The data is generally provided by the manufacturer of the inverter. PVSyst© does not check these values and accepts no liability here. When checking two inverters from different manufacturers, it was found that in both cases there were average deviations of 0.3 to 0.4 % points between measurements and the values specified in the ond. file. The measurements for this comparison were carried out at Fraunhofer ISE in the TestLab Power Electronics1. Since the efficiencies of current inverters are very high overall, a comparison of different inverters in PVSyst© is heavily dependent on the reliability of the inverter data. Due to the origin of the data, a comparison of efficiency curves with similar values close to each other is therefore not reliable according to the authors opinion. In practice, decisions on which inverter to use are influenced not only by costs but also by the results of yield simulations. The interest of the manufacturers to be as good as possible here is correspondingly high. Whether these results also correspond to the practice is impossible to evaluate after the construction of the plant, since the plant is built only with one of the selected inverters. Due to the aforementioned inaccuracy of the data and the very similar efficiency curves, it is therefore questionable from the authors' point of view whether a comparison of inverters in PVSyst© leads to realistic results. When doing a yield analysis in PVSyst© or other software with different inverters this fact should always be taken into account.

CONCLUSION

The investigations carried out in this study have shown that single-MPPT inverters can lead to higher yields in most scenarios. Especially in homogeneous solar PV systems, single-MPPT inverters contribute to higher yields. This applies to modules with different orientations and tilts. Moreover, this applies to ground-mounted systems with fixed tilt or with single-axis trackers. Near shading losses can likely be more than compensated for by the higher efficiencies of single-MPPT inverters. It can be assumed that this leads to additional income for plant owners.

Nonetheless, in two of the simulated scenarios, an increase in yield could be achieved by using multi-MPPT inverters. These include an asymmetric string configuration of the PV generator (cf. table 3) and a heterogeneous shading scenario (e.g., caused by a tree, (cf. table 6). In both cases, the yield gain was up to 1% of the total yield. This value can be considered as a maximum yield gain. When taking the efficiency of real inverters into account, this value will probably be reduced as the efficiency of multi-MPPT inverters can be assumed to be lower than the efficiencies of single-stage inverters. In all other cases investigated, the possible additional yield is considerably lower and the calculated gain here is below 0.1%.

The calculations carried out refer entirely to calculations based on crystalline Si modules. Even when considering aging effects, this effect does not lead to yield losses over the modules lifetime due to mismatch or falling below the minimum inverter input voltage. For other PV technologies such as thin film the impact may be more relevant.

The results can be explained very well with the P,V characteristics of the modules. Especially around the area of the MPP the curve is very flat and therefore leads only to small losses in case of deviations. As a rule of thumb one can say that a 1% deviation in the voltage only leads to a 0.1% power loss. This is shown in the following example.

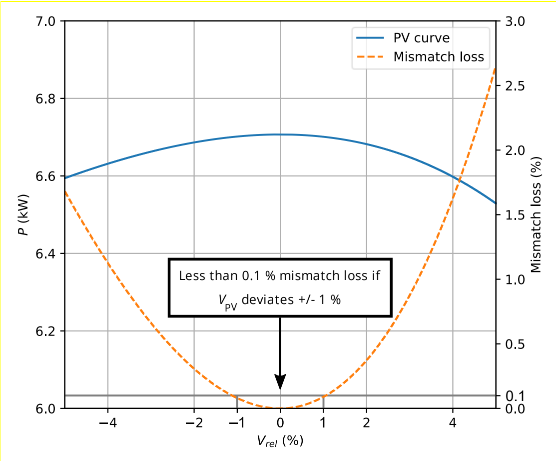


Figure 11: Deviations in the power of a PV module resulting from deviations in the voltage

The influence of the geographical location of the PV system is relatively small and does not lead to a qualitative change of the results. The individual effects illustrated above, and possible other effects investigated but not included in this paper are shown in the following figure 10.

Losses /Effect	Max yield gain with Multi-MPPT	Comment
heterogenous string configuration	**up to 1 %**	**Yield gain may be reduced by lower effiency of Multi-MPPT inverter**
Near Shading losses by a tree	**~ 1 %**	**Yield gain may be reduced by lower effiency of Multi-MPPT inverter**
Near Shading losses by PV table with fixed tilt	< 0.1 %	for plant with optimized PR
Near Shading losses by PV table with single axis tracking	< 0.1 %	for plant with optimized PR
Moving Clouds	*not relevant*	*Effect can be neglected*
Soiling losses	*not relevant*	*Effect can be neglected*
Module degradation (Aging)	*not relevant*	*Effect can be neglected*
Mismatch losses due to dispersion of parameters	< 0.01 %	
Mismatch due to variation of tilt	< 0.01 %	
Mismatch due to variation of orientation	< 0.1 %	
Mismatch due to inhomogenous temperature dispersion	< 0.1 %	
Ohmic DC losses (String cable length)	< 0.01 %	
Inverter losses due to efficiency	*not considered in detail*	Data quality and reliability questionable
Inverter losses due to voltage threshold	*not relevant*	No losses if string length is designed carefully
Inverter AC output voltage	*not considered in detail*	*Detailed analysis necessary*

Figure 7: Summary and evaluation of the results

One question that is not answered in this study is whether cost savings can be achieved on system level due to the higher AC voltages of multi-MPPT inverters. Another aspect which has not been discussed here is the influence of power transmissions with single-MPPT inverters based on 1500 VDC, lower cable costs and reduced cable cross sections. However, by referring to the "Virtual Central approach of PV string inverters – A cost benefit" study, one will have a clue on which technology best provides cost saving possibilities.

Neckarsulm, January 18, 2022.