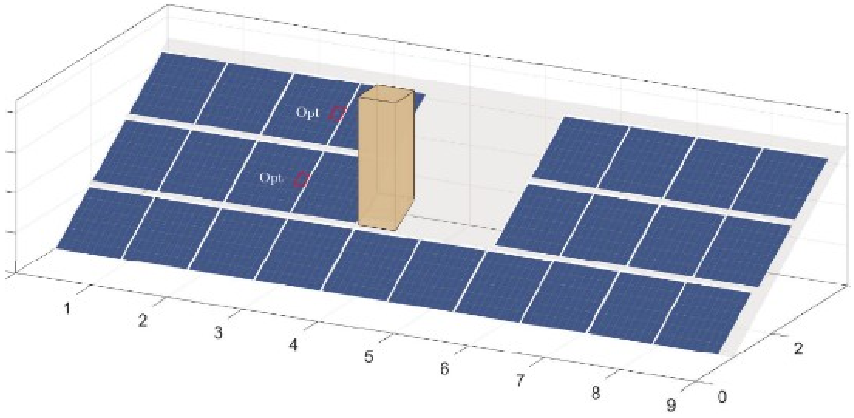
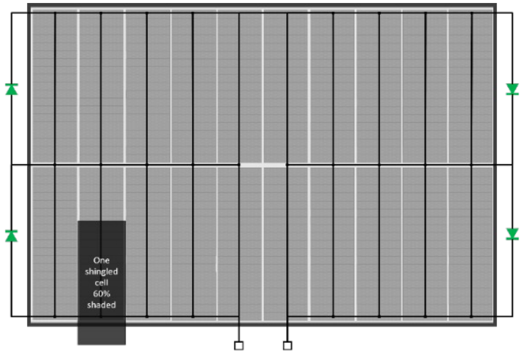
Zurich University
of Applied Sciences

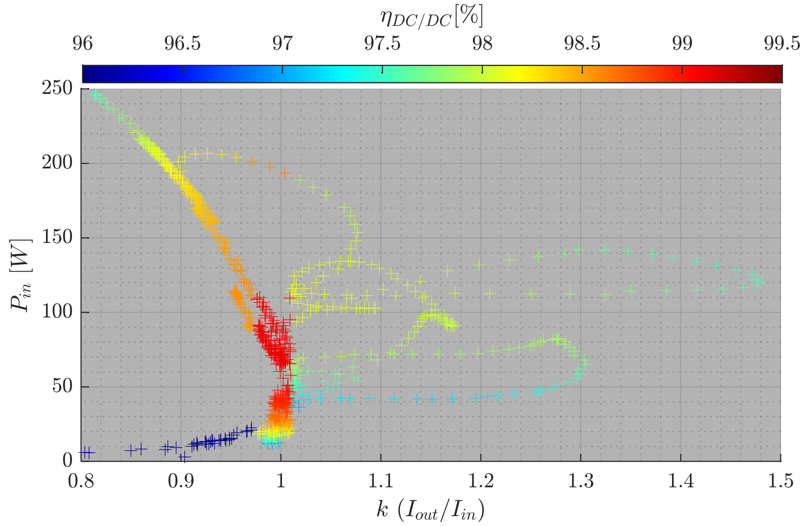
School of Engineering

IEFE Institute of Energy Systems
and Fluid-Engineering

Weniger Komplexität und mehr Zuverlässigkeit hinter jedem Solarmodul

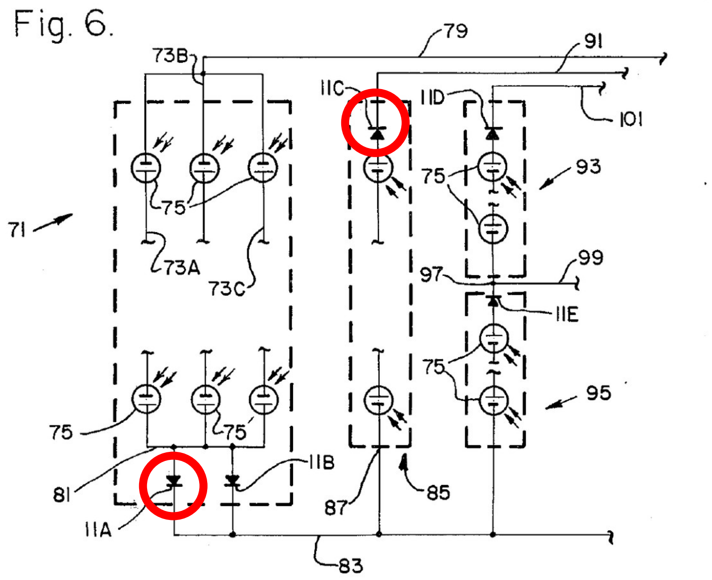


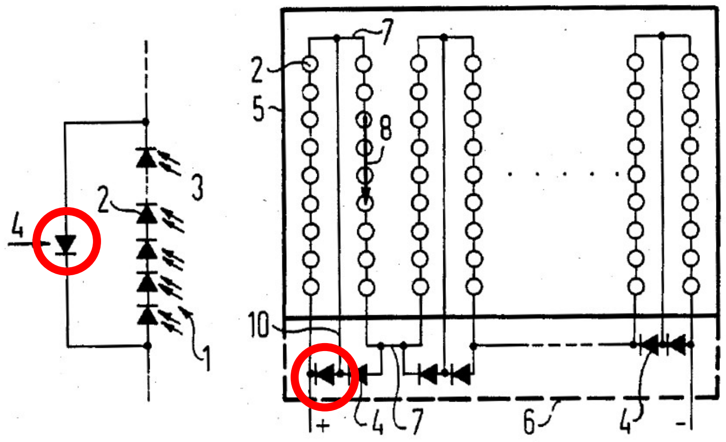


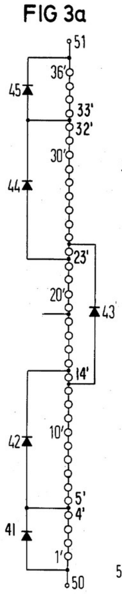


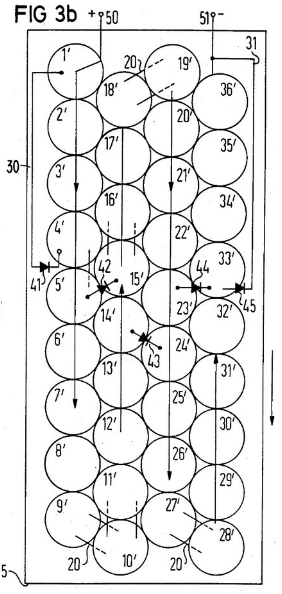
F. Baumgartner, A. Widler, L. Baumann, Cyril Allenspach
Zurich University of Applied Sciences, School of Engineering, IEFE, Switzerland;   www.zhaw.ch/=bauf
Energie-Innovationen, Vortrag in Session D2 am 15.02.2024, Graz, Österreich

Blocking- and bypass diodes to protect PV modules









Blocking diode
Wolff, G. et al., 1973 patent US3952324
Solar Panel Mounted Blocking Diode
Hughes Aircraft, California US

Bypass diode
Hollaus, R. et al., 1984 applied, patent US 4567316
Solar Cell Modul
Siemens, Germany

Time line in PV module BD design and shading analyses

- 1964 PV in Space started with diodes to fix malfunction; W. Baron, Effect of shadows
- 1984 Bypass Diodes (BP) wiring in the PV module - Siemens
- 1994 DC/AC Module inverter OKE4 – H. Oldenkamp – EUPVSEC, Solar Energy2003
- 2010 DC/DC Solar Edge introduced Optimizer – EUPVSEC talk
- 2017 Low forward voltage (30mV) bypass diode for each cell – W.v. Sark, Prog. PV
- 2020 Losses of Optimizer are critical – ZHAW – EUPVSEC 20 & 21
- 2021 Electrical Yield of shaded single modules, several BD– TU Delft, Solar Energy
- 2022 Short strings & string inverters, reliabiltiy – Tesla white paper
- 2023 Shading Tolerant Utility Module Wiring – ISE FhG - L. Rendler, IEEE PVSC

Power electronic setups used by PVshade

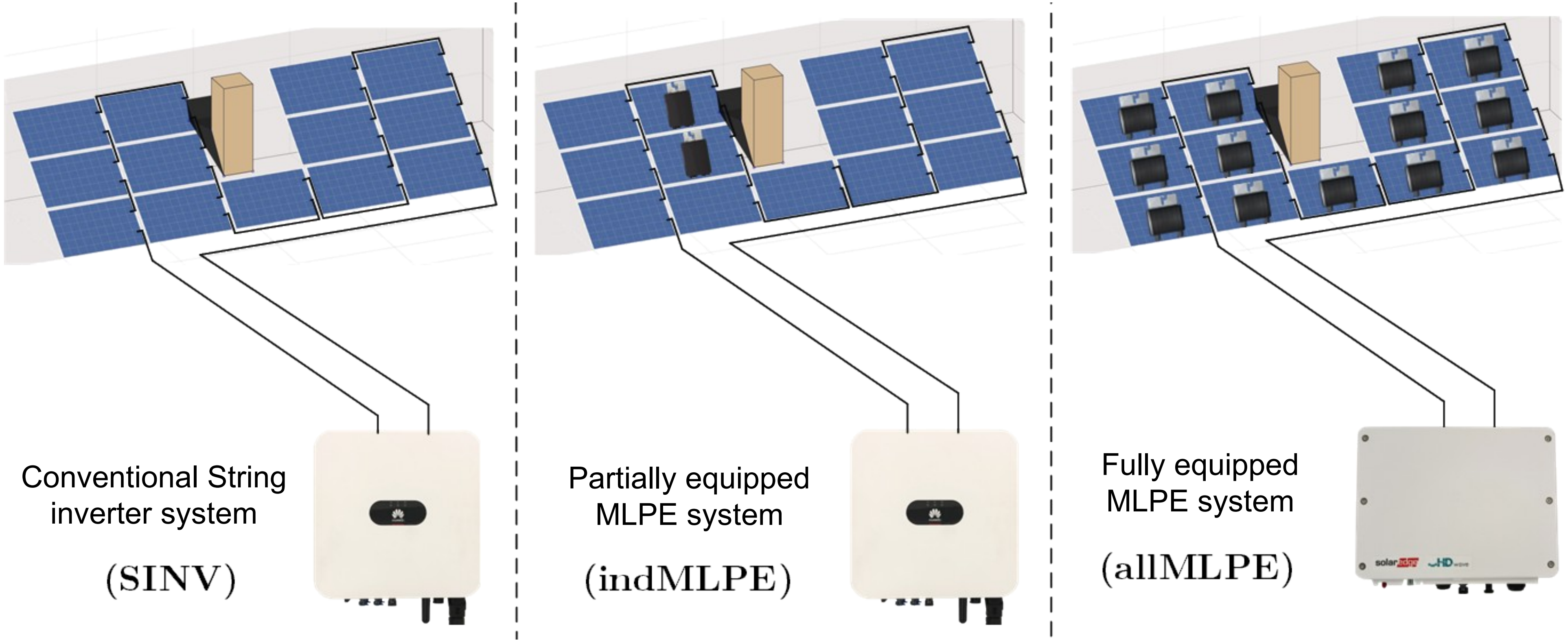
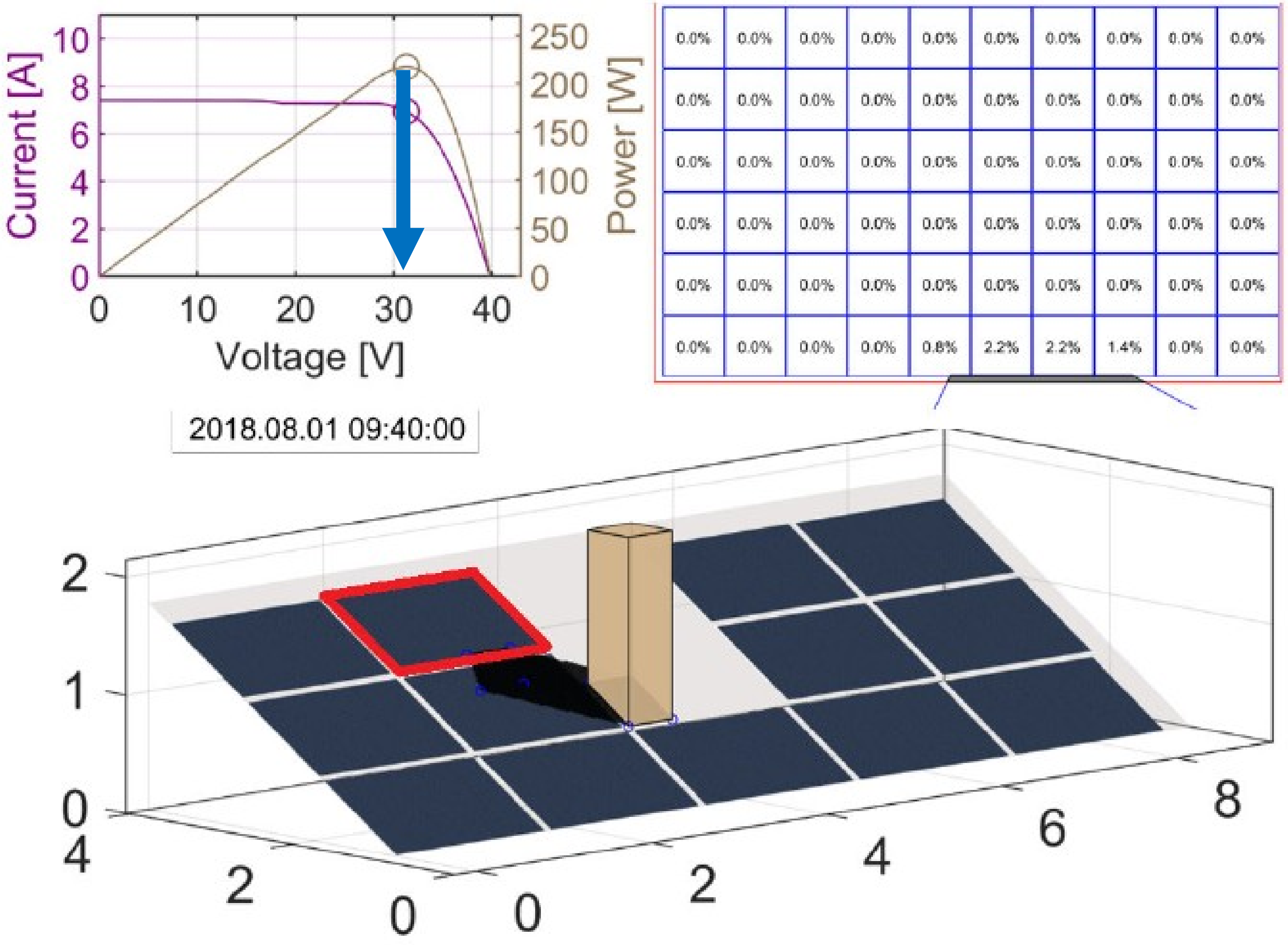


Abb. 6 – Overview of common PV system configurations investigated in the thesis (from left to right). Conventional string inverter system without MLPE (SINV), system with independent optimizer in which a few shaded PV modules are equipped with power optimizer of the buck converter type (indMLPE) and a PV system in which all PV modules are equipped with a power optimizer (allMLPE).

Example: Shading situation 1 at 9:40

- Optimum voltage of shaded PV module at about Vmp= 30V
- MLPE and SINV equal before 9:40



2018.08.01 09:40:00

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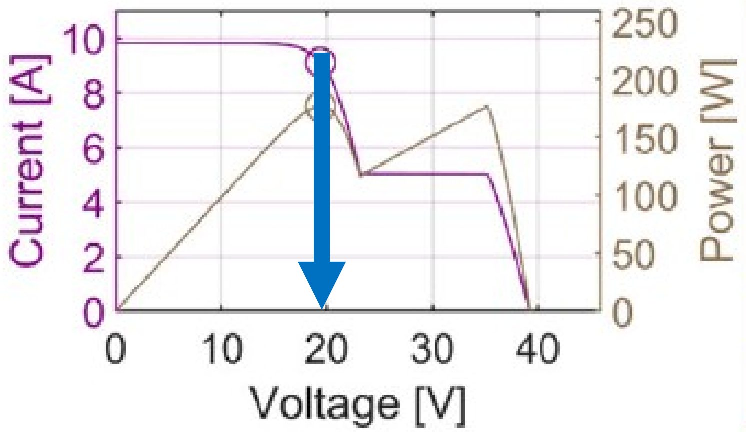
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.8%	2.2%	2.2%	1.4%	0.0%	0.0%

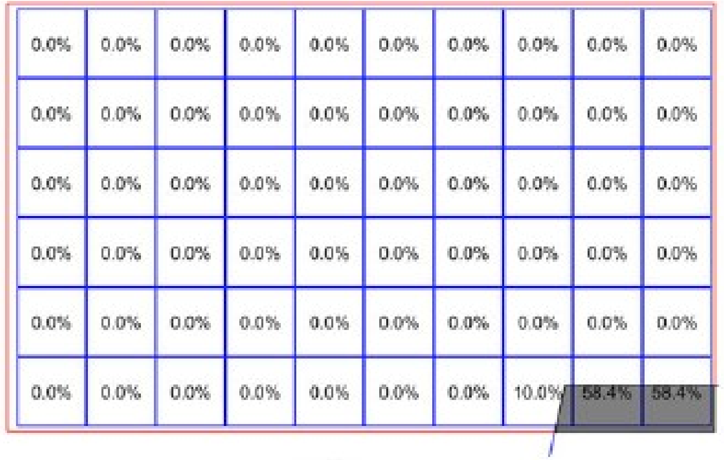
Example: Shading situation 1 at 11:05

- Optimum voltage
  of shaded PV module
  at about Vmp= 20V

- MLPE beneficial
  at 30V
  form 9:40 to 11:05

- SINV and MLPE
  same operating point
  from 11:05 to 11:50





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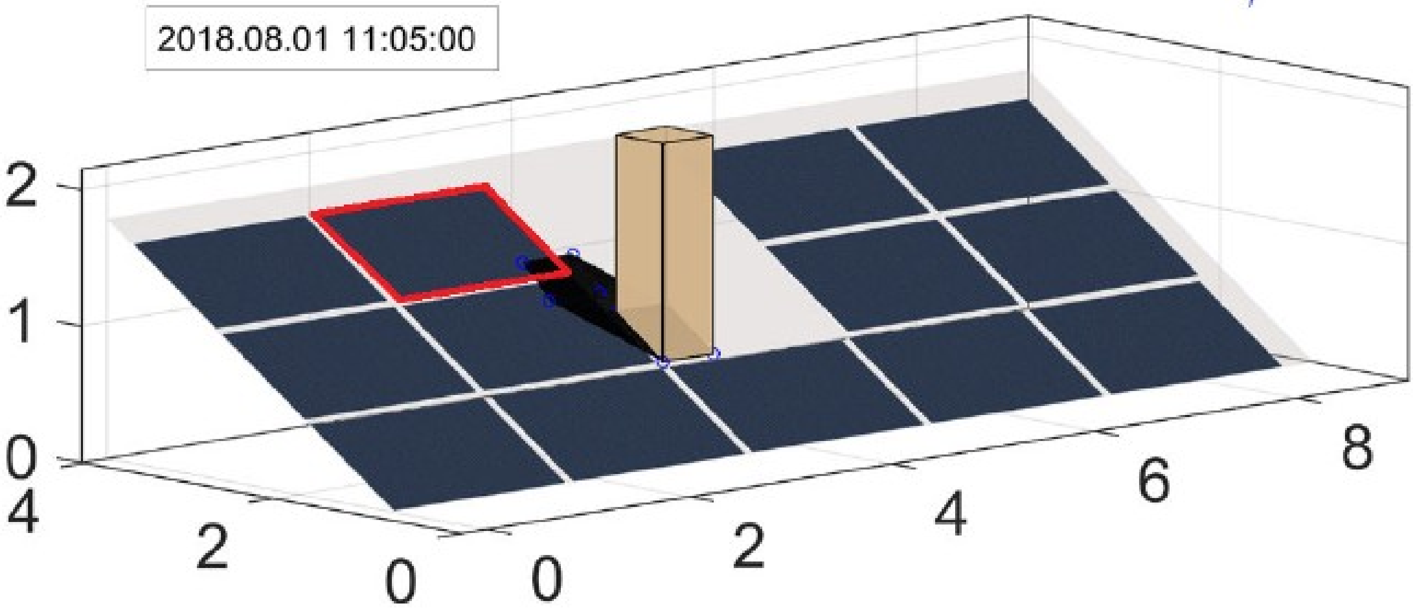
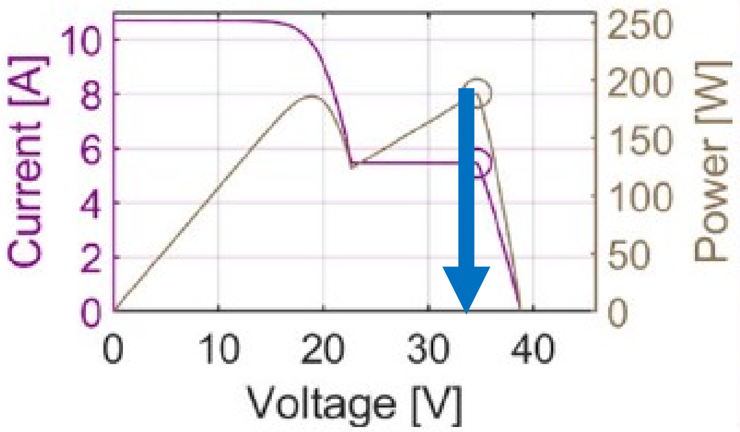
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	58.4%	58.4%

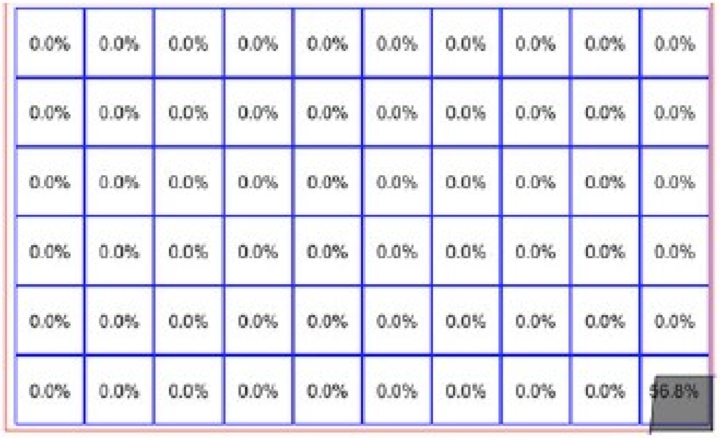


Example: Shading situation 1 at 11:50

- Optimum voltage of shaded PV module at about Vmp= 32V

- MLPE beneficial for about only 10 minutes





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0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
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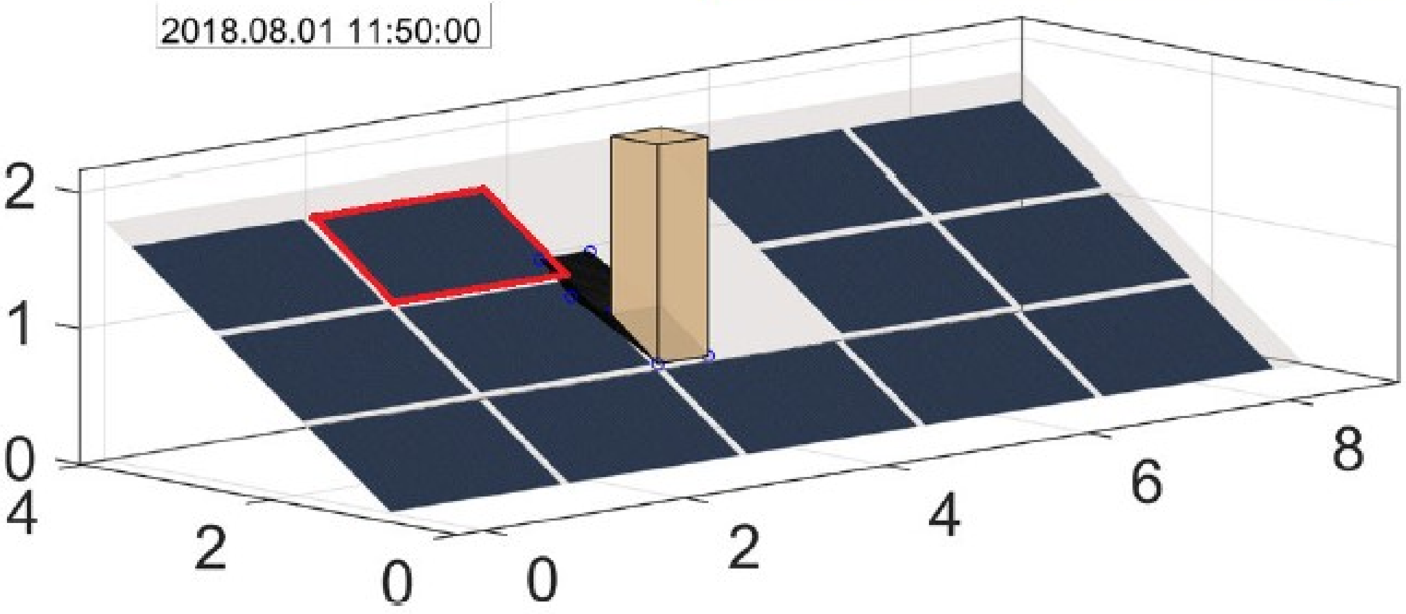
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	56.8%

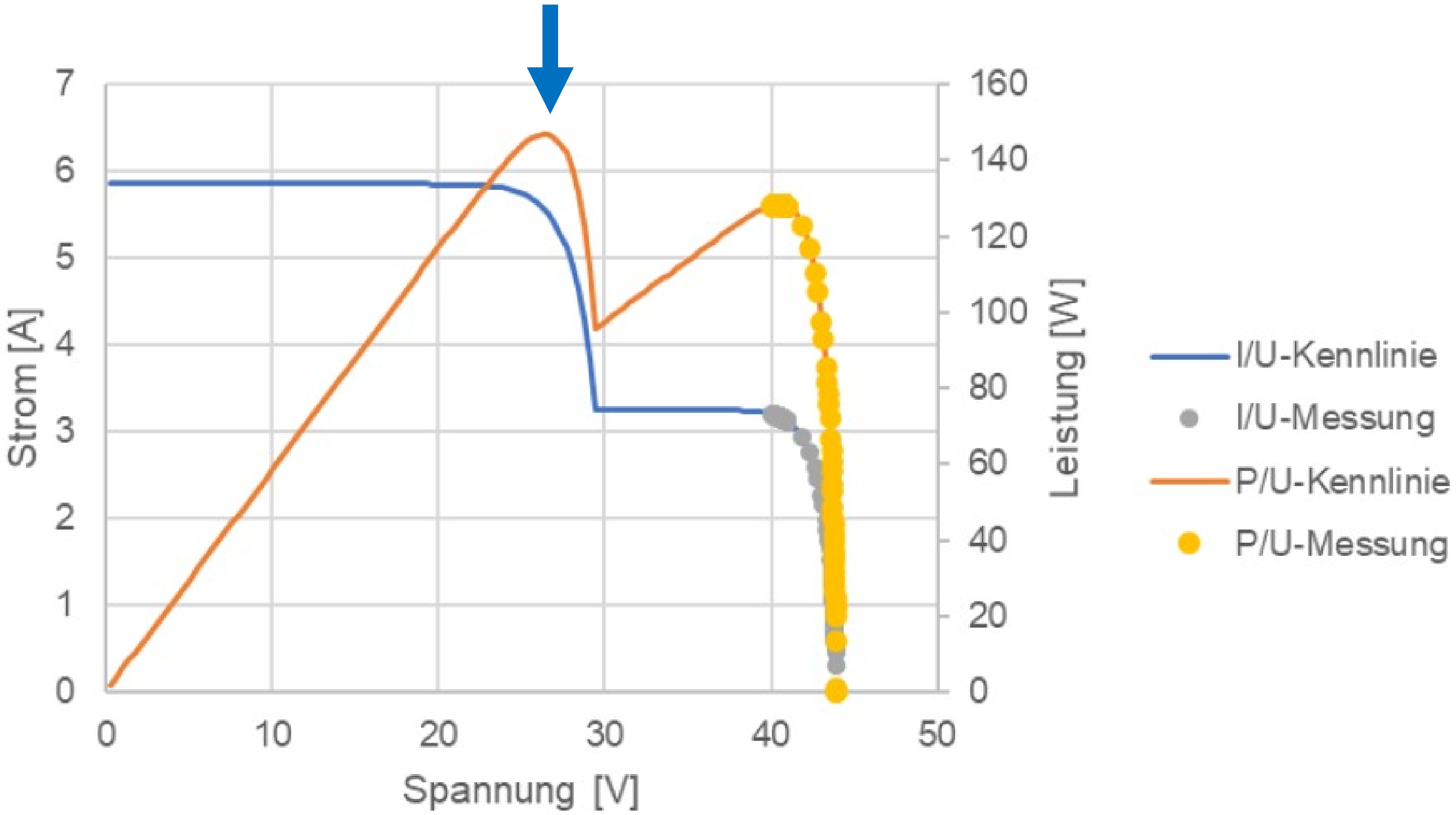


2018.08.01 11:50:00

ZHAW Labtest 1 - commercial MPP Tracking failed

- MPP Tracking works in the morning but not the whole day perfect
- We could not find evidence of successful global MPP tracking from about 40V to about 26V global MPP within one hour!
  Device under Test SolarEdge S500B (see in the right)
  (Ref.: A. Widler, L. Baumann, ZHAW Bachelor Project Thesis 2023)

absolute MPP was not reached!

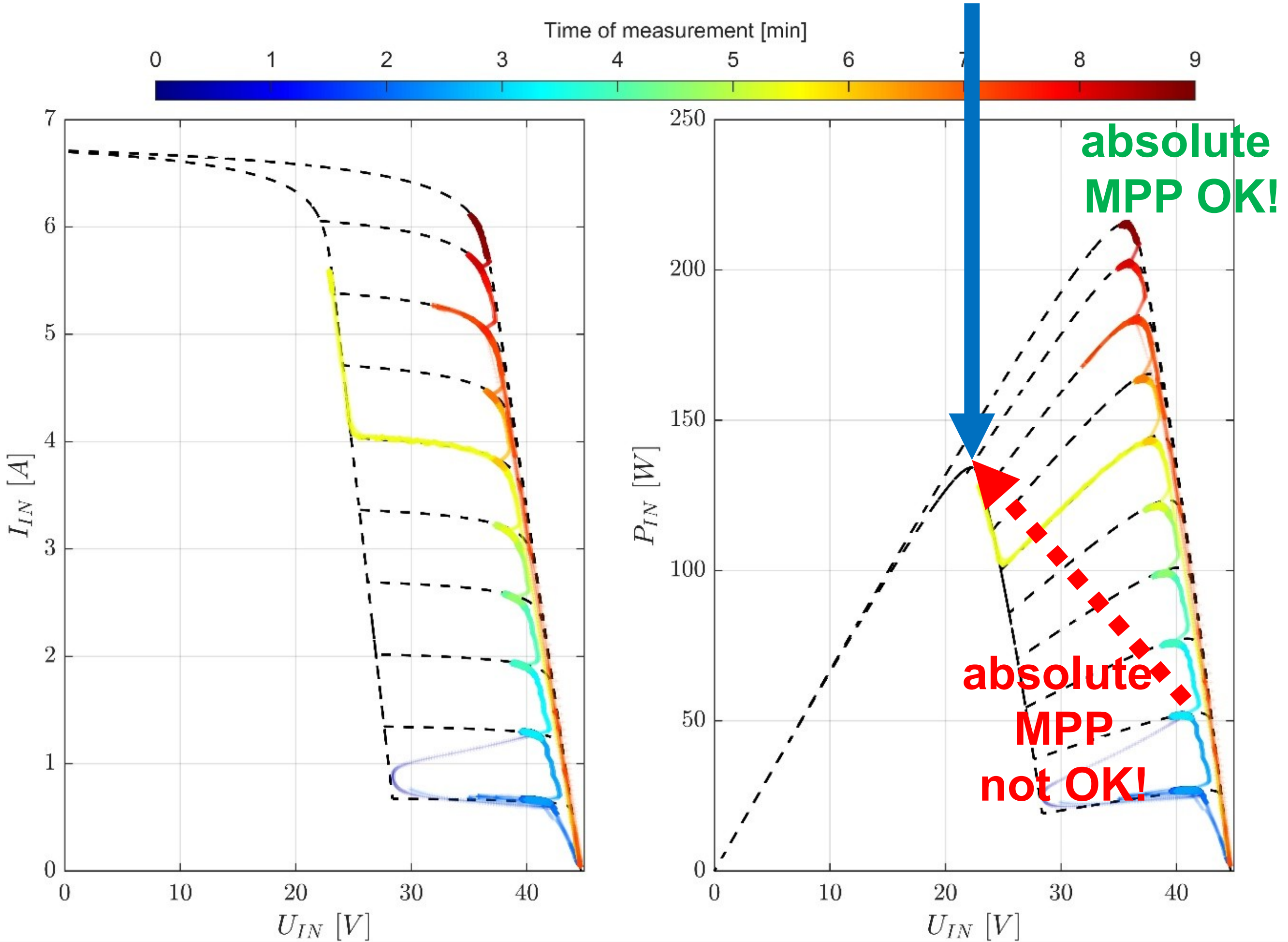


ZHAW Labtest 1 - commercial MPP Tracking failed

School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

- MPP Tracking works in the morning

- MPP failures occurred to find global MPP by switching from about 40V to about 22V global MPP within several minutes, for strong shading of a single solar cell! Device under Test Huawei 450W-P
(Ref.: C. Allenspach Masterthesis ZHAW 2023)
- It works for lower shading at higher voltages 42V to 35V



absolute MPP was not reached for strong shading!

absolute MPP OK!

absolute MPP not OK!

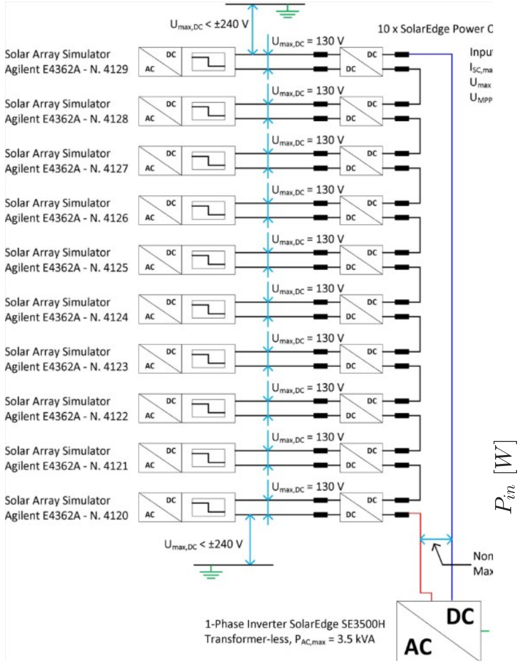
ZHAW PVshade method for yield calcuation

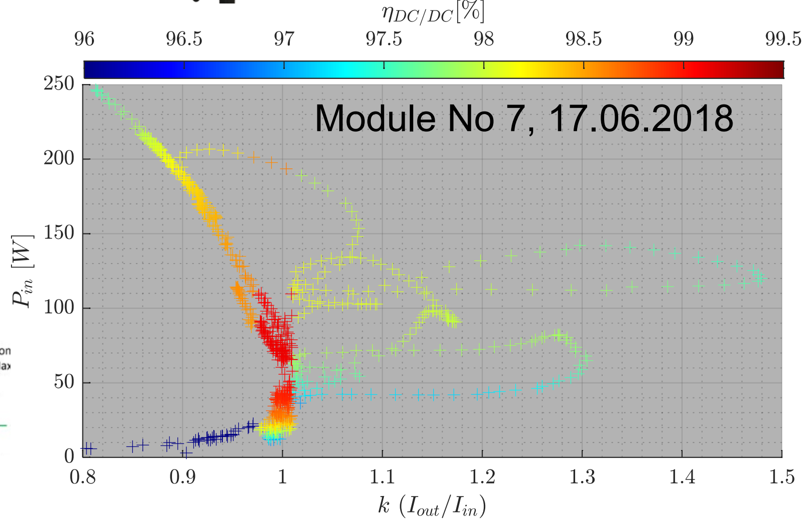
Indoor measurement

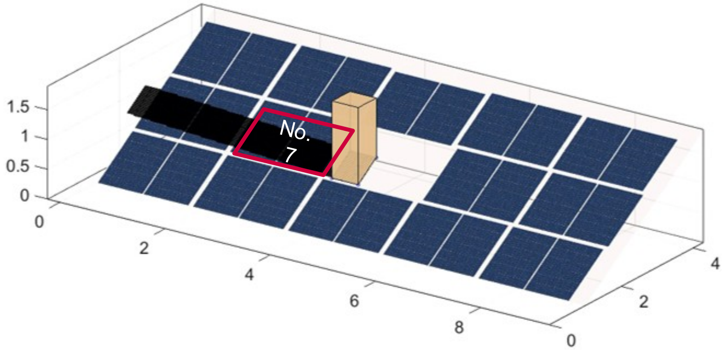
of power electronic components in the relevant operation area

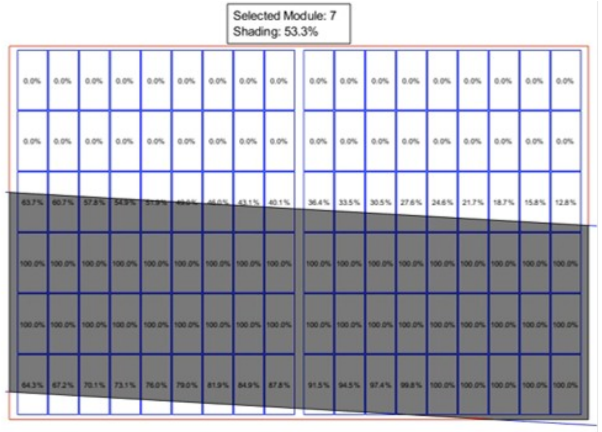
Annual simulation

of shadow propagation & losses for each power electronic component / optimizer









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0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
63.7%	60.7%	57.8%	54.9%	51.9%	49.0%	46.0%	43.1%	40.1%	36.4%	33.5%	30.5%	27.6%	24.6%	21.7%	18.7%	15.8%	12.8%
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
64.3%	67.2%	70.1%	73.1%	76.0%	79.0%	81.9%	84.9%	87.8%	91.5%	94.5%	97.4%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%

C. Allenspach, F. Baumgartner, et al. Sol. RRL 2022, 2200596

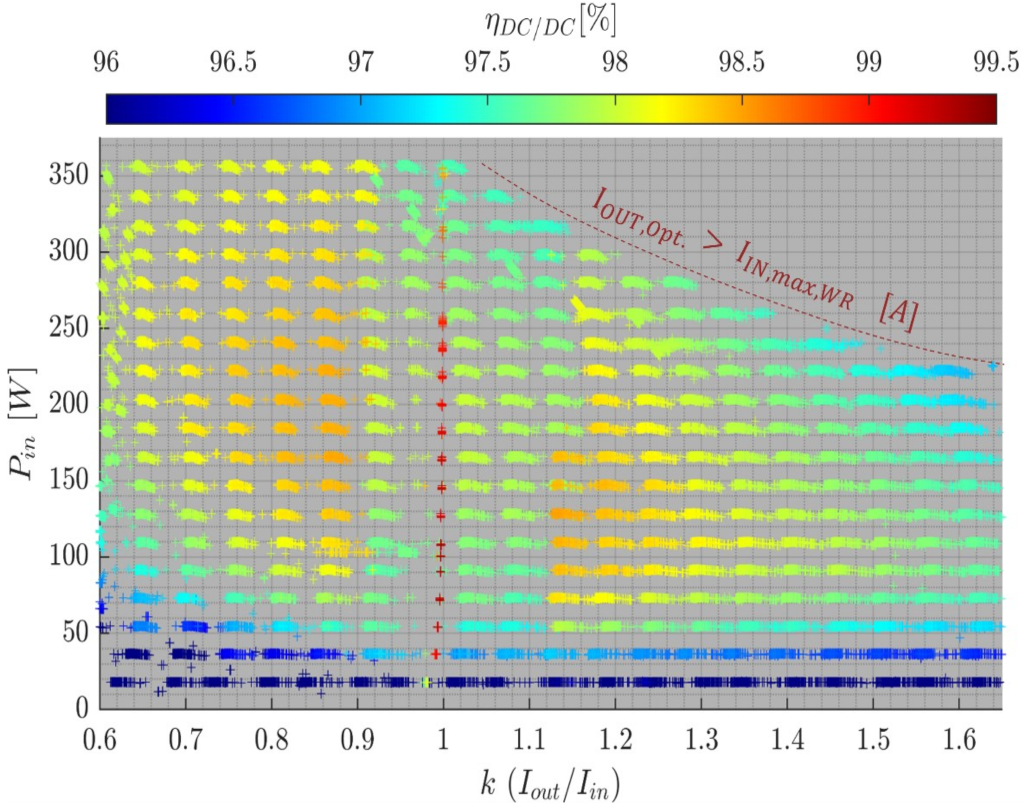
Efficiency of Module Level Power Electronic (MLPE)

- Indoor Lab – Measurement

PV-Wechselrichter	Power Optimizer
SMA SunnyBoy 3.6	Solaredge P370
Solaredge SE3500	Solaredge P370i
Solaredge SE3500H	Solaredge P405
Huawei SUN2000-3.68KTL	**Solaredge S500B**
Fronius Symo 5kW	Huawei SUN2000-450W-P
	Tigo TS4-A-O

Results data sheet -1.5%

SolarEdge P370



Several DC/DC optimizer analysed at ZHAW

- Findings: massive Eff. reductions -2%
- Data sheet values shown only at highest 99% ratings $U_{in}=U_{out}$
- Problem:
for this operating condition DC/DC converters are in the non-switching mode!!

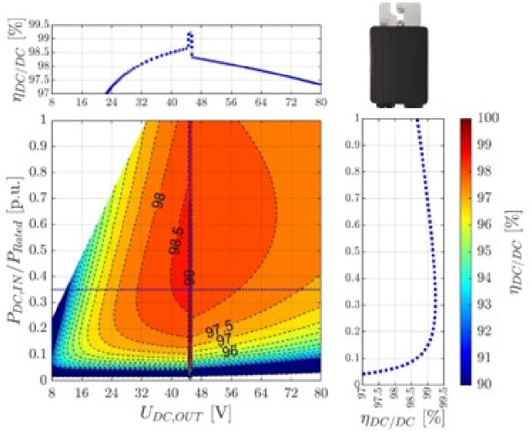


Figure 12: DC/DC efficiency mapping of the triple-mode power loss model (individual power loss calculation for buck, boost and passthrough mode), as a function of the relative DC input power, $P_{DC,IN}/P_{Rated}$ [p.u.], and DC output voltage, $U_{DC,OUT}$ [V], for the SolarEdge S500B (2023 Edition) - based on 157'900 points of measurement. Input voltage was set to 45V.

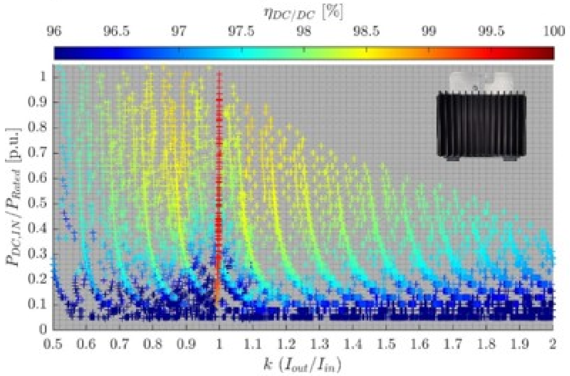


Figure 13: SolarEdge S500B static DC/DC efficiency $\eta_{DC/DC}$ measurement with a constant input voltage, U_{IN} = [20 : 5 : 80]V as a function of the output to input current ratio I_{OUT}/I_{IN}, k_N = [0.5 : 2] and P_{IN} = [0.05 : 1] P_{Rated}.

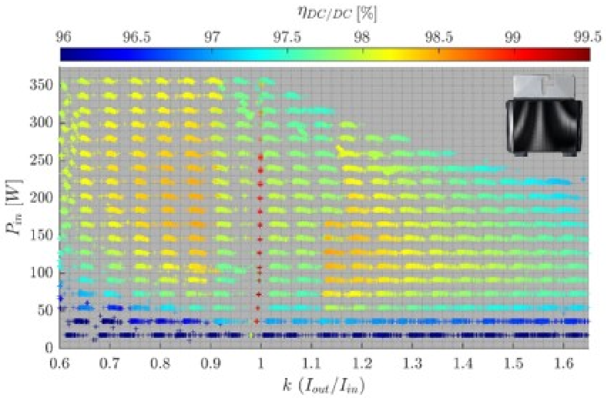


Figure 14: SolarEdge P370 static DC/DC efficiency $\eta_{DC/DC}$ measurement with a constant input voltage, U_{IN} = 35V as a function of the output to input current ratio I_{OUT}/I_{IN}, k_N = [0.6 : 1.65] and input power, P_{IN} = [0.05 : 1] relative to P_{Rated}

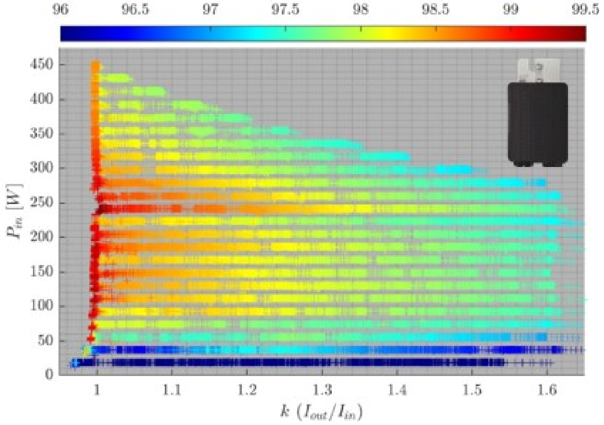
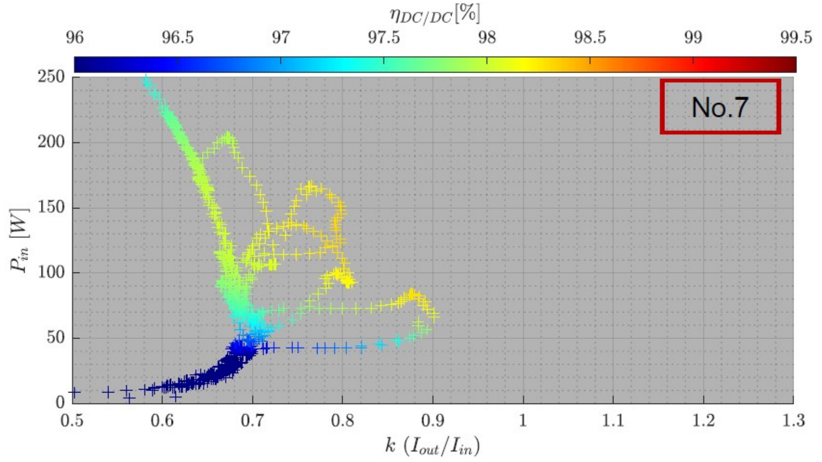
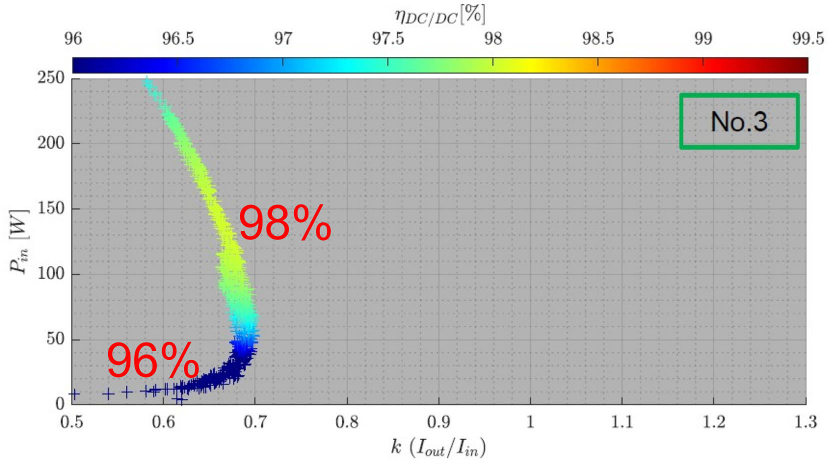


Figure 15: Huawei SUN2000-450W-P static DC/DC efficiency $\eta_{DC/DC}$ measurement with a static input voltage, U_{IN} = 35V as a function of the output to input current ratio I_{OUT}/I_{IN}, k_N = [0.95 : 1.6] and input power, P_{IN} = [0.05 : 1] relative to P_{Rated} [13].

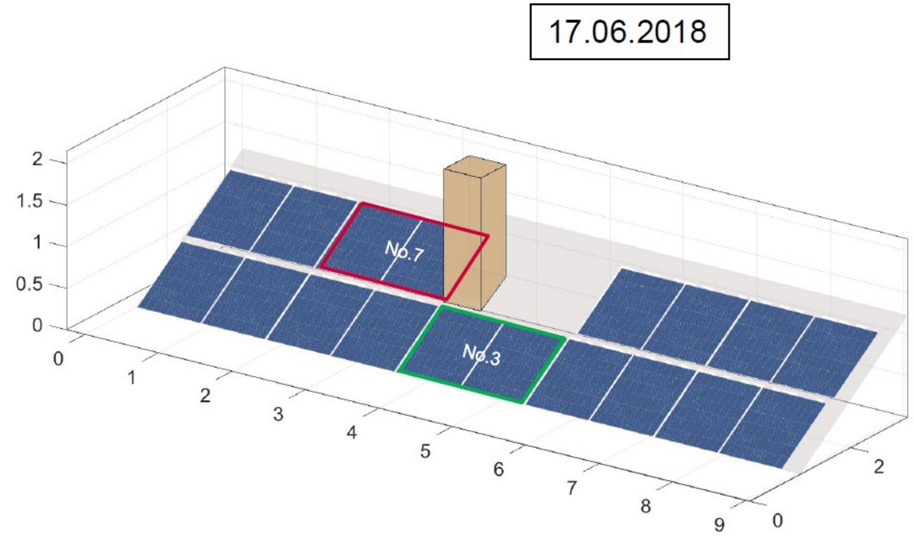
Plant design recommendation – low yield





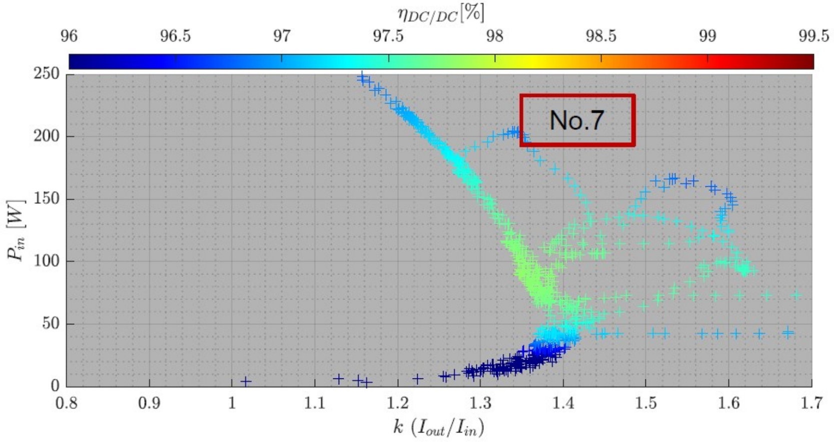
not shaded
PV modules

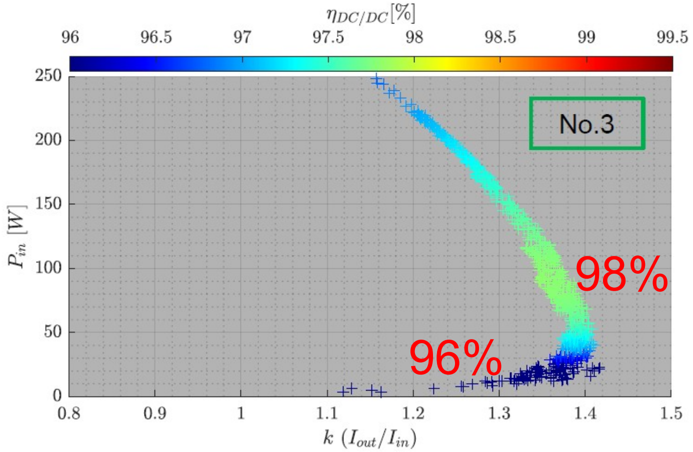
Optimizer SolarEdge P370 inverter at DC input 370V



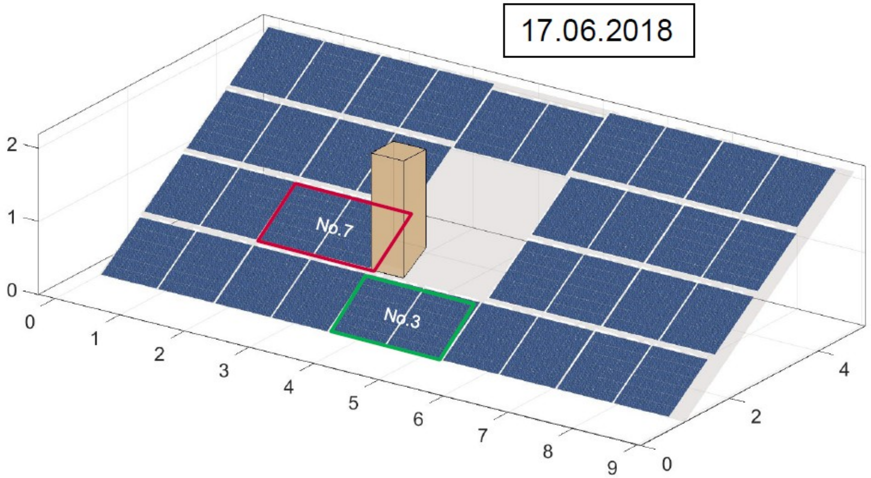
- High DC/DC losses if only 9 Optimizer used in the allMLPE string
- Optimizer efficiency 96% to 98% at 50% nominal power of module

Plant design recommendation – low yield





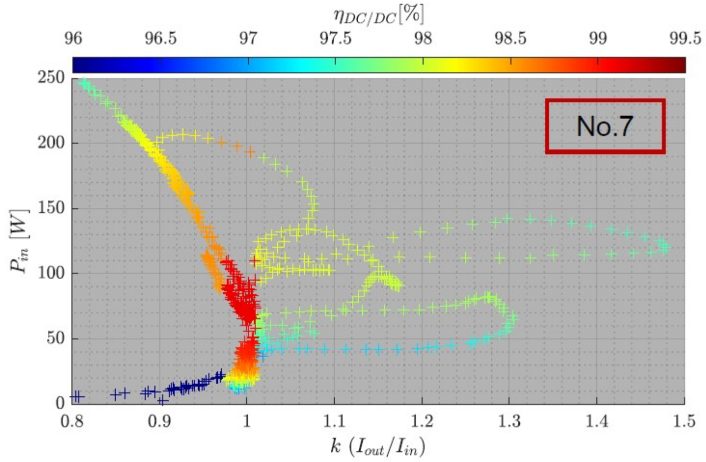
Optimizer SolarEdge P370 inverter at DC input 370V

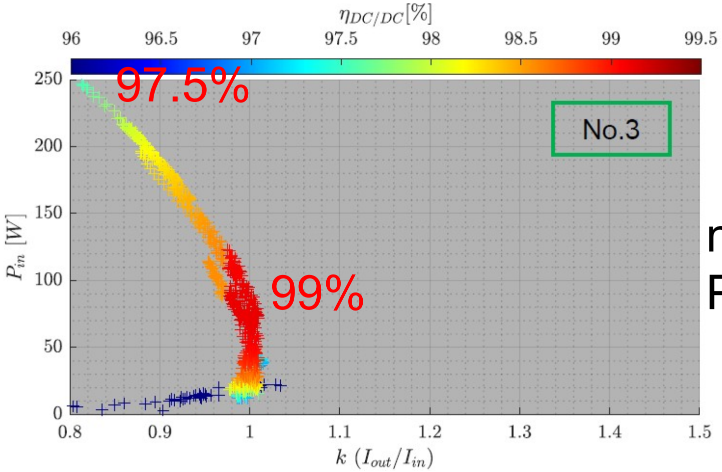


not shaded
PV modules

- High DC/DC losses if max 18 Optimizer used in the allMLPE string
- Optimizer efficiency 96% to 98% at 50% nominal power of module

Plant design recommendation – high yield



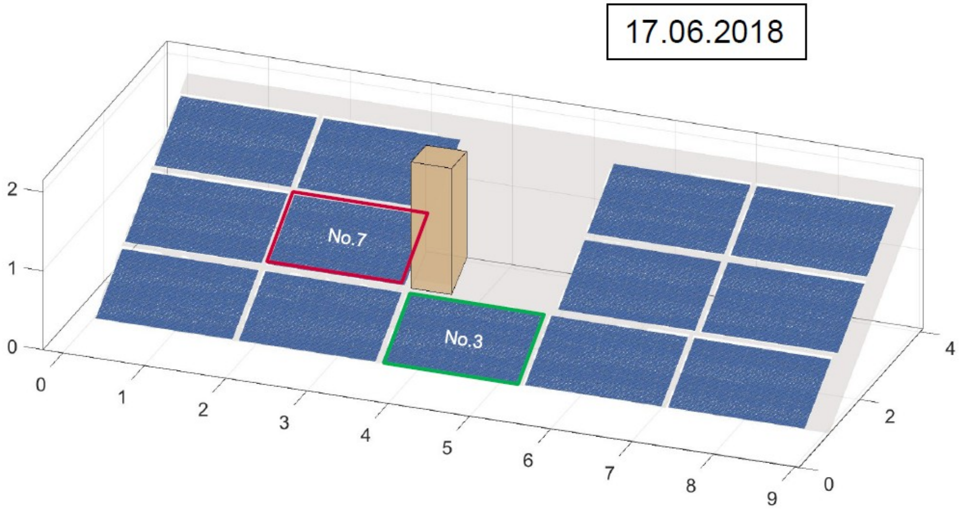


97.5%

99%

not shaded
PV modules

Optimizer SolarEdge P370 inverter at DC input 370V

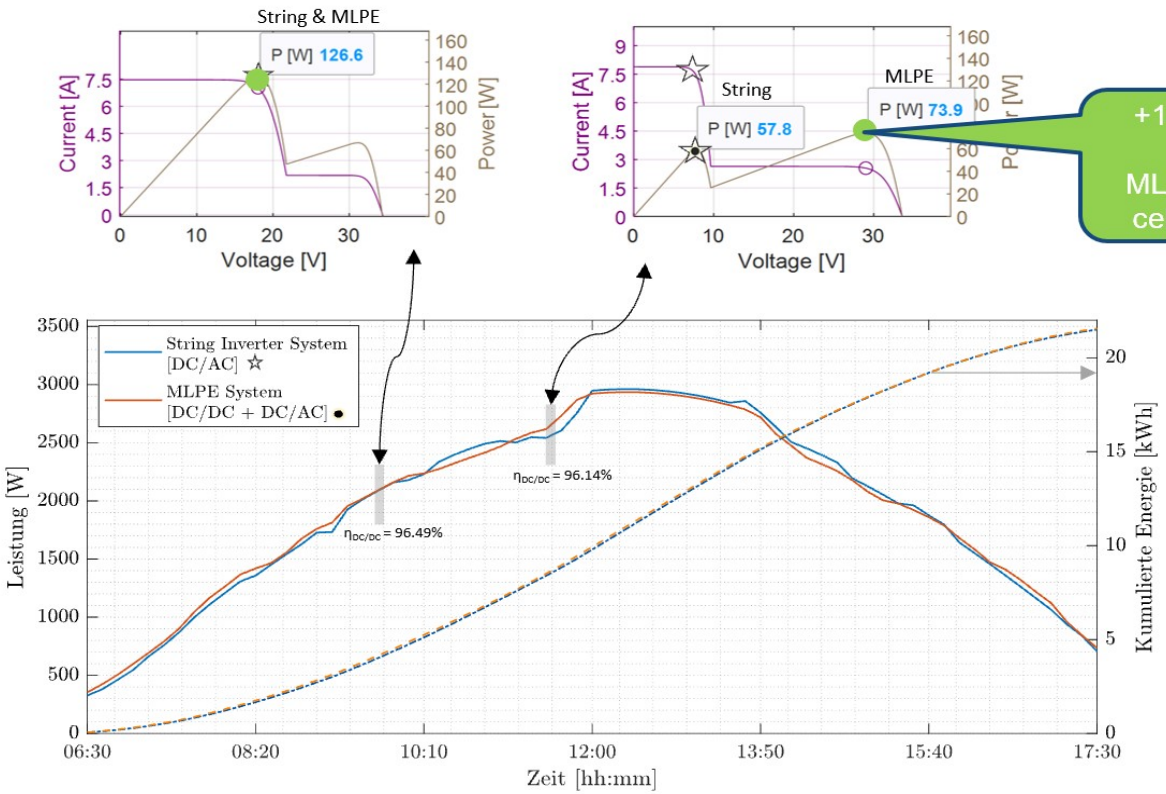


- Low DC/DC losses if 13 Optimizer used in the allMLPE string
- Optimizer efficiency 97.5% to 99% at 30% nominal power of module

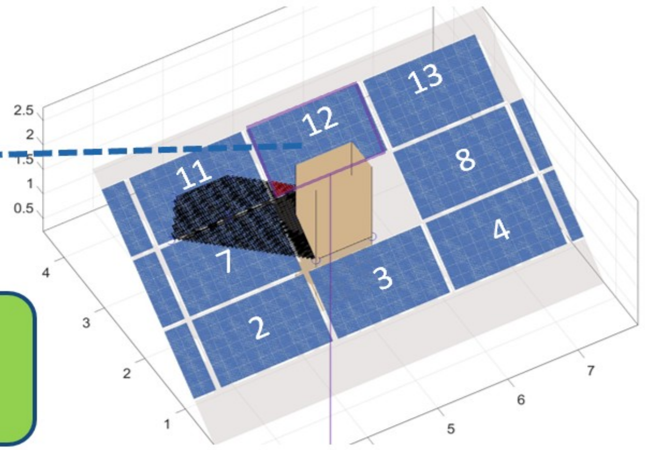
Theoretical annual yield gain at 100% DC/DC efficiency

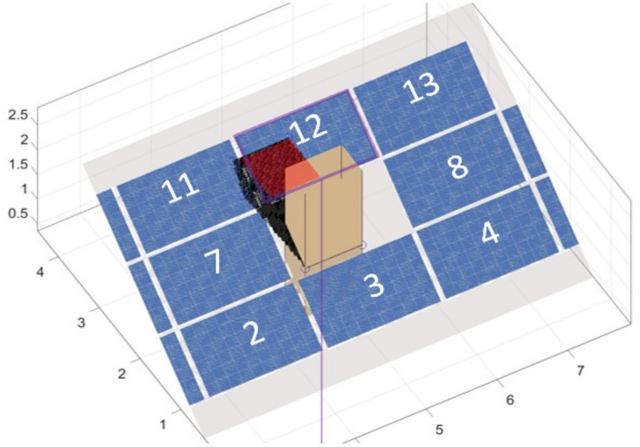
- Simulation of a plant with string inverter setup (SINV) and same installation with Power Optimizers (MLPE)

Module 12



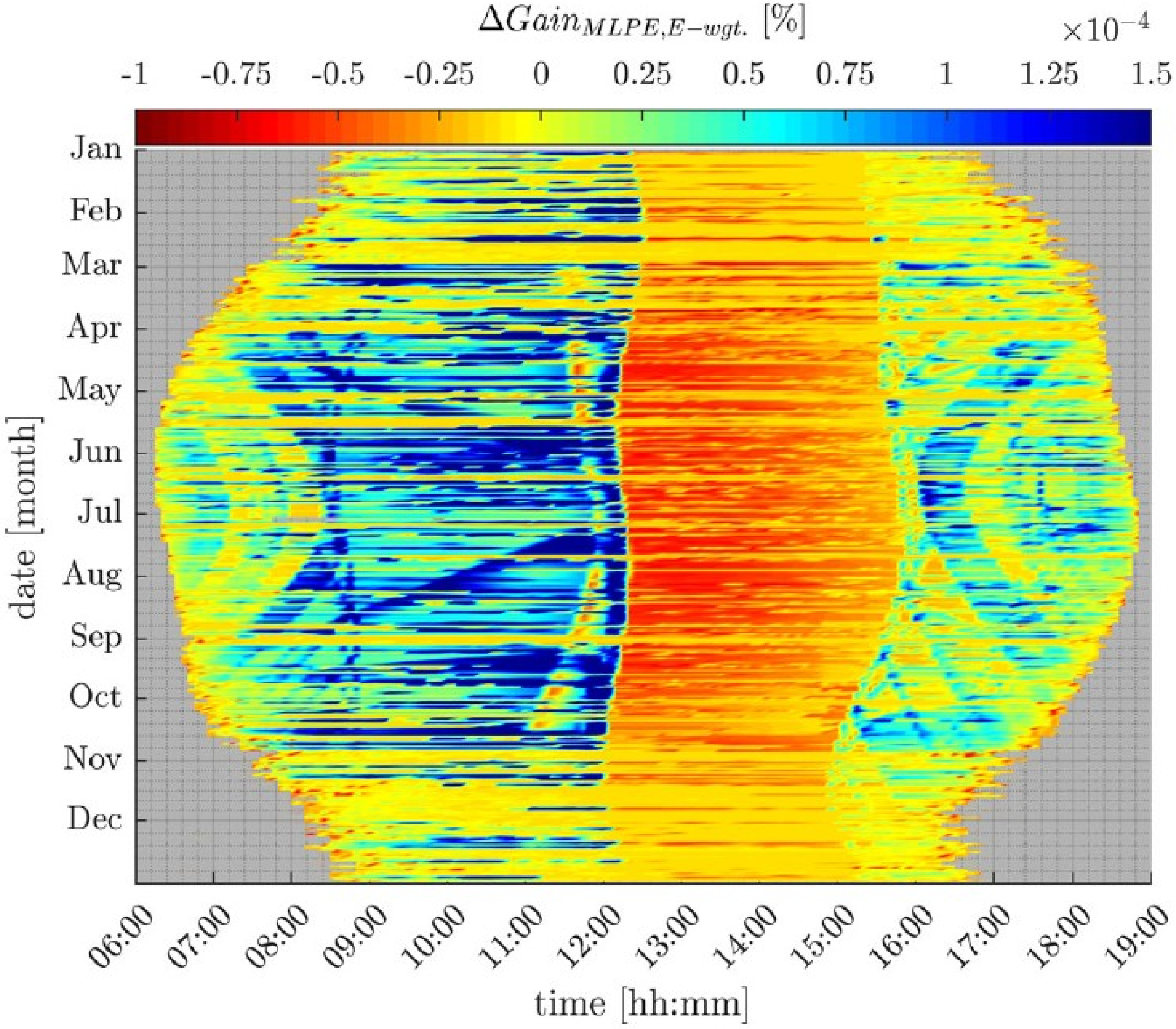
+16W from 2500W
+0.6%
MLPE benefit only if cell shading < 40%

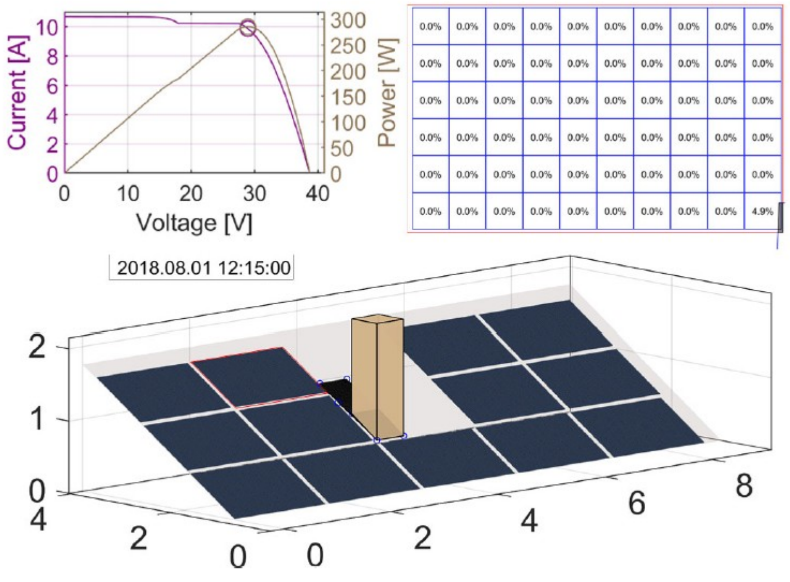




Gain of MLPE reduced by higher optimizer losses

at low shading periods –see afternoon in annual mapping



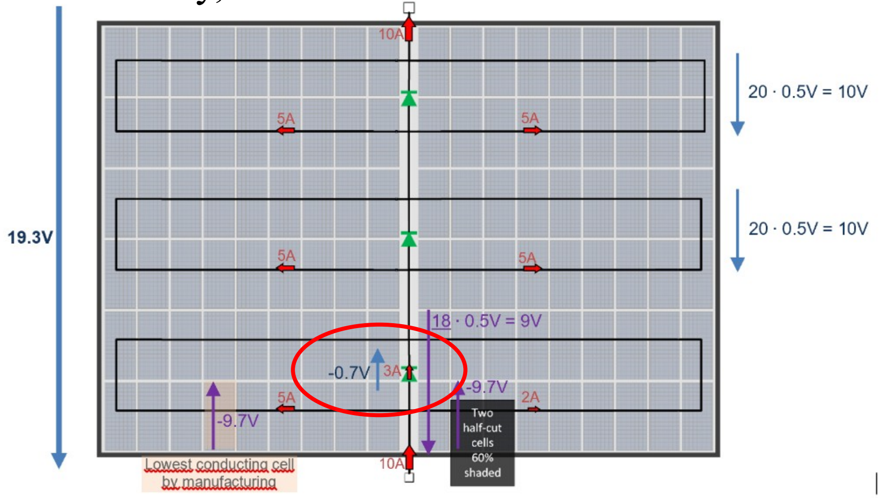


0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.9%

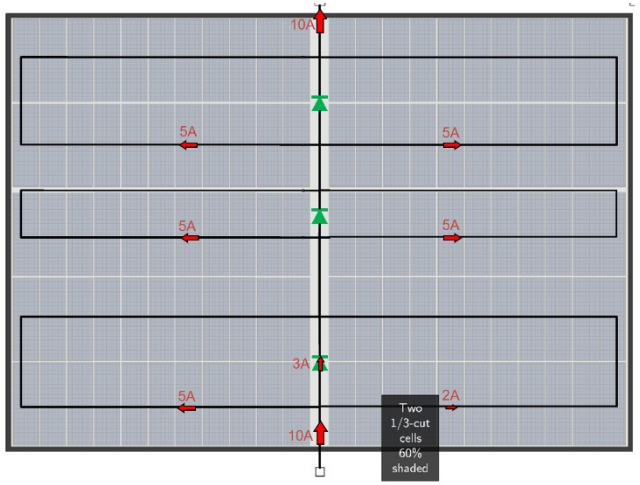
Figure 8. Fourth time step of the simulated PV system at 12:15 of August 1, 2018 (same shading scenario as described in the caption

Shading tolerant modules analysed by PVshade

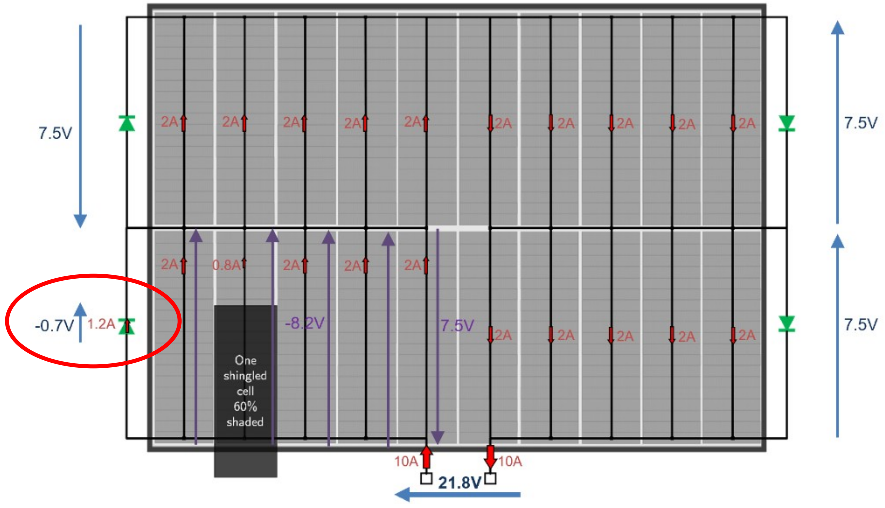
3 BD in the reference standard module
butterfly, silicon half-cut cells

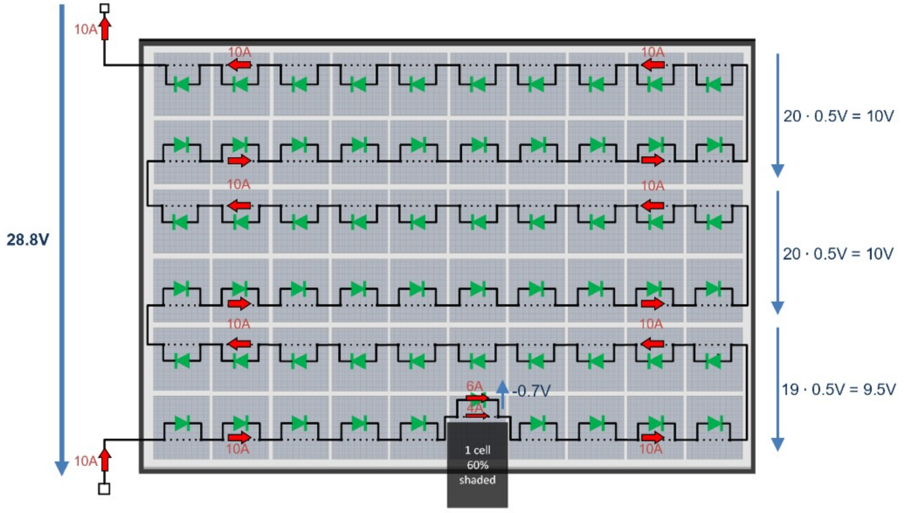


3 BD in the reference standard module

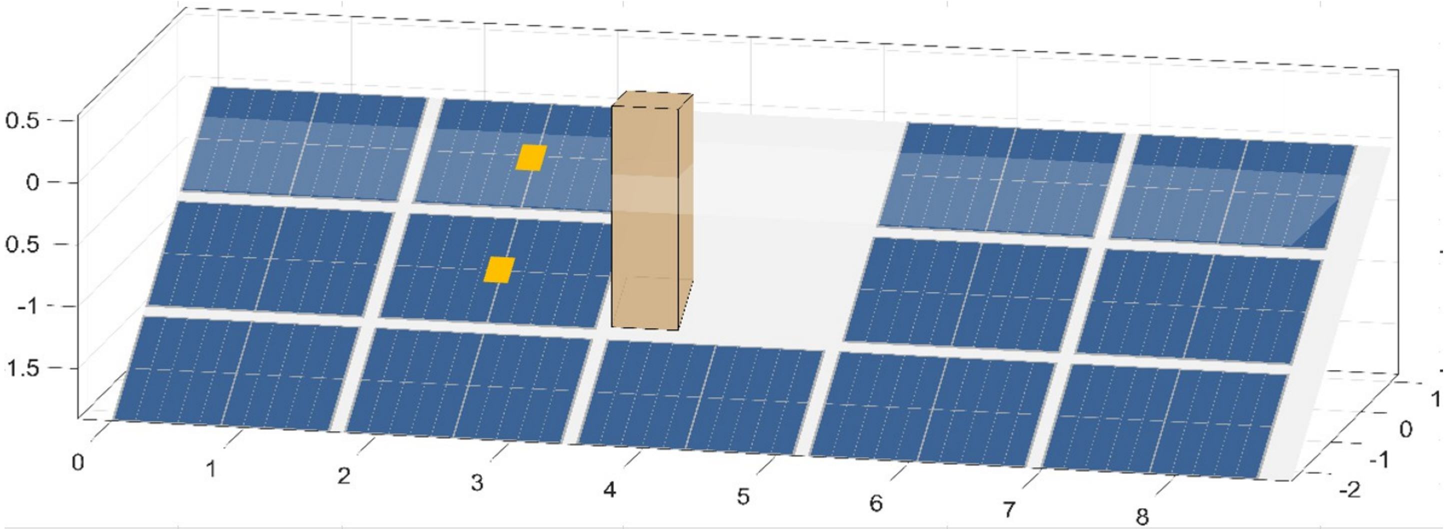


Shading Tolerant PV Module





ZHAW PVshade results – low shading by chimney



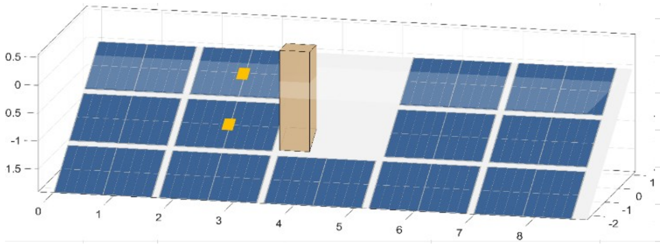
	Relative Annual Energy	Full Cell PV Module	Half-cut cell PV Module	Third-cut cell PV Module	4 quadrant shingled	Shading-resistant All Cells + Diode	
	Unshaded + no losses			100			%
	shaded + no losses	96.8	96.8	96.8	98.4	97.8	%
SINV	Relative Energy	93.0	92.9	92.7	94.0	93.9	%
indMLPE	Relative Energy	93.8	93.6	93.1	94.6	94.8	%
	MLPE Gain	0.9	0.8	1.1	0.6	0.4	%
allMLPE	Relative Energy	93.3	92.8	93.7	94.4	94.2	%
	MLPE Gain	0.3	-0.2	0.4	0.3	-0.1	%
	Average Rel. Energy	93.3	93.1	93.2	94.4	94.3	%

Max. SINV diff.: 1.4%
Max. indMLPE diff.: 1.8%

+1.8%

Max. allMLPE diff.: 1.2%
Max. Difference Tot: 2.1%

ZHAW PVshade results – low shading

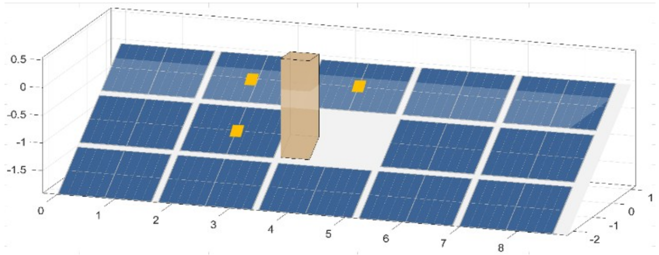


#13 PV modules
SI about 2%

+1.8%

Relative Annual Energy		Full Cell PV Module	Half-cut cell PV Module	Third-cut cell PV Module	4 quadrant shingled	Shading-resistant All Cells + Diode	
Unshaded + no losses		100					%
shaded + no losses		96.8	96.8	96.8	98.4	97.8	%
SINV	Relative Energy	93.0	92.9	92.7	94.0	93.9	%
indMLPE	Relative Energy	93.8	93.6	93.1	94.6	94.8	%
	MLPE Gain	0.9	0.8	1.1	0.6	0.4	%
allMLPE	Relative Energy	93.3	92.8	93.7	94.4	94.2	%
	MLPE Gain	0.3	-0.2	0.4	0.3	-0.1	%
Average Rel. Energy		93.3	93.1	93.2	94.4	94.3	%

Max. SINV diff.: 1.4%
Max. indMLPE diff.: 1.8%
Max. allMLPE diff.: 1.2%
Max. Difference Tot: 2.1%



#14 PV modules
SI about 3%

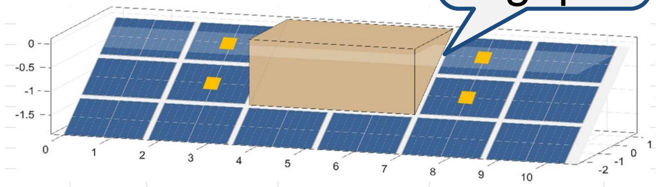
+3.1%

		Full Cell PV Module	Half-cut cell PV Module	Third-cut cell PV Module	Shading-resistant 4 quadrant	Shading-resistant All Cells + Diode	
Unshaded + no losses		100					%
shaded + no losses		95.3	96.0	95.8	98.0	97.0	%
SINV	Relative Energy	90.7	91.7	91.2	93.0	92.9	%
indMLPE	Relative Energy	92.1	92.7	92.1	93.8	93.4	%
	MLPE Gain	1.4	1.1	1.6	0.8	0.5	%
allMLPE	Relative Energy	91.6	91.9	92.6	93.9	93.0	%
	MLPE Gain	0.9	0.3	1.1	0.9	0.1	%
Average Rel. Energy		91.5	92.1	92.0	93.6	93.1	%

Max. SINV diff.: 1.9%
Max. indMLPE diff.: 1.3%
Max. allMLPE diff.: 2.3%
Max. Difference Tot: 2.2%

ZHAW PVshade results – medium dormer shading

smaller gap

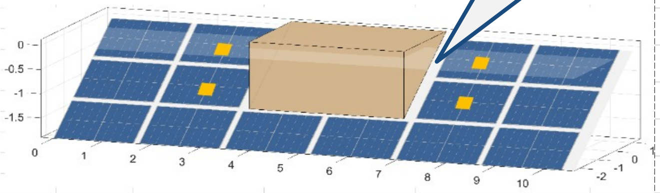


#14 PV modules
SI about 3 - 6%

+4.3%

		Full Cell PV Module	Half-cut cell PV Module	Third-cut cell PV Module	Shading-resistant 4 quadrant	Shading-resistant All Cells + Diode	
	Unshaded + no losses	100					%
	shaded + no losses	94.3	93.3	93.5	96.5	96.6	%
SINV	Relative Energy	88.4	87.4	87.1	90.8	92.3	%
indMLPE	Relative Energy	90.6	88.7	88.7	91.6	92.7	%
	MLPE Gain	1.4	1.4	1.7	0.8	0.3	%
allMLPE	Relative Energy	89.6	89.4	89.7	92.5	92.7	%
	MLPE Gain	2.4	2.2	2.9	1.8	0.4	%
	Average Rel. Energy	89.5	88.5	88.5	91.7	92.5	%
		Max. SINV diff.:	5.1%		Max. allMLPE diff.:	3.0%	
		Max. indMLPE diff.:	3.9%		**Max. Difference Tot:**	**5.5%**	

larger gap +15cm



#14 PV modules
SI about 3 -5%

+3.0%

	Relative Annual Energy	Full Cell PV Module	Half-cut cell PV Module	Third-cut cell PV Module	Shading-resistant 4 quadrant	Shading-resistant All Cells + Diode	
	Unshaded + no losses	100					%
	shaded + no losses	95.2	94.4	94.6	97.3	97.1	%
SINV	Relative Energy	90.1	89.1	88.9	92.1	92.9	%
indMLPE	Relative Energy	91.0	90.0	90.1	92.6	93.1	%
	MLPE Gain	1.0	1.1	1.4	0.6	0.3	%
allMLPE	Relative Energy	91.4	90.4	90.8	93.2	93.1	%
	MLPE Gain	1.5	1.5	2.1	1.2	0.3	%
	Average Rel. Energy	90.8	89.8	90.0	92.6	93.0	%
		Max. SINV diff.:	3.9%		Max. allML		
		Max. indMLPE diff.:	3.0%		**Max. Difference Tot: 4.3%**		

+1.0%

Several shading situations are analysed by the use of ZHAW PVShade Tool

Cases	No:	Shading Severity	Shading index $SI_{DC,Max}$ [%]	Simulated annual yield [kWh]				MLPE Gain [%]
				no shading & no loss [kWh]	no losses [kWh]	allMLPE [kWh]	SINV [kWh]	
Dormer (s)	1	Low	0.9	4410	4368	4207	4247	-1.0
Vent. Pipe	2	Low	2.9	4410	4282	4122	4129	-0.2
Chimney	3	Low	3.6	6337	6109	5904	5858	0.8
Tree 1	4	Medium	5.0	5295	5029	4862	4802	1.3
Tree 2	5	Medium	6.0	4410	4145	3987	3926	1.5
Building	6	Medium	7.9	4410	4062	3905	3802	2.7
Dormer (L)	7	Heavy	9.1	5295	4812	4643	4435	4.7
Roof Edge	8	Heavy	12.7	4410	3847	3693	3621	2.0

Remarks

Shading Index definition according to NREL's Ref. [4]

Shading Adaption Efficiency Definition described in Ref [1]

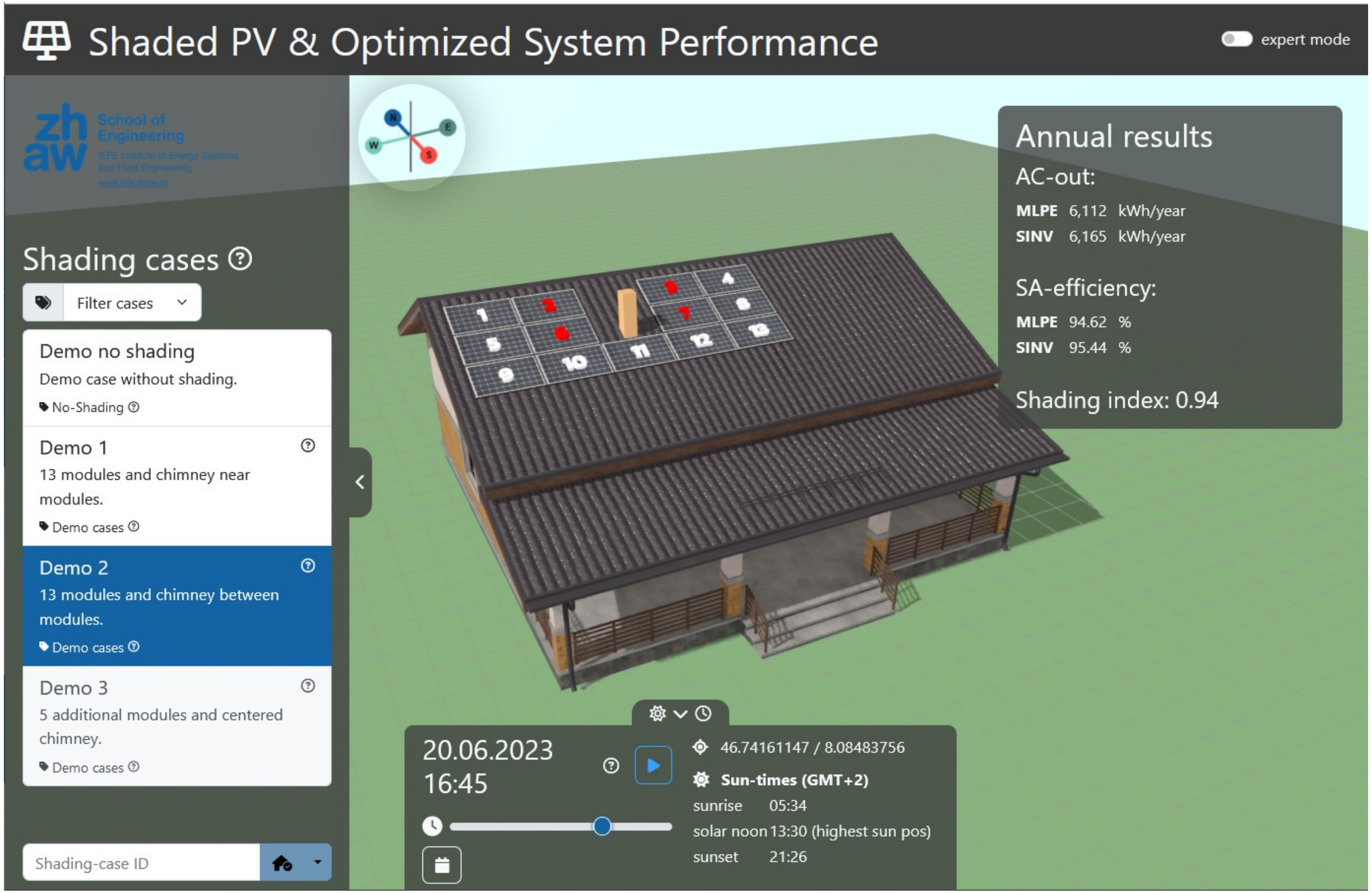
allMLPE all optimizer systems

SINV String Inverter Systems

MLPE Gain shows the % annual yield gain using allMLPE versus SINV for specific efficient components described in [1, 2]]

Ref: [1] C. Allenspach, F. Baumgartner, et al. Sol. RRL 2022, 2200596
[2] C. Allenspach, 4DO.1.1, EUPVSEC 2023
[3] F. Baumgartner et. al., IEA PVPS Task 13 Subtask 2.5 Final Report, partial shading 2024

ZHAW interactive website WebPVshade



Shaded PV & Optimized System Performance

expert mode

Shading cases ⓘ

Filter cases

Demo no shading
Demo case without shading.
No-Shading ⓘ

Demo 1 ⓘ
13 modules and chimney near modules.
Demo cases ⓘ

Demo 2 ⓘ
13 modules and chimney between modules.
Demo cases ⓘ

Demo 3 ⓘ
5 additional modules and centered chimney.
Demo cases ⓘ

Shading-case ID

Annual results

AC-out:

MLPE	6,112	kWh/year
SINV	6,165	kWh/year

SA-efficiency:

MLPE	94.62	%
SINV	95.44	%

Shading index: 0.94

20.06.2023
16:45

46.74161147 / 8.08483756

Sun-times (GMT+2)

sunrise	05:34
solar noon	13:30 (highest sun pos)
sunset	21:26

Conclusions and Recommendations

- Don’t trust the sales departments of DC/DC power optimizer (MLPE) if they are claiming several 10% yield gain, this is typical not annual yield!
- Don’t trust manufactures optimizer date sheet values if they are promising 99% average optimizer efficiency (typical between 96 to 98%) – ask about efficiency mapping
- For heavy shading, all optimizer PV plant solution will offer highest yield or PV plants with different PV module orientation and to short strings
- For medium shading max yield is found for conventional string inverter using shading tolerant modules plus independent optimizer. Without optimizer the annual yield is only slightly reduced, about 1%
- Shading tolerant modules equipped with too many additional bypass diodes, above about 6 produce, will produce more losses
- For low shading use string inverter without optimizer and no shading tolerant modules
- Shading tolerant modules with a few robust bypass diodes without optimizer helps to increase reliability and thus reducing risk of costs of € if modules or optimizer have to be replaced on the roof, of up to thousand or several thousand € manpower.
- Try to reduce high sophisticated power electronics and control devices to mount behind the hot modules on the roofs

Thank you for your attention

Franz & Co-authors
ZHAW website

ZHAW
web
PVshade

See also webpage of International Energy Agency
IEA PVPS T13 side events, PV & Shading Subtask 2.5
and final report at end of 2024 https://iea-pvps.org

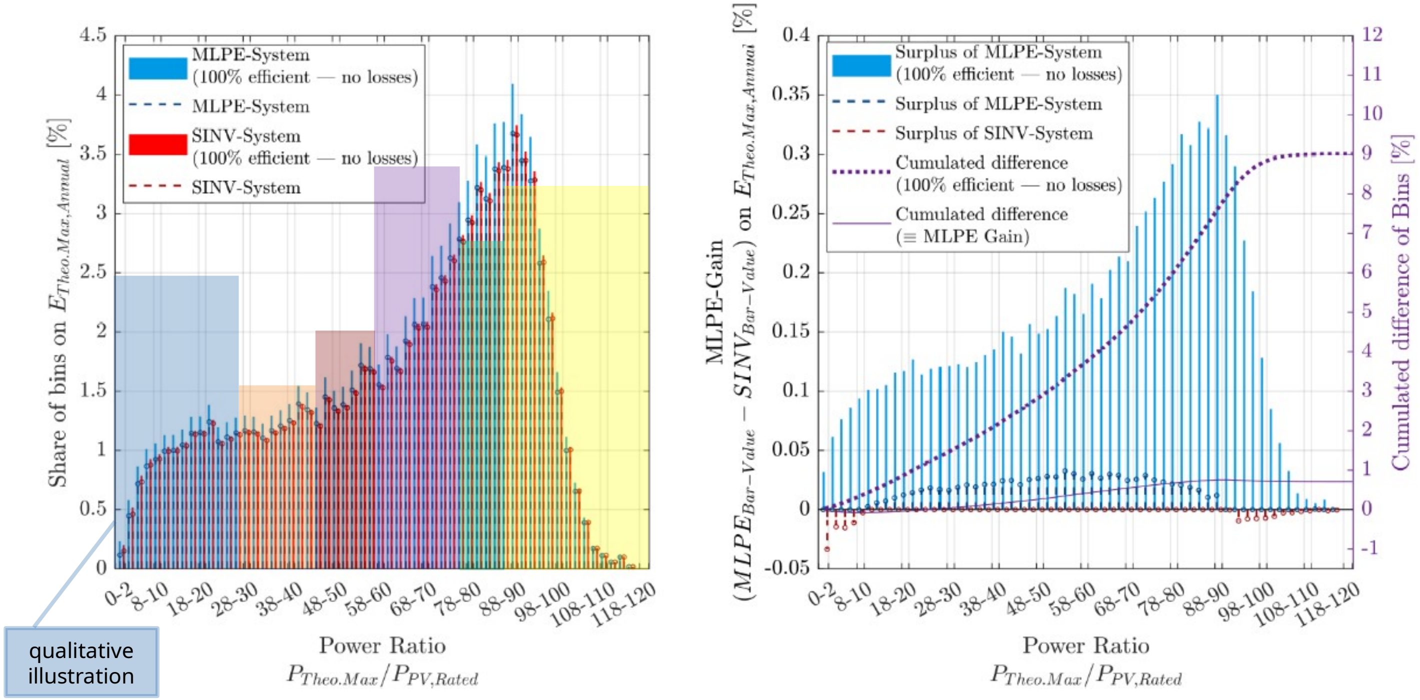
C. Allenspach, F. Baumgartner, et al. Solar. RRL 2022; Wiley Journal

PV Optimizer Performance Talk
EUPVSEC 2021 video
https://youtu.be/NlLg1MOyvWg

Average shading efficiency on the data sheets

$$\eta_{shad,a}(SAE) = \sum_{t=0}^{T=1yr.} \frac{P_{AC}}{\sum_{i=1}^{k} P_{mod,i}} \quad \textbf{(1)}$$

$$\eta_{shad,a} = \sum_{n=1}^{N} \eta_{shad,a,n} \cdot w_{shad,a,n} \quad \textbf{(2)}$$



qualitative illustration

Figure 10 – Statistical illustration of the proportion of the individual bins in relation to their power ratio (Power Ratio = $P_{Theo,Max}/P_{PV,Rated}$) based on the annual simulation of a PV system with 13 modules and chimney shading.

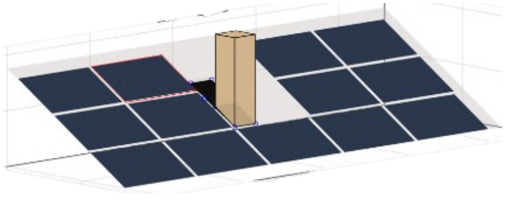


Figure 9 – 3D model of a PV system with 13 modules and chimney shading.

Quantity for performance with shading

- **Shading Adaption Efficiency:**
  What percentage of the maximum DC power of all solar modules can be fed into the grid. (individual modules are operated at the individual optimum - assumption: 100% efficient MLPE).
- Statistical evaluation to identify weighting factors and determine operating points.

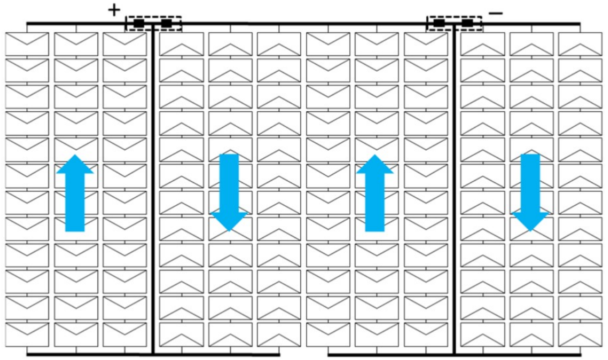
Table 2 – Description of the defined weighting factors $w_{shad,a,n}$ and characteristic shading moments ***n*** for the chimney shading case.[1]

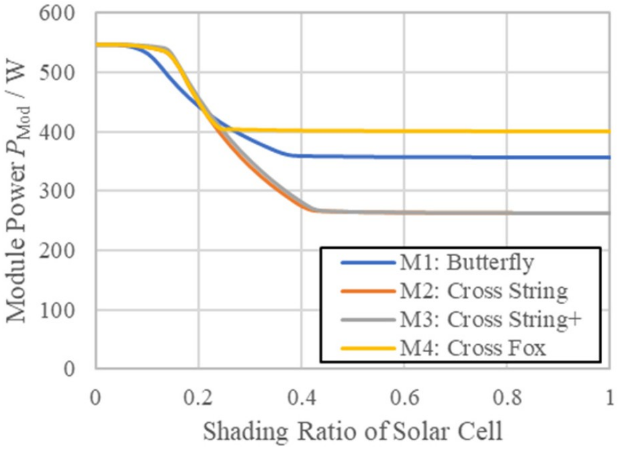
Shading moments n:	1	2	3	4	5	6
Power ratio [%] $P_{MLPE-noLoss,Max}/P_{PV,rated}$:	0 - 30	31 - 44	45 - 60	61 - 78	79 - 88	89 - 120
Weighting factors $w_{shad,a,n}$:	0.16	0.10	0.13	0.22	0.18	0.21
Date + Time of shading moments n:	July 3rd, 10:55	April 3rd, 08:55	Aug. 13th, 10:00	Sept. 4th, 14:50	June 9th, 14:35	April 17th, 12:20

[1] C. Allenspach, F. Carigiet, A. Bänziger, A. Schneider and F. Baumgartner; "Power Conditioner Efficiencies And Annual Performance Analyses With Partially Shaded Photovoltaic Generators Using Indoor And Shading Simulations," Solar RRL, Wiley, 2022.

Robust NEW shading tolerant PV modules concepts
of module layouts with more robust bypass diodes

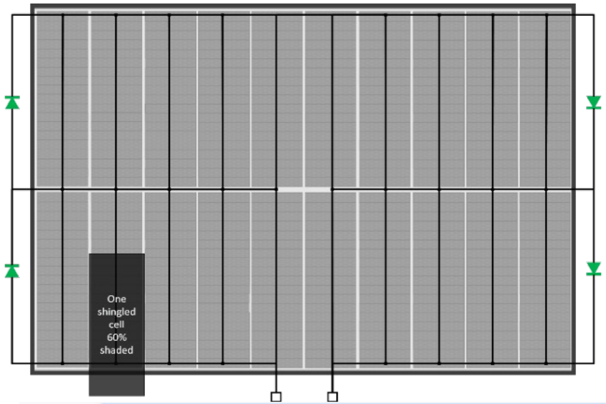
Research Results

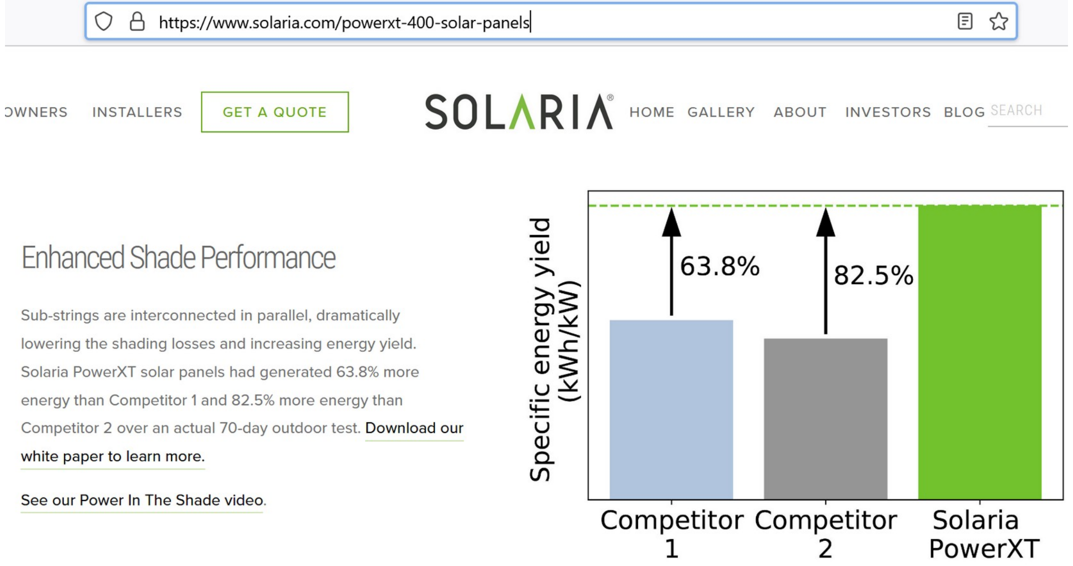




see L. Rendler et al. FhG ISE, *"Innovative Layouts for Utility-Scale PV Modules",* IEEE PVSC June 2023
e.g. 144 half cells, 12cells in a string, 4 bypass diodes

Products on the markets





Enhanced Shade Performance

Sub-strings are interconnected in parallel, dramatically lowering the shading losses and increasing energy yield. Solaria PowerXT solar panels had generated 63.8% more energy than Competitor 1 and 82.5% more energy than Competitor 2 over an actual 70-day outdoor test. Download our white paper to learn more.

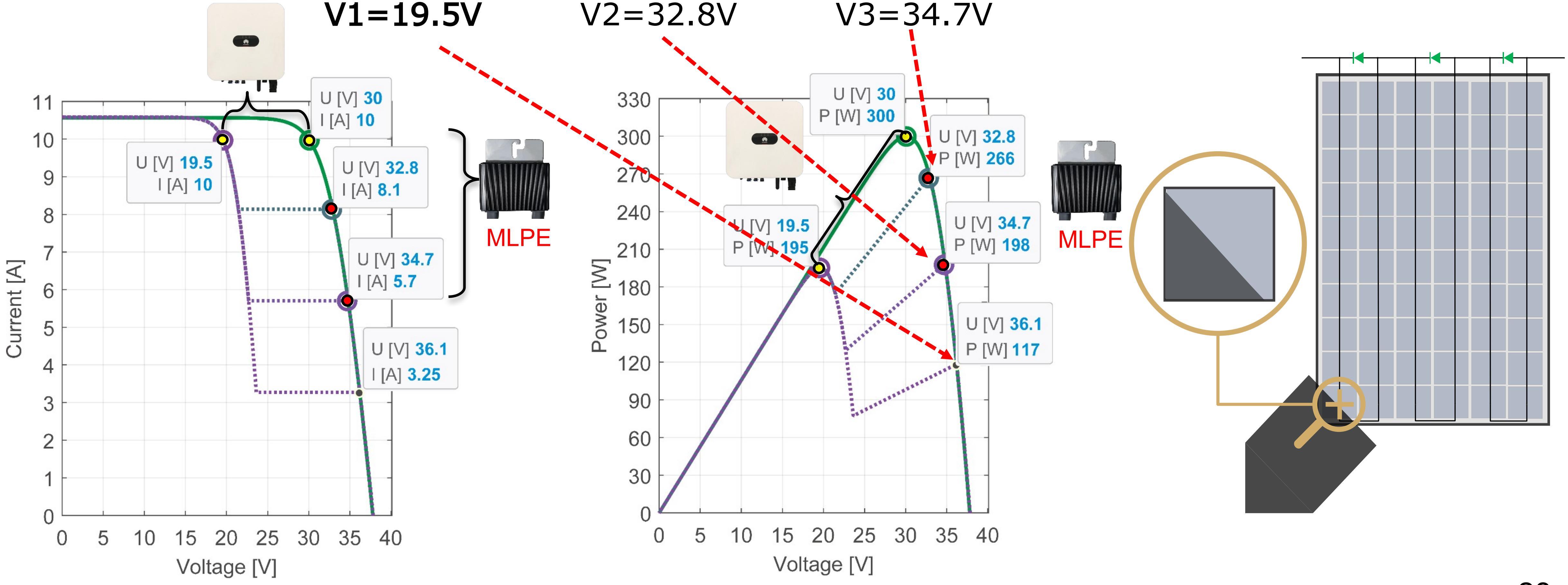
See our Power In The Shade video.

Single cell shaded – 3 bypass diodes

by 20% (MLPE benefical), 43% (equal), 66% (MLPE same to SINV)

P1=195W | P2=266W | P3=198W

V1=19.5V V2=32.8V V3=34.7V



C. Allenspach, F. Baumgartner, 2023-05-22, www.zhaw.ch/~bauf