



The Impact of Optimizers for PV-Modules

A comparative study

Assoc. Prof. Dr. W.-Toke Franke

Research report, May 2019

Summary

This study shows that PV systems have typically a higher yield if no module optimizers are applied. To demonstrate that, extreme scenarios have been chosen where optimizers are expected to bring the highest benefits. But only for some small niches where complete PV modules have significantly different irradiation at any given time, do the optimizers help produce more energy than they actually consume.

Contents

1	Introduction	3
1.1	Concepts for PV-Inverters	3
1.2	String Inverters	3
1.3	Maximum Power Point Tracker	4
1.4	Module Optimizer	5
1.5	Purpose of the Investigation	5
1.6	The Test setup	6
1.6.1	The Test Site	6
1.6.2	PV inverter system selection	6
1.7	Data Acquisition	7
2	Test Results	8
2.1	Scenario with no shadow	8
2.1.1	Period	8
2.1.2	Sunny Day	9
2.1.3	Cloudy Day	10
2.1.4	Conclusion	11
2.2	Scenario with different irradiation at one module	12
2.2.1	Period	12
2.2.2	Sunny Day	13
2.2.3	Cloudy Day	14
2.2.4	Conclusion	15
2.3	Scenario with moving shadow over the day	16
2.3.1	Period	16
2.3.2	Sunny Day	17
2.3.3	Cloudy Day with many changes between sun and clouds	18
2.3.4	Overcast Day without sunshine	19
2.3.5	Conclusion	19
2.4	Energy production over one year	20
3	Final Conclusion	21

1 Introduction

1.1 Concepts for PV-Inverters

In general PV-inverters can be categorized according to their topologies [1]:

- Module integrated inverters: Each PV-module has its own PV inverter with a single-phase grid connection and a typical power range of 50 to 400 W.
- String Inverters: A String of several PV-modules is connected to one inverter with a single-phase grid connection and a typical power range of 0,4 to 5 kW.
- Multistring inverters: One or more strings are connected to one inverter often with individual maximum power point trackers (MPPT). The grid connection can be single- or three-phase depending on the power rating that is typically between 1,5 and 150 kW
- Central inverter: Multiple strings are connected to one MPP-Tracker. The inverter has a three-phase grid connection and a power rating between 100 and 5000 kW.

In this report the focus is on residential and commercial string inverters.

1.2 String Inverters

The general concept of a string inverter is shown in Figure 1. The PV generator consists of several identical PV-modules which are connected in series to a PV-string. The number of PV modules per string is given by the minimum and maximum input voltage of the inverter. To increase the input range of the inverter to lower voltages, it often has a boost converter at the input stage that ensures that the DC to AC inverter stage has always a sufficient input voltage to feed energy to the grid.

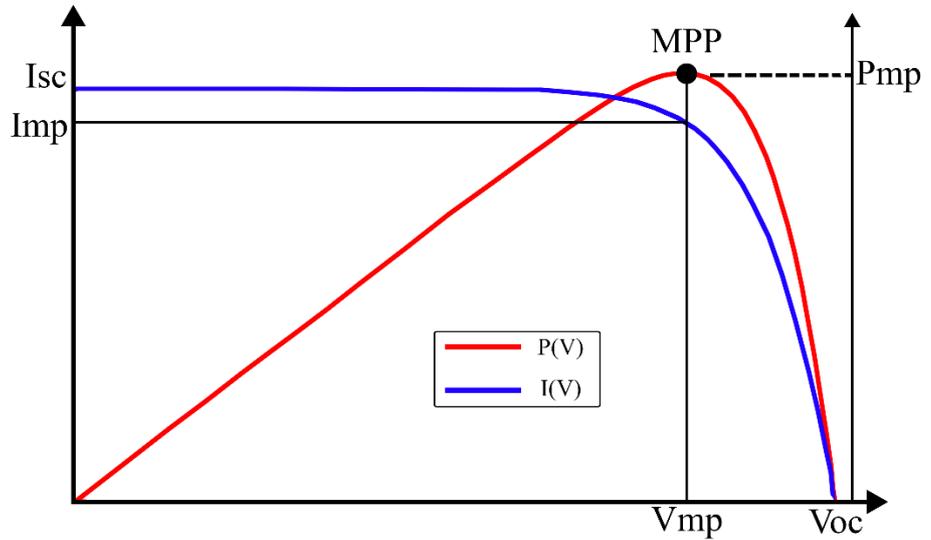
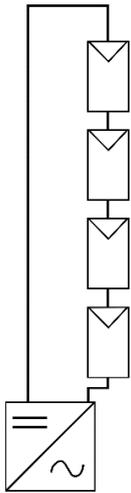


Figure 1: String concept Figure 2: Voltage-Current-Power Characteristic

1.3 Maximum Power Point Tracker

The electric characteristic of a solar module and thereby also the characteristic of a PV string is shown in Figure 2 [2]. The curve shows that for a certain voltage a certain current can be drawn from the string. For the maximum current (short circuit current) the voltage is zero and for the maximum voltage (Open circuit voltage) the current is zero. In both cases also the power is zero, so that no energy can be produced. To find the current and voltage with the maximum power, the area below the curve need to be maximal [3].

The maximum power point tracker controls the current in a way such that the maximum power is always obtained from the PV-string. If the irradiation changes the MPPT finds the new maximum power point. For conventional MPPT the technique works very well if all PV modules have the same irradiation meaning no shading and the same orientation. If the irradiation changes at only a few PV-modules for example due to partial shading the curve changes as shown in Figure 3.

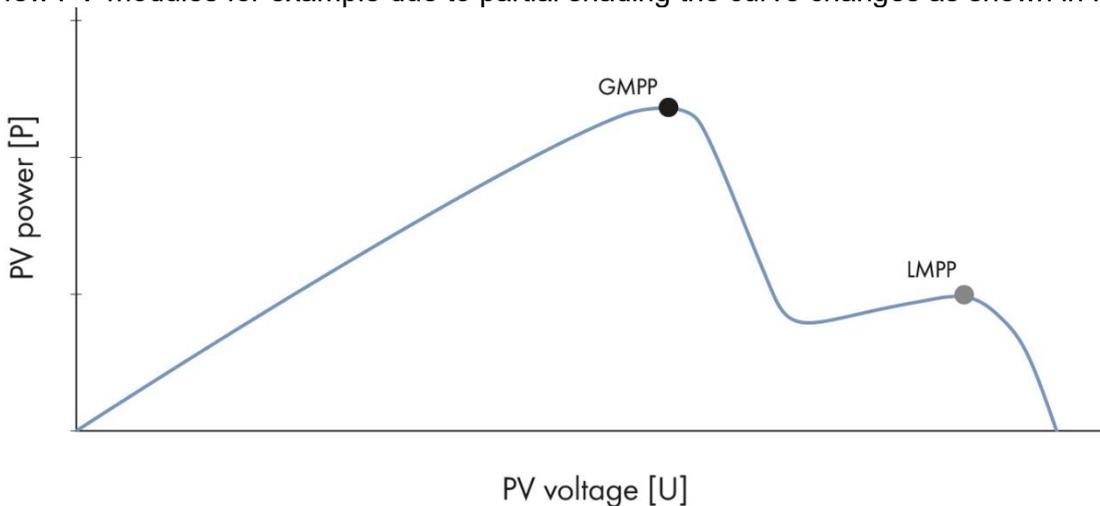


Figure 3: PV-Power with partial shading

The conventional maximum power point tracker might now only find a local maximum, shown as LMPP on Figure 3, and thereby the inverter does not deliver the maximum possible energy. Advanced MPPT have the purpose to ensure that the PV generator finds the global maximum

operating point, shown above as GMPP, by performing a sweep over the complete voltage range. Such a sweep needs to be executed from time to time since the shading might change over the day and, depending on the shadow, the tracker might find only a local MPP after a cloud passes the string. Different orientations of the PV modules have similar effect as shading.

1.4 Module Optimizer

Module optimizers or module-level power electronics (MLPE) have the purpose to ensure that each module is always working in its optimal operating point [4]. Therefore, an additional device – the optimizer – is connected to each PV module. The typical functions of an optimizer are:

- Local MPP-Tracking for each module
- Disconnection of the module to limit the system voltage in case of a failure
- Monitoring on module level

But module optimizers also come with a few drawbacks:

- MLPE have an energy self-consumption that leads to additional power losses in both the additional connectors and more significant in the internal power electronics
- Any electrical connector is a potential failure source (fire or breakdown of string), especially if connectors from different manufacturer are applied (this is typically the case, since PV modules and MLPEs are coming from different companies)
- An increase in the number of components also increases the risk that one of the components fails

There are different solutions available on the market: Some follow a universal approach, so that the optimizers work in an open ecosystem and can be connected to nearly any PV-inverter (e.g. Tigo). Other follow a proprietary concept, where the MLPEs and PV-inverters operate in a closed ecosystem (e.g. SolarEdge).

1.5 Purpose of the Investigation

As described in section 1.4 optimizers have a couple of advantages and disadvantages. This research project is to better understand the total effect on the energy production of different inverter-optimizer systems in relation to an inverter with advanced power point tracking.

Therefore, three different scenarios are investigated:

- The first scenario represents an optimal installation where all PV panels have the same irradiation and no shadows occur (Chapter 2.1).
- The second scenario simulates a niche application where one PV-module has always a different irradiation than the others. This is achieved by covering one module with a thin and semi-transparent blanket, while the remaining 13 modules of each string have the full irradiation (Figure 8). An application for that could be that this module has a different orientation compared to the rest of the string. (Chapter 2.2)
- The third scenario simulates a situation where a small shadow moves over the panels during the day. Therefore, a pole of 1,2 m high and 20 cm diameter is placed in a distance of 30 cm from the PV panels in the middle of each PV- string as shown in Figure 12. Over the day the shadow of the pole moves over the panels in the morning and in the evening shading up to 4 modules, while at noon only one module is shaded. This example simulates partial shading coming from nearby objects such as a chimney or dormer affecting a portion of the PV-array during the typical day. (Chapter 2.3)

1.6 The Test setup

1.6.1 The Test Site

The test site is a small ground mounted PV field in southern Denmark. It consists of 42 identical PV modules with an orientation to south-south-west (201 degree) (Figure 4).



Figure 4 Satellite picture of test site (Source: google maps)

The tilt is fixed to 42 degree.

The 42 panels in the red box in Figure 4 are connected in three strings. The first 14 panels from the left (seven of the lower row, seven of the upper row) are equipped with an open optimizer system (MLPE system A) that can be connected to nearly any inverter. These optimizers are connected to each PV module. The 14 panels in the middle feed their energy through a proprietary optimizer system (MLPE system B). Also, here MLPEs are installed to each PV-Module, but in contrast to an open system, a dedicated inverter is needed. The 14 panels most right in the red box are directly connected to a modern string inverter with advanced MPP-tracking.

1.6.2 PV inverter system selection

To achieve comparable results similar power ratings for all three inverter systems have been chosen. For the reference system without MLPEs a modern string inverter with advanced MPPT from SMA is chosen. For the MLPE system A optimizers from Tigo and the same inverter as for the reference system is selected. In that way the impact of the optimizers on the overall performance can be easily investigated. For the MLPE system B an inverter-optimizer system from SolarEdge is chosen. Table 1 shows which components are applied for the different inverter systems.

Table 1: Components for the different PV inverter systems

PV-Inverter System	Components	EU-Efficiency
Modern String Inverter	SMA SB3.6-1AV-40	96,5%
MLPE System A	SMA SB3.6-1AV-40 + Tigo TS4-R-O MLPE	96,5% _{inverter} x MLPE efficiency
MLPE System B	SolarEdge SE HD Wave 3,6 + P300 MLPE	98,8% _{inverter} and 98,8% _{MLPE} combined total 97,6%

Since the aim of this study is not to compare DC to AC conversion efficiency of inverters, but the impact of optimizers on the overall energy production, only the real measured data are considered for this study. However, the reader should keep in mind that future generations of string inverters with higher efficiency will further increase the energy yield compared to systems equipped with optimizers.

1.7 Data Acquisition

The energy production is recorded by measuring current and voltage at the grid side of the inverters every 5 seconds. For the data recording the WattsOn Universal Power Transducer from ELKOR is applied. The absolute accuracy of the power reading is specified by 0.2%. However, for this investigation the deviation between each channel is most relevant. Therefore, pre-test have been conducted where all channels have measured the same current and same voltage. The output reading was exactly the same for all channels and thereby allowing a fair comparison of the three different systems.

Over the course of the year it occurs that some test arrays are unevenly shaded from nearby trees after 5:22 pm. To ensure that this has no bias on the results, comparative measurements are only taken until 5:22 pm each day.

2 Test Results

2.1 Scenario with no shadow

The test site was running from 31.5.2018 to the 14.08.2018 without any artificial shading. To insure equal conditions the panels were cleaned on the 30.05.2018.

2.1.1 Complete testing period

The energy production over the whole period is shown in Figure 5. The daily production averaged over the 3 systems is shown as yellow bars with the scale on the right side. The curves show the relative power systems generation where the system without any module optimizer is the reference (red line, 100%). Relative to that are the two systems with module optimizers. The blue one is MLPE system B and the green one the MLPE system A.

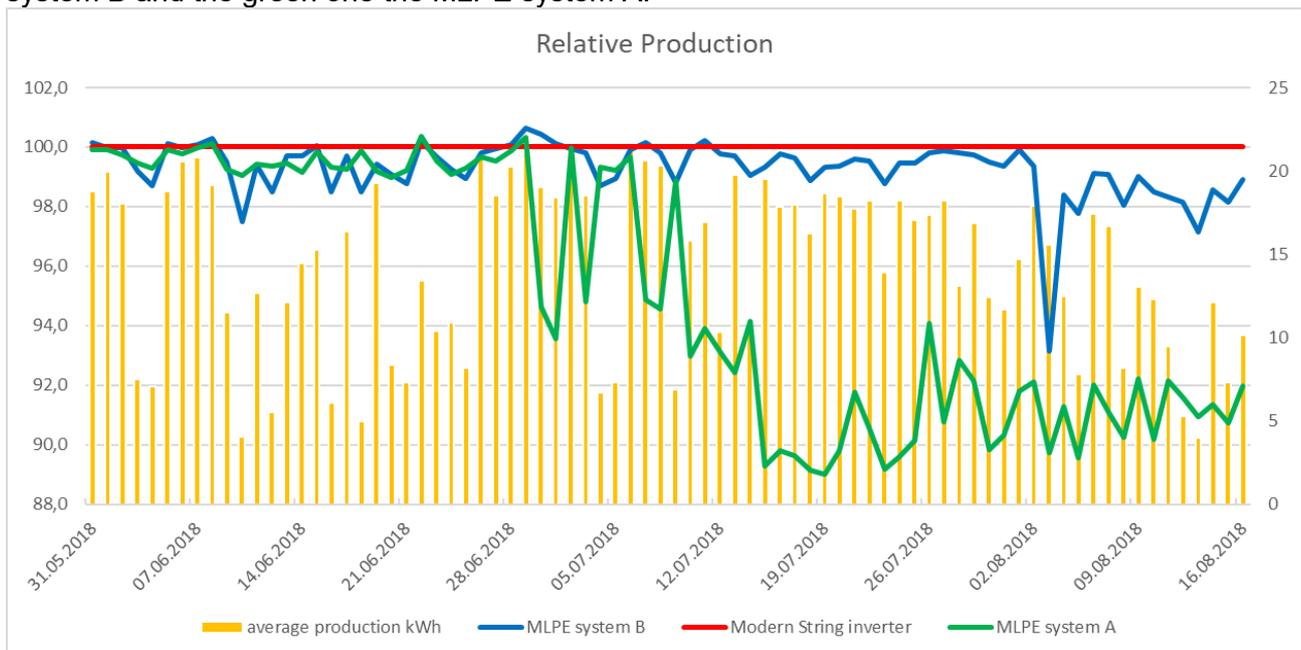


Figure 5: Energy production without shading

There are two main findings from this period: For a system without any shadows over the day, the highest energy harvest is achieved without any optimizers clearly visible by the red line that is always on top of the others. The reason for that can be found in the power electronic architecture of the systems: The system without any optimizer consists only of the modules, the connectors between the modules and the inverter that is made of a booster for MPP-tracking and the bridge circuit for the AC output. The two systems with module optimizers have one optimizer per module plus twice as many connectors. The power electronics inside the optimizers are connected in series, meaning that all the string current must pass through it. Even if the optimizers are not active, there is at least one power semiconductor device with a certain voltage drop that causes power losses (product of the current and the voltage drop). The losses of each optimizer box are within a

few Watts not very high in relation to the total production of a few kW, but since each optimizer contributes to the losses, the numbers add up and cause the difference in production as shown in Figure 5. However, this result is still surprising since the total conversion efficiency of the MLPE system B is stated by the manufacturer with 97,6% while the inverters of the other 2 systems have an efficiency of 96,5%. The MLPE system B should therefore, in theory, always outperform the other systems.

The second observation is that after a short time of operation one of the optimizers of MLPE system A failed. It is assumed that the risk of failing MLPEs is not brand specific. However, the chance that one single component fails is, by nature, relatively high for any system applying MLPEs due to the very high component count. Even though the data was recorded on a 5 second interval, the failure was not detected immediately because an analysis of the data was needed to spot the failure. Normally an automatic failure notification would be provided via a web-based notification, however this feature was not activated due to nature of this study as well as the additional costs for setting up this service.

2.1.2 Sunny Day

June 7th 2018 was a sunny day without any clouds. The energy production curves of the 3 systems are shown in Figure 6. It could be seen, that during the dawn a minor production begins. As the sun rises, the production follows the typical bell-shaped curve. As discussed in section 1.7, from app. 6:00pm onwards neighbouring trees begin to cast a shadow on a portion of the PV array from the west. The first system affected by the afternoon shading is the MLPE system A and later reaching also the modules of the MLPE system B.

The total energy production is very similar for all three systems with a slightly higher peak production of the system without any optimizers. Numerically this is expressed in Table 2.

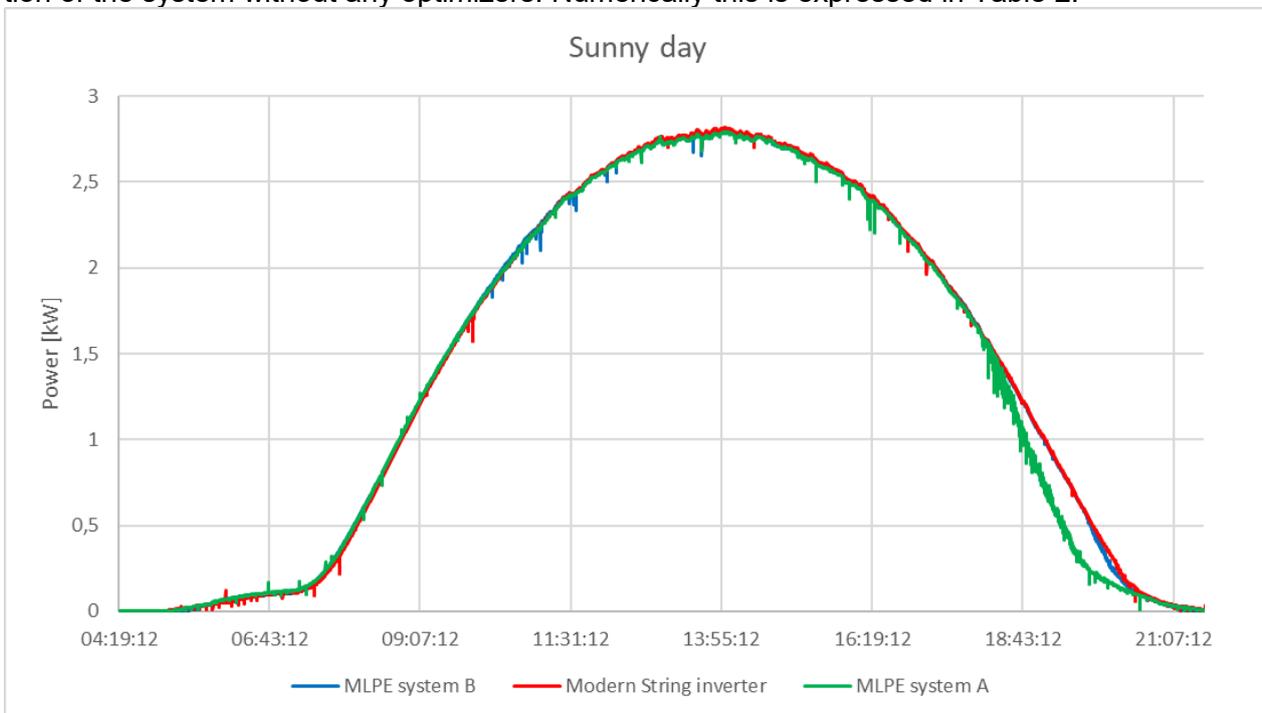


Figure 6: Energy production on a day (7.6.2018) without shading

Table 2: PV production until 5:22pm

Date: 7.6.2018	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	20,870	20,917	20,831
Percentage difference to string inverter w/o MLPEs	99,8%	100,0%	99,6%

Without optimizers the energy production is 0,2 to 0,4 percentage points higher than with optimizers.

2.1.3 Cloudy Day

June 9th 2018 starts off overcast. Around noon the clouds begin to recede a bit and it was partly cloudy until the afternoon. The energy production curves of the three systems are shown in Figure 7. Once again, it is observed that the modern string inverter has a slightly higher production over the entire day. As shown in Table 3 the use of optimizers results in about 1% lower energy harvest on a typical cloudy day.

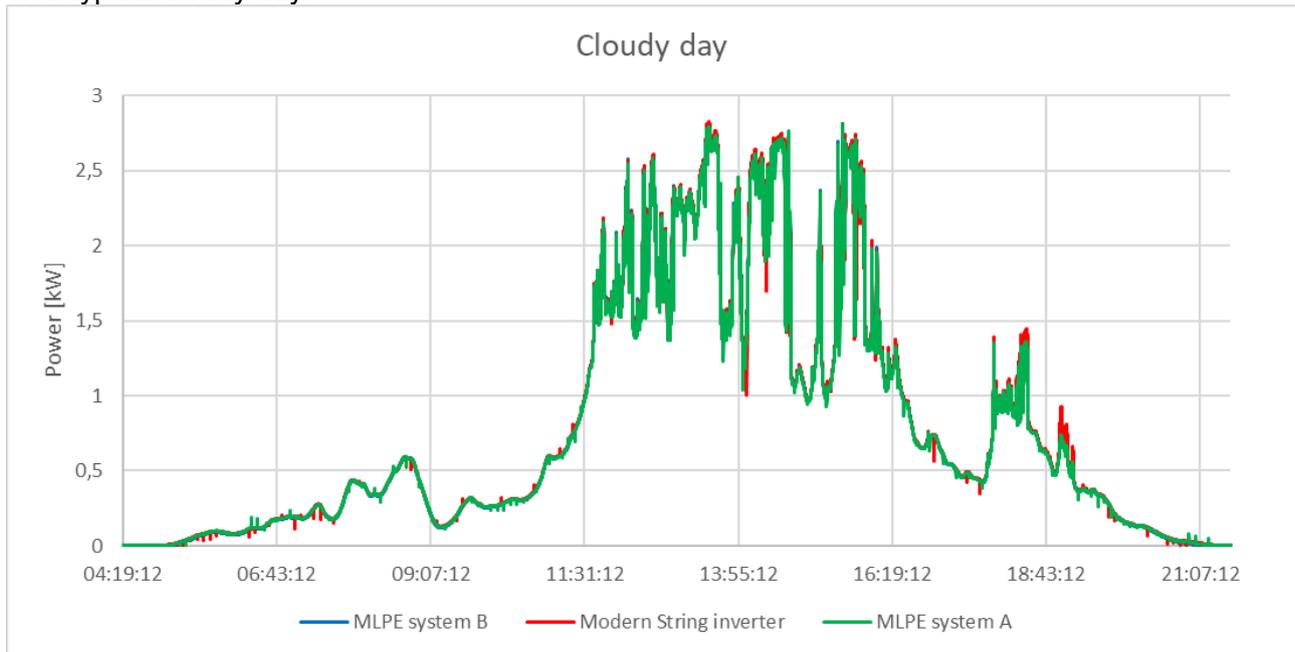


Figure 7: Energy production on a single day (9.6.2018) without shading

Table 3: PV production until 5:22 pm

Date: 9.6.2018	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	11,520	11,602	11,475
Percentage difference to string inverter w/o MLPEs	99,3%	100,0%	98,9%

2.1.4 Conclusion

Comparing the result without any shading of a sunny day and a cloudy day it can be observed that the difference between a system with optimizers and a system without is more pronounced on days with clouds. The reason for this is the result of the power consumed by the optimizers themselves. The energy required to operate the optimizers is independent from the weather conditions. If the solar irradiance is low, the impact of the MLPE self-consumption on the total energy production increases, and therefore the overall performance of the optimizers at low irradiation is less effective compared to a modern string inverter.

In general, it can be concluded that optimizers for PV-installations that have no shading elements provide less benefit regarding energy production than a modern string inverter-based system with advanced MPP tracking. Furthermore, the risk for failing components increases which leads to additional cost for service and due to reduced yield.

2.2 Scenario with different irradiation at one module

As described in section 1.5 the scenario simulates one PV module with constantly a different irradiation.



Figure 8: Reduced irradiation setup

2.2.1 Complete measuring period

The period where one out of 14 modules has been constantly shaded with a thin cotton sheet to simulate a different orientation of this module from the rest of the string lasted from mid of August until end of September (Figure 9). The broken MLPE of system A was exchanged on the same day when the sheets were installed.

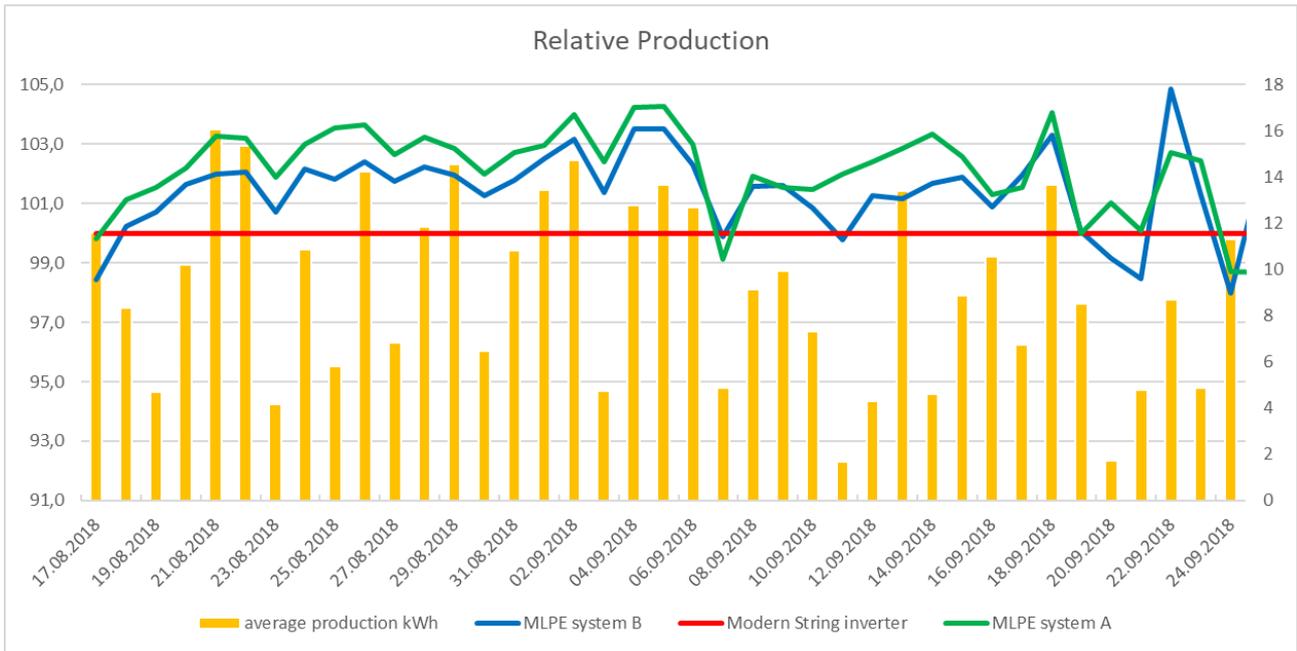


Figure 9: Energy production with constant shading

2.2.2 Sunny Day

August 22nd, 2018 was the sunniest day within the period with reduced irradiation on one module. The energy production curves of the three systems are shown in Figure 10. The systems with optimizers compensate best the module with reduced irradiation, the blue and green lines are always on top of the red curve for the system without any optimizers. In absolute values MLPE system A delivers 0,477kWh and MLPE system B 0,294kWh more energy before the external shadow from the nearby trees distorts the comparison (Table 4).

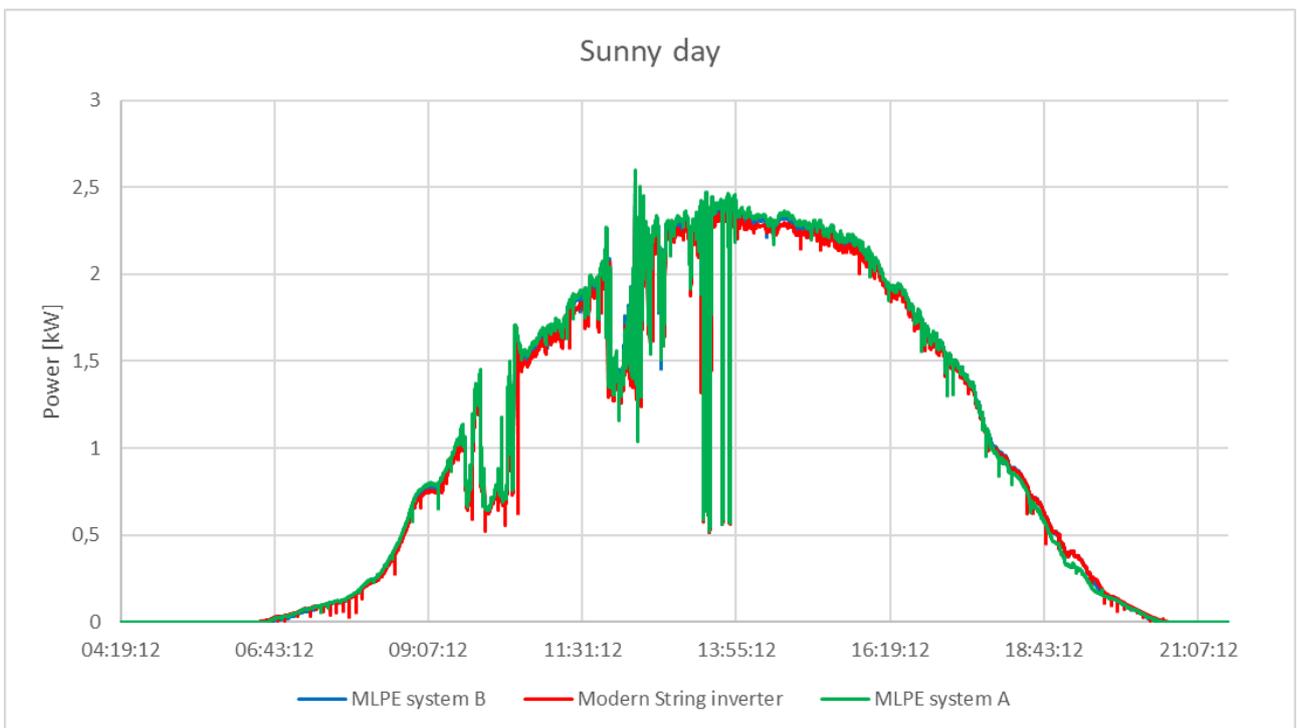


Figure 10: Energy production on a single day (22.8.2018) with constant shading

Table 4: PV production until 5:22pm

Date: 22.8.2018	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	15,389	15,178	15,572
Percentage difference to string inverter w/o MLPEs	101,4%	100,0%	102,6%

2.2.3 Cloudy Day

August 23rd, 2018 was overcast with a few minutes of sunshine at noon (Figure 11). The positive effect on the energy production of the optimizers is also measurable at low irradiation, but the overall gain is reduced mainly due to the more pronounced energy self-consumption of the optimizers. In absolute values MLPE system A delivers 0,063kWh and MLPE system B 0,021 kWh more energy before the shadow by nearby trees distorts the comparison (Table 5).

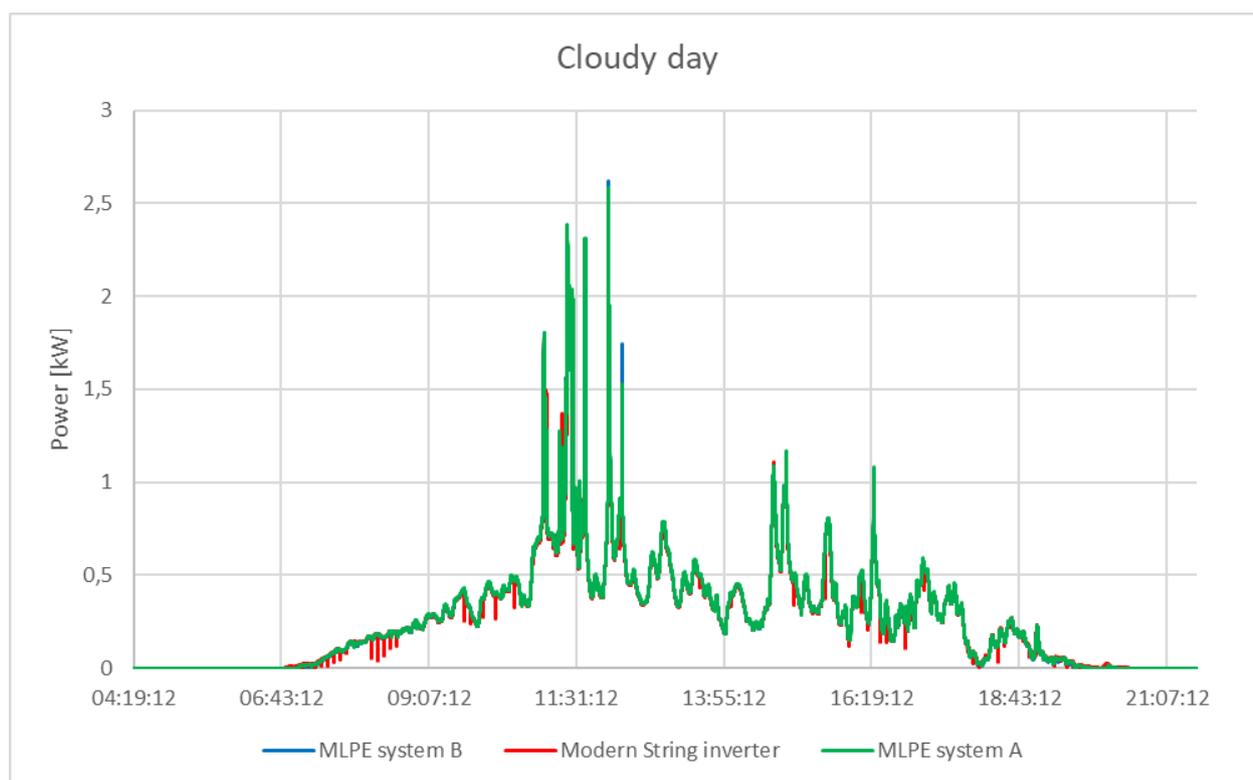


Figure 11: Energy production on a single day (23.8.2018) with constant shading

Table 5: PV production until 5:22pm

Date: 23.8.2018	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	4,189	4,178	4,241
Percentage difference to string inverter w/o MLPEs	100,3%	100,00%	101,5%

2.2.4 Conclusion

In situations where it is impossible to install all modules of a string in the same orientation, so that one or more modules always have a different irradiation exposure, optimizers can improve the total energy harvest by 1-3% per module, but only if complete PV-modules are affected meaning that without MLPEs, all bypass diodes of the panel would have been active.

Conversely that means that if only parts of a panel have different irradiation (e.g. due to shadows from dormers or trees) but one internal cell string of a panel is exposed to full irradiation, one bypass diode is not active, then the optimizer cannot improve the energy harvest.

For systems with more than 4 PV-modules within a single string having a different orientation, an alternative configuration using short strings and two advanced MPP-trackers could be a better alternative.

2.3 Scenario with moving shadow over the day

As described in section 1.5 a shadow from a pole is moving over the panels throughout the day. In the late evening the shadow also hits the neighbouring string. But this does not affect the results, since it always happens after 5:22 p.m. where no data are taken for comparison.



Figure 12: Pole placement for each PV-string

2.3.1 Complete measurement period

The considered period is from mid-April until mid-June 2019. Analysing the aggregate production over this time period, none of the systems outperform the others. The weather conditions of each day determine the relative production of each system.

A clear statement can be given for sunny days with a clear sky. In this case the system without any optimizers has the best performance mainly due to the fact the shadow during highest production point is smallest and thereby the effect of the optimizers is low.

For days with clouds, the types of clouds have to be distinguished: For overcast days without any direct sunshine the relative production is similar to sunny days. For cloudy days with many changes between sun and clouds the MLPE reacted faster to the changes in irradiance.

Calculating the production over the 2 month period, the results show almost the same energy harvest across all three systems: While the MLPE system B is 0,39 percent points higher than the system without optimizers, the MLPE system A is 0,39 percent-points lower.

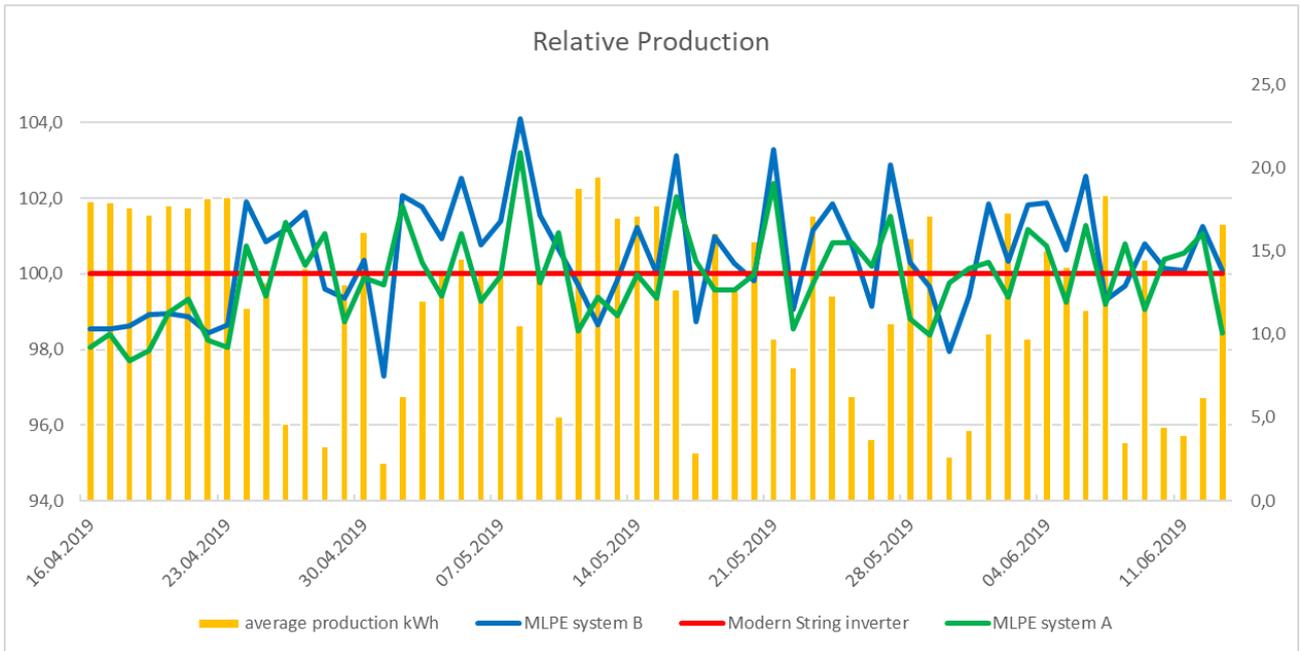


Figure 13 Energy production with moving shadows

2.3.2 Sunny Day

A typical sunny day with moving shadows looks not much different than a sunny day without any shadows (Figure 14). The curves are less even and have small peaks and dips when the shadow leaves a module or hits another one. Over noon the system without optimizers has a significant higher energy production than the others. In the morning and in the afternoon the other systems are better, mainly because more modules are shaded.

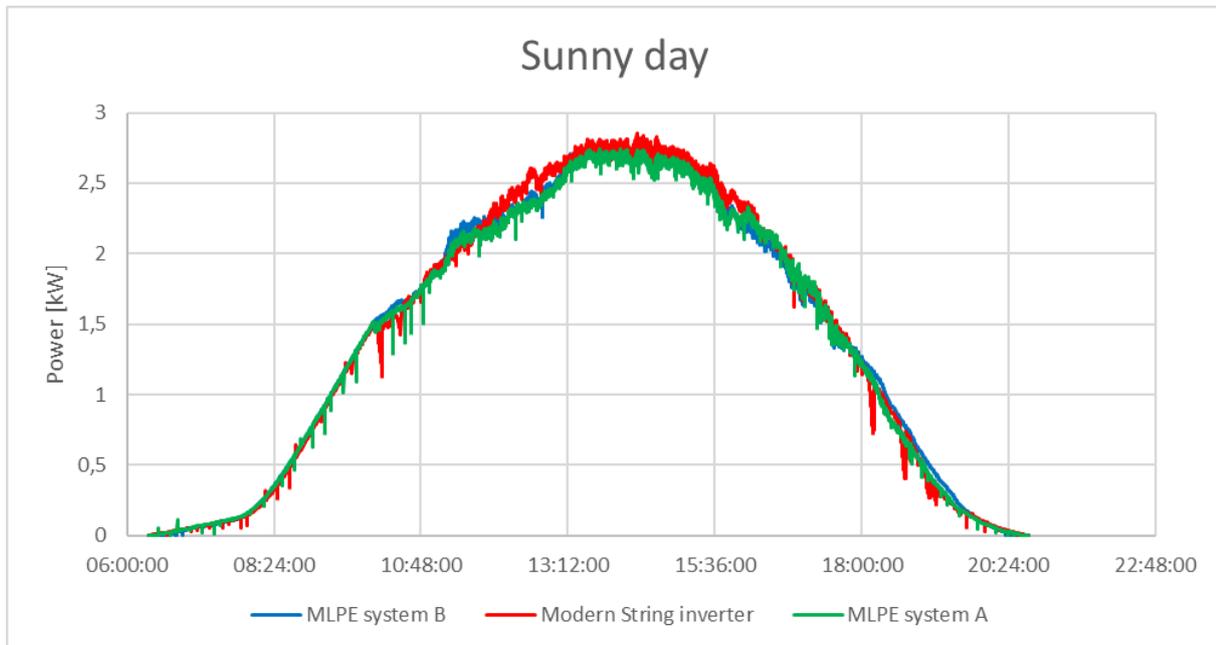


Figure 14: Energy production on a single day (23.4.2019) with moving shading

Table 6: PV production until 5:22pm

Date: 23.4.2019	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	18,252	18,495	18,123
Percentage difference to string inverter w/o MLPEs	98,7%	100,0%	98,0%

2.3.3 Cloudy Day with many changes between sun and clouds

For cloudy days the optimizer systems perform better with the settings applied. One reason for that might be, that after a cloud the systems with optimizers will find the MPP faster, while the system without optimizers might first get into a local maximum and stay there until MPP tracking system finds the global maximum by performing a sweep. The absolute numbers in Table 7 confirm that.

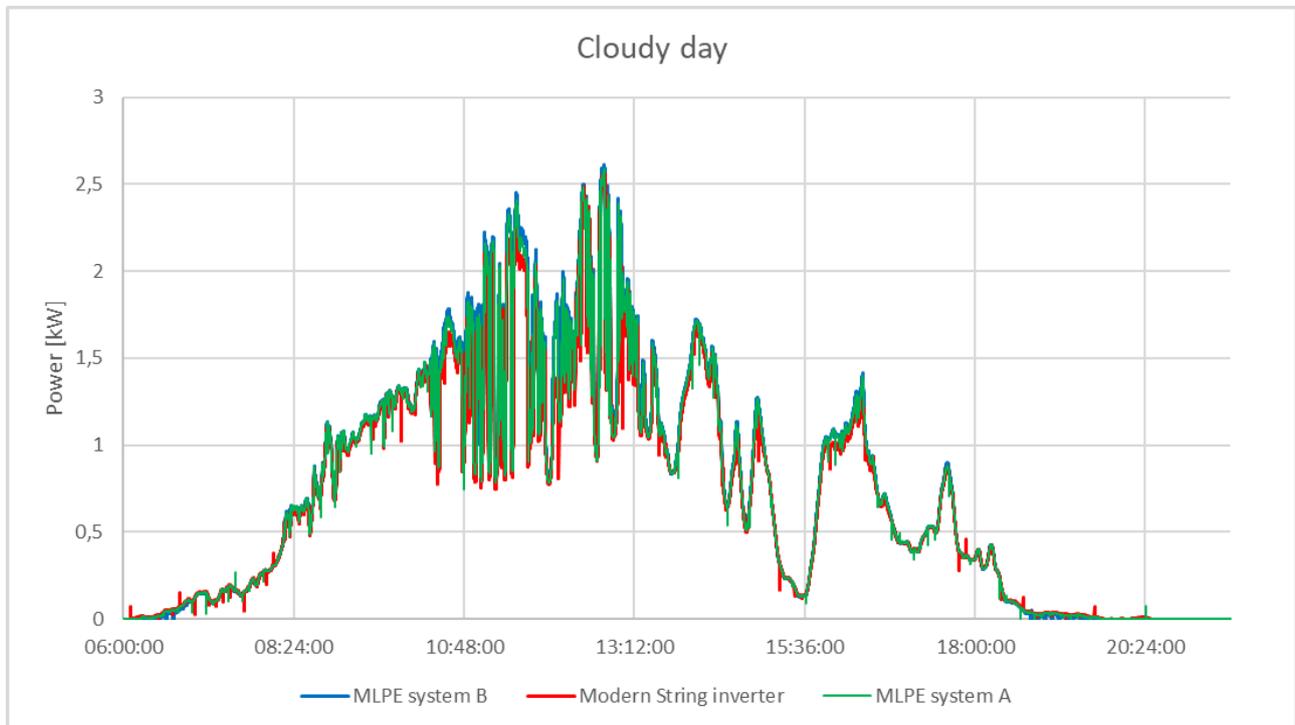


Figure 15 Energy production on a single day (8.5.2019) with moving shading

Table 7: PV production until 5:22pm

Date: 8.5.2019	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	10,726	10,295	10,612
Percentage difference to string inverter w/o MLPEs	104,2%	100,0%	103,1%

2.3.4 Overcast Day without sunshine

For overcast days without direct sun on the PV panels, the system without optimizers achieves the highest energy harvest. Due to the steady irradiation the MPP- tracker stays in its global maximum. The efficiency losses of the MLPEs lead to a lower energy production. The numbers in Table 8 confirm that.

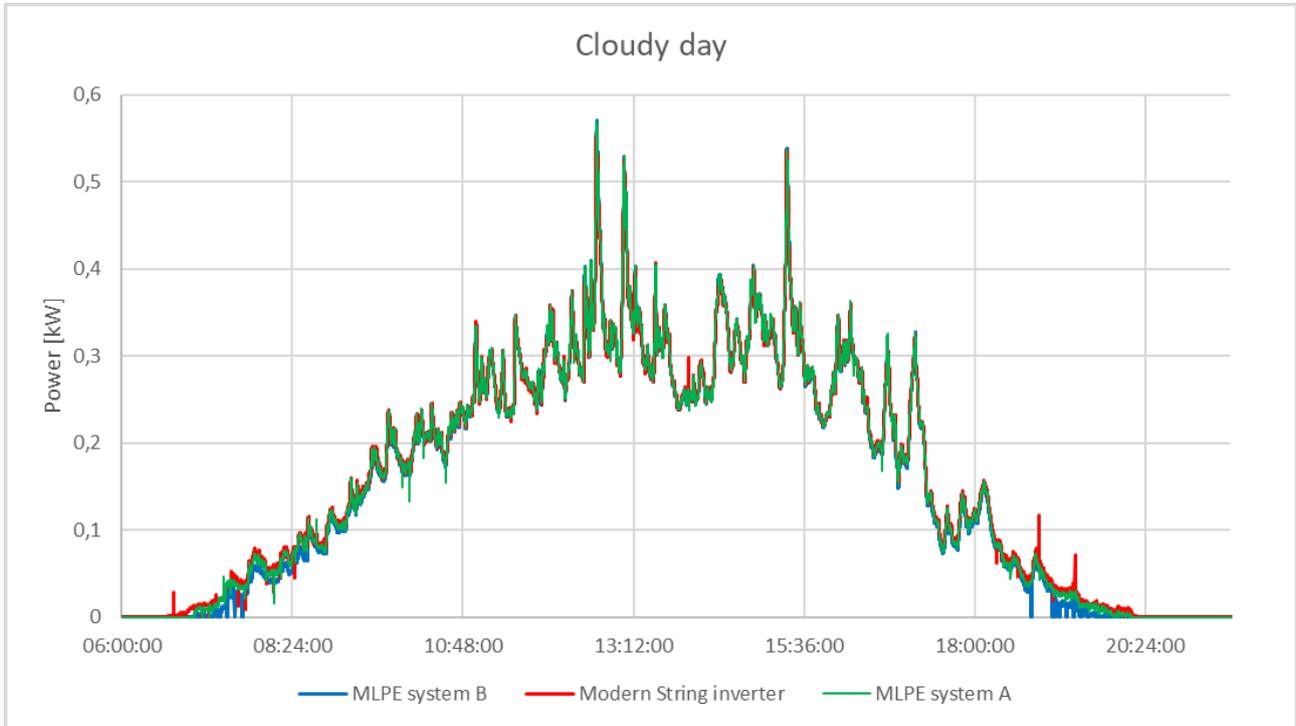


Figure 16 Energy production on a single day (1.5.2019) with moving shading

Table 8: PV production until 5:22pm

Date: 1.5.2019	MLPE system B	Modern String inverter	MLPE system A
Production [kWh]	2,309	2,350	2,341
Percentage difference to string inverter w/o MLPEs	98,3%	100,0%	99,6%

2.3.5 Conclusion

The shadow of a single pole influences the energy production depending on the weather conditions.

For sunny days the energy production cannot benefit from optimizers since the shading is only on parts of a PV module and the optimizer has no possibilities to optimize the energy harvest on submodule level.

For days with fast-moving clouds and thereby many alternations between sun and shadow the systems with optimizers show some advantages since they appear to be more dynamic in finding the global maximum. It can be expected that a more dynamic MPP tracking in the string inverters would yield similar results.

On overcast days all modules are exposed to the same diffuse irradiation. This leads to a reduced energy harvest in the systems with optimizers due to their self-consumption.

Despite the observed small advantages of optimizers during days with quickly changing irradiation, the overall production in this observation period is equal for all three systems.

2.4 Energy production over one year

Taking the total energy production over one year with all the different scenarios taken into account, all systems are on a similar level with the modern string inverter slightly outperforming the others, see Table 9. The significant lower production of MLPE system A is mainly due to the defective optimizer in the beginning of the experiment. This also shows the impact of failing MLPE. By comparing only the daily production, such a failure it is very hard to notice since the missing production is still within typical variation of production. Only a detailed analysis or the observation over a longer period allows the detection of such an event. Therefore, a monitoring system for the optimizers should be installed and broken optimizers should ideally be replaced immediately after the detection of the failure.

Table 9: total PV production over 1 year until 17:22

Date: 31.5.2018-13.6.2019	MLPE sys- tem B	Modern String in- verter	MLPE sys- tem A
Production [kWh]	1.453,578	1.454,261	1.418,588
Percentage difference to string inverter w/o MLPEs	99,95%	100%	97,55%

3 Final Conclusion

The common marketing claims of additional energy production by applying optimizers could not be confirmed by this experiment. In fact, there are only very few scenarios where the use of optimizers improves the system performance. The most significant scenarios are when the modules of one string have different orientations or if ample shadows cover complete modules for a large portion of the day. Often these scenarios can be avoided by a proper layout of the PV-string.

Even if the shadow of a streetlight pole, a flagpole, power pole, chimney or dormer shades the string, the optimizers do not lead to a significant gain in energy production. Especially, if the pole is further away from the PV panels than in this experiment, the shadow will get more diffuse and even less impact is expected.

In addition, the risk of a failing component in one of the many MLPEs should not be underestimated. Finally, the additional connectors for the optimizers come with risk of bad connections that could lead to a failing system or even worse be the root cause for a fire. This risk is much more than doubled since systems from different manufacturers (Module and optimizer producer) are combined, and often the connectors do not exactly fit to each other.

A concluding overview is given in Table 10.

Table 10: Overview of collected data

	MLPE system B	Modern String inverter	MLPE system A
No shading			
Clear sky	99.8%	100%	99.6%
Overcast	99.3%	100%	98.9%
Different orientation of single module			
Clear sky	101,4%	100,0%	102,6%
Overcast	100,3%	100,0%	101,5%
Shading by pole			
Clear sky	98,7%	100,0%	98,0%
Cloudy	104.2%	100,0%	103.1%
Overcast	98,3%	100,0%	99,6%
Overall			
Data of the year	99.95%	100%	97.55%

Literature

- [1] R. Teodorescu, M. Liserre, P. Rodriguez, and F. Blaabjerg, *Grid Converters for Photovoltaic and Wind Power Systems*. John Wiley and Sons Inc, 2011.
- [2] M. Kaltschmitt and A. Wiese, *Erneuerbare Energien*. Springer-Verlag, 1997, pp. 177-196.
- [3] A. A. Elbaset, S. A. M. Abdelwahab, H. A. Ibrahim, and M. A. E. Eid, *Performance Analysis of Photovoltaic Systems with Energy Storage Systems*. Springer, 2019.
- [4] B. K. Bose, *Power Electronics in Renewable Energy Systems and Smart Grid: Technology and Applications*. Wiley, 2019.

