Automated Quantification of PV Hosting Capacity in Distribution Networks under User-defined Control and Optimization Procedures

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Outline

Hosting capacity

- Definition
- Thresholds and power system criteria evaluation

PVHC (developed PowerFactory plugin)

- Presentation
- The algorithm behind

User-defined control strategies

- Smart inverter control
- Smart load shifting

Simulation results

Conclusion

PV hosting capacity

Fast and accurate analysis of increasing PV penetration

Concerns for power quality and grid reliability

"Hosting capacity is a feeder's ability to accommodate PV without adversely impacting reliability or power quality issues." *Rylander et al. (2016)*

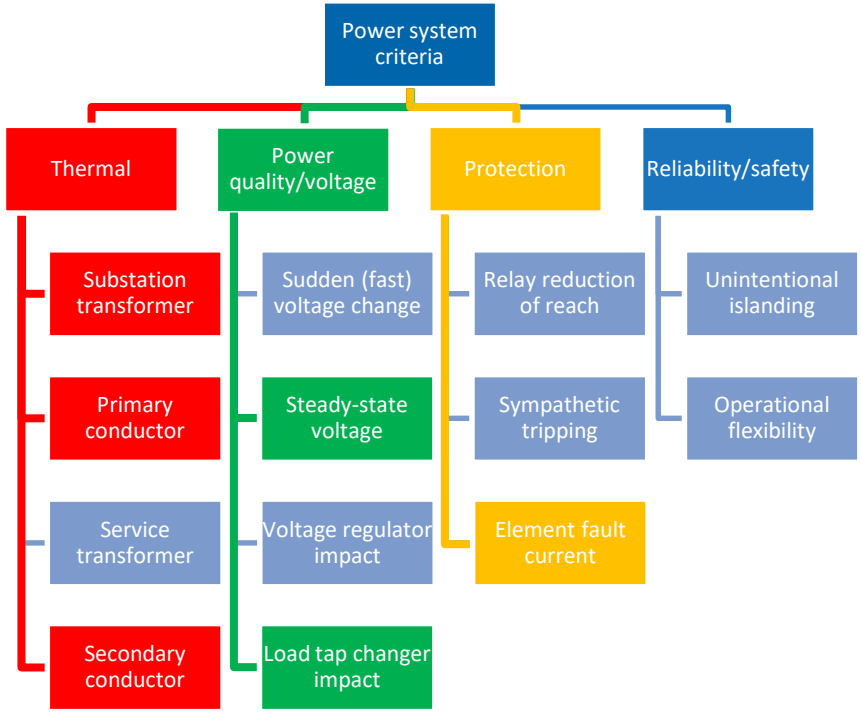
Screening new interconnection requests

Future planning of PV deployment

Power system criteria

PV hosting capacity limited by feeder thresholds and power quality standards

EPRI's evaluation criteria



J. Smith and M. Rylander "Distribution Planning with DER: Distribution System-Wide Impact Assessment Methods" [1]

EN 50160 standards*

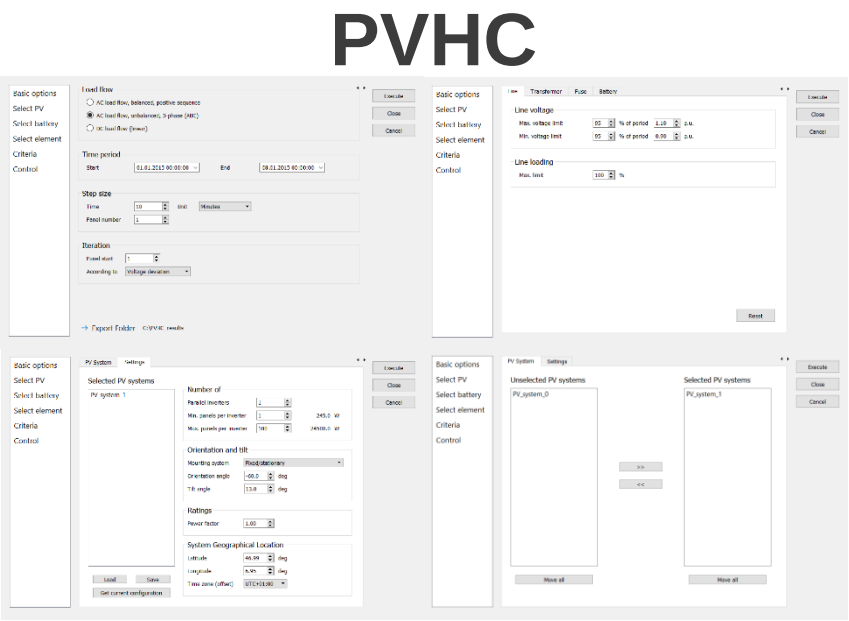
No	Parameter	Supply voltage characteristics according to EN 50160	Low voltage characteristics according to EMC standard EN 61000	
			EN 61000-2-2	Other parts
1	Power frequency	LV, MV: mean value of fundamental measured over 10 s ±1% (49.5 - 50.5 Hz) for 99.5% of week -6%/+4% (47- 52 Hz) for 100% of week	2%	
2	Voltage magnitude variations	LV, MV: ±10% for 95% of week, mean 10 minutes rms values (Figure 1)		±10% applied for 15 minutes
3	Rapid voltage changes	LV: 5% normal 10% infrequently $P_{lt} \leq 1$ for 95% of week MV: 4% normal 6% infrequently $P_{lt} \leq 1$ for 95% of week	3% normal 8% infrequently $P_{st} < 1.0$ $P_{lt} < 0.8$	3% normal 4% maximum $P_{st} < 1.0$ $P_{lt} < 0.65$ (EN 61000-3-3) 3% (IEC 61000-2-12)
4	Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips caused by load switching on: LV: 10 - 50%, MV: 10 - 15% (Figure 1)	urban: 1 - 4 months	up to 30% for 10 ms up to 60% for 100 ms (EN 61000-6-1, 6-2) up to 60% for 1000 ms (EN 61000-6-2)
5	Short interruptions of supply voltage	LV, MV: (up to 3 minutes) few tens - few hundreds/year Duration 70% of them < 1 s		95% reduction for 5 s (EN 61000-6-1, 6-2)
6	Long interruption of supply voltage	LV, MV: (longer than 3 minutes) <10 - 50/year		
7	Temporary, power frequency overvoltages	LV: <1.5 kV rms MV: 1.7 U_c (solid or impedance earth) 2.0 U_c (unearthed or resonant earth)		
8	Transient overvoltages	LV: generally < 6kV, occasionally higher; rise time: ms - µs. MV: not defined		±2 kV, line-to-earth ±1 kV, line-to-line 1.2/50(8/20) Tr/Th µs (EN 61000-6-1, 6-2)
9	Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some locations	2%	2% (IEC 61000-2-12)
10	Harmonic voltage	LV, MV: see Table 2	6%-5[h], 5%-7[h], 3.5%-11[h], 3%-13[h], THD <8%	5% 3rd, 6% 5th, 5% 7th, 1.5% 9th, 3.5% 11th, 3% 13th, 0.3% 15th, 2% 17th (EN 61000-3-2)
11	Interharmonic voltage	LV, MV: under consideration	0.2%	

*P.Q.A. Guide, "Voltage Disturbances", *Stand. EN*, vol. 50160 [2]

PVHC

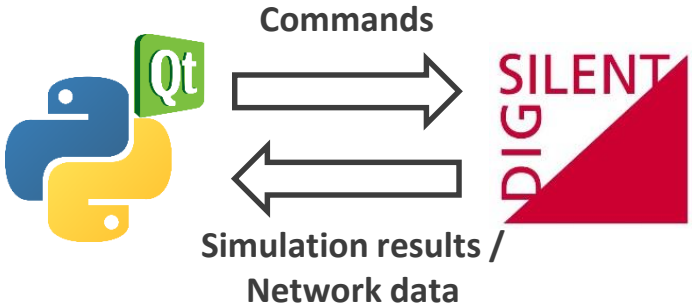
Developed a tool (PVHC) capable of:

- Estimating the PV hosting capacity, **rapidly and accurately**
- **Evaluating** current state of grid in terms of power quality under chosen PV configurations
- **Detecting** power system criteria and standards' violations and their location
- Being **highly expandable** and **portable**



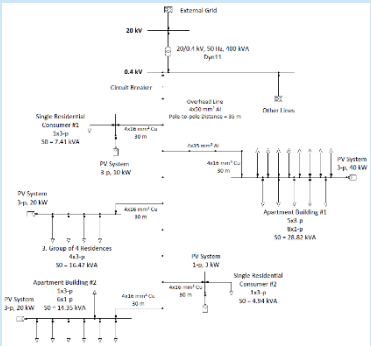
How:

- PyQt for the GUI (PowerFactory-inspired)
- PowerFactory for the electrical grid simulation
- Python scripting for automation of tasks

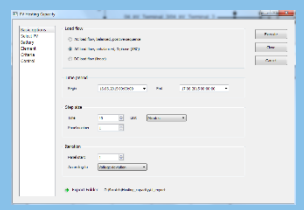


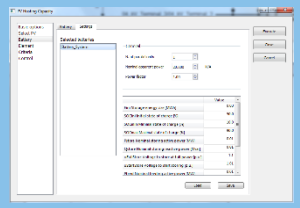
Developed add-on

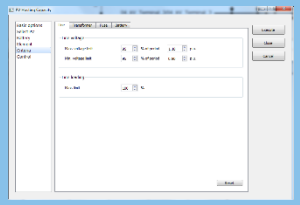
Setup



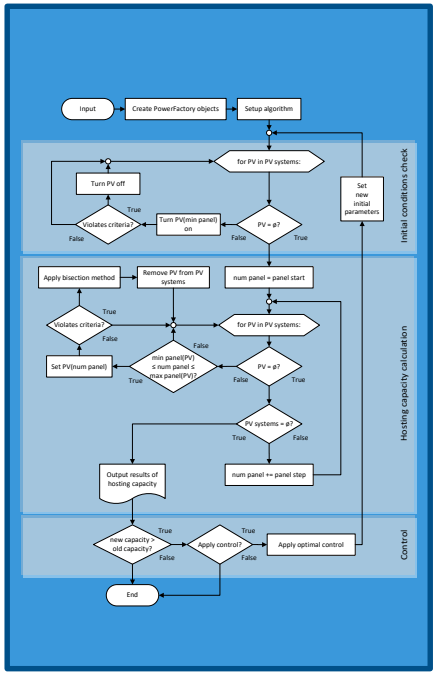
GUI



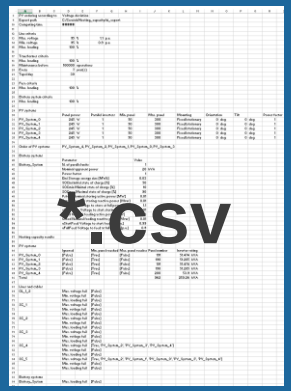


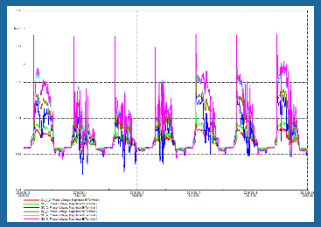


PVHC computation



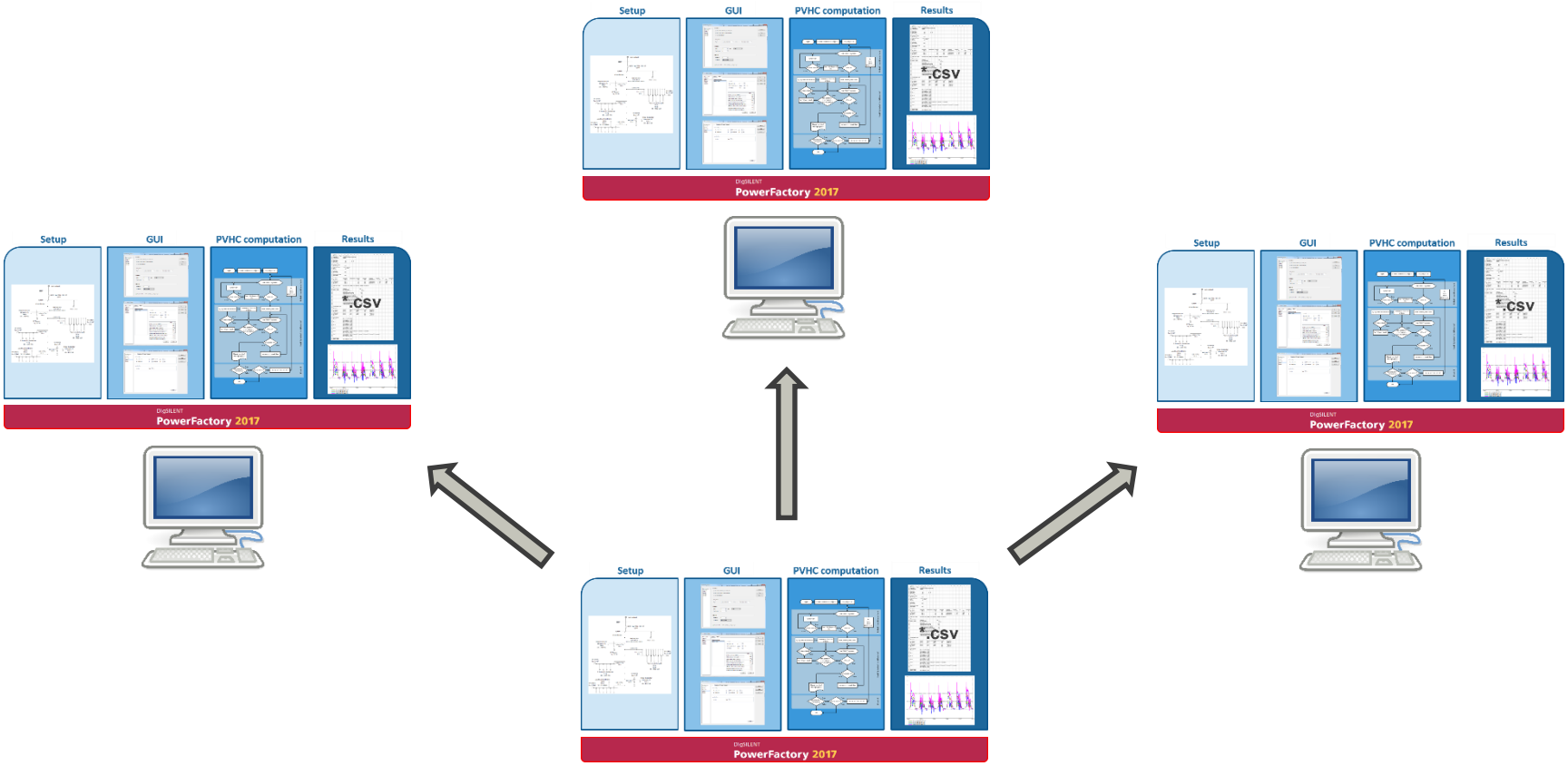
Results





DIgSILENT
PowerFactory 2017

High portability



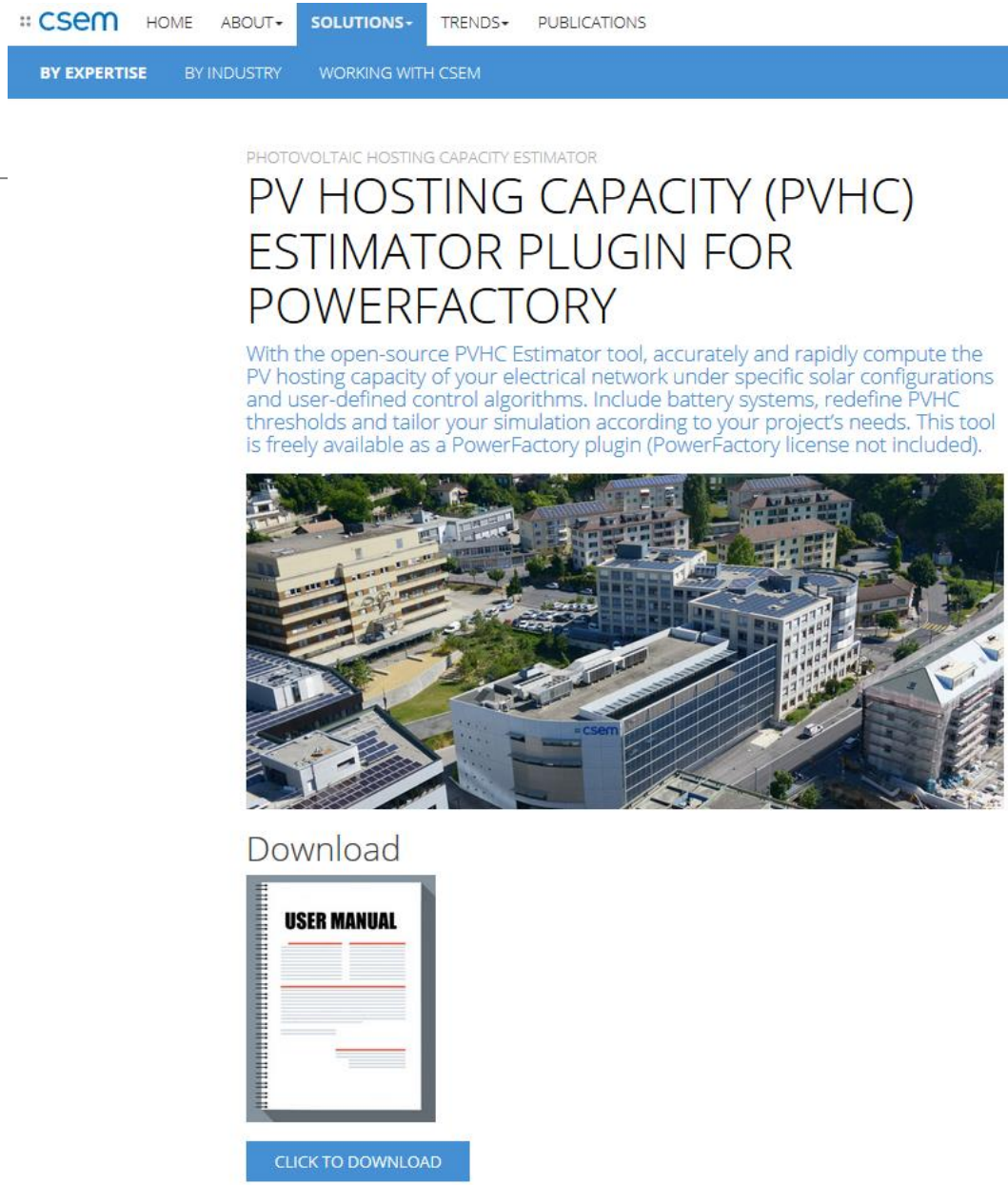
Free download

PVHC is an open-source tool.

Access the source code and documentation at:

www.csem.ch/PVHC

PVHC can be expanded to adjust to your project's needs

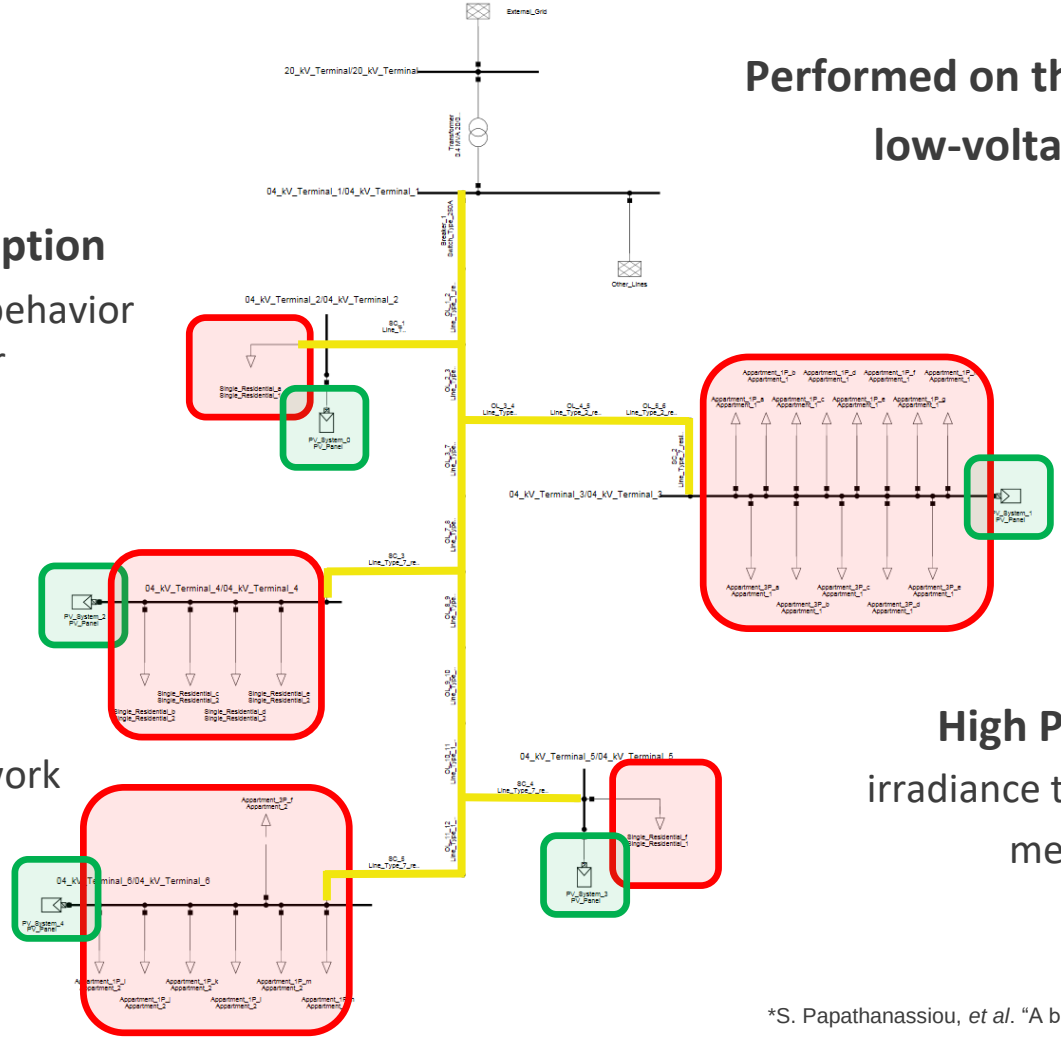


Tool validation

Performed on the CIGRE benchmark low-voltage microgrid*

Load consumption

generated by a behavior simulator



Overhead lines

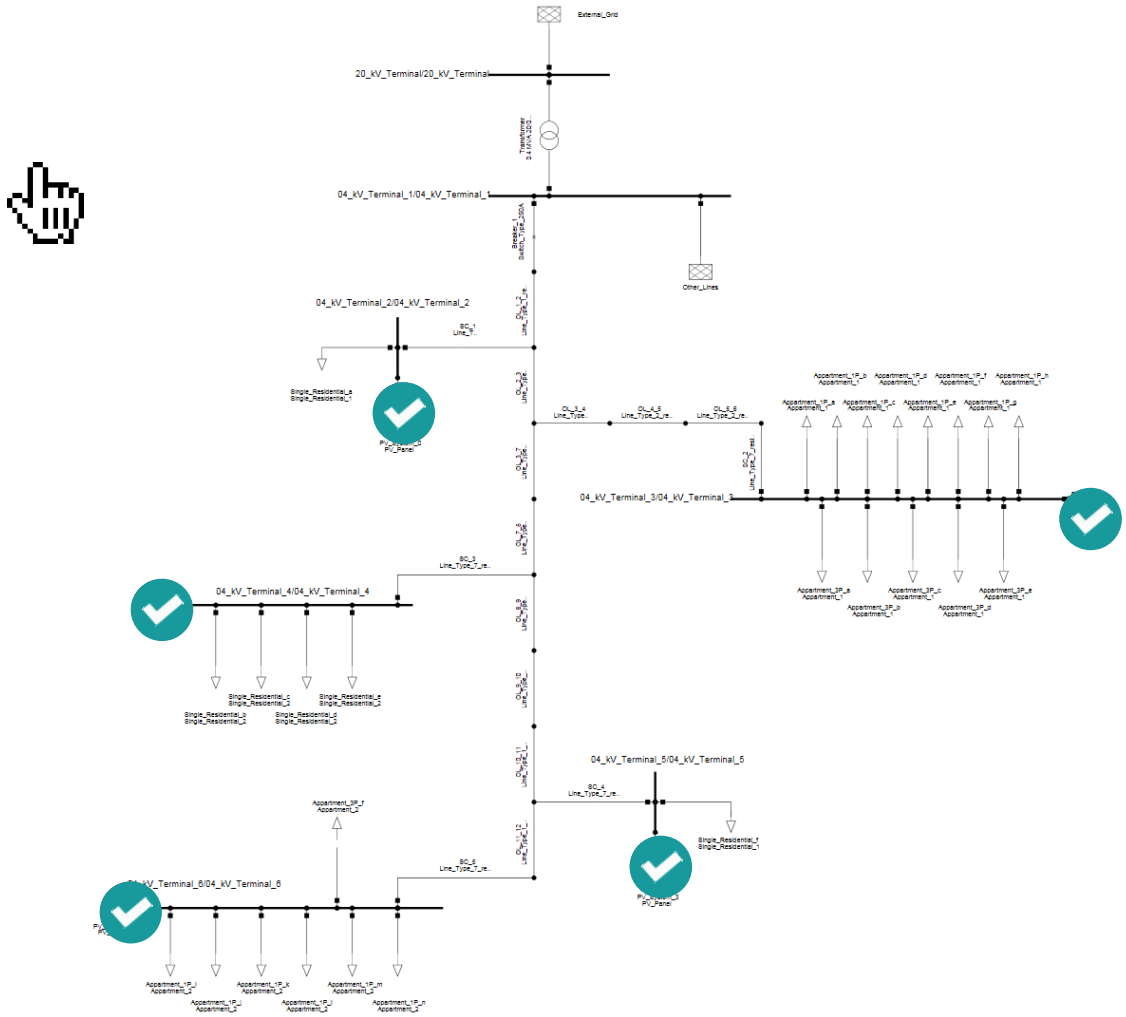
forming a radial network

High PV penetration

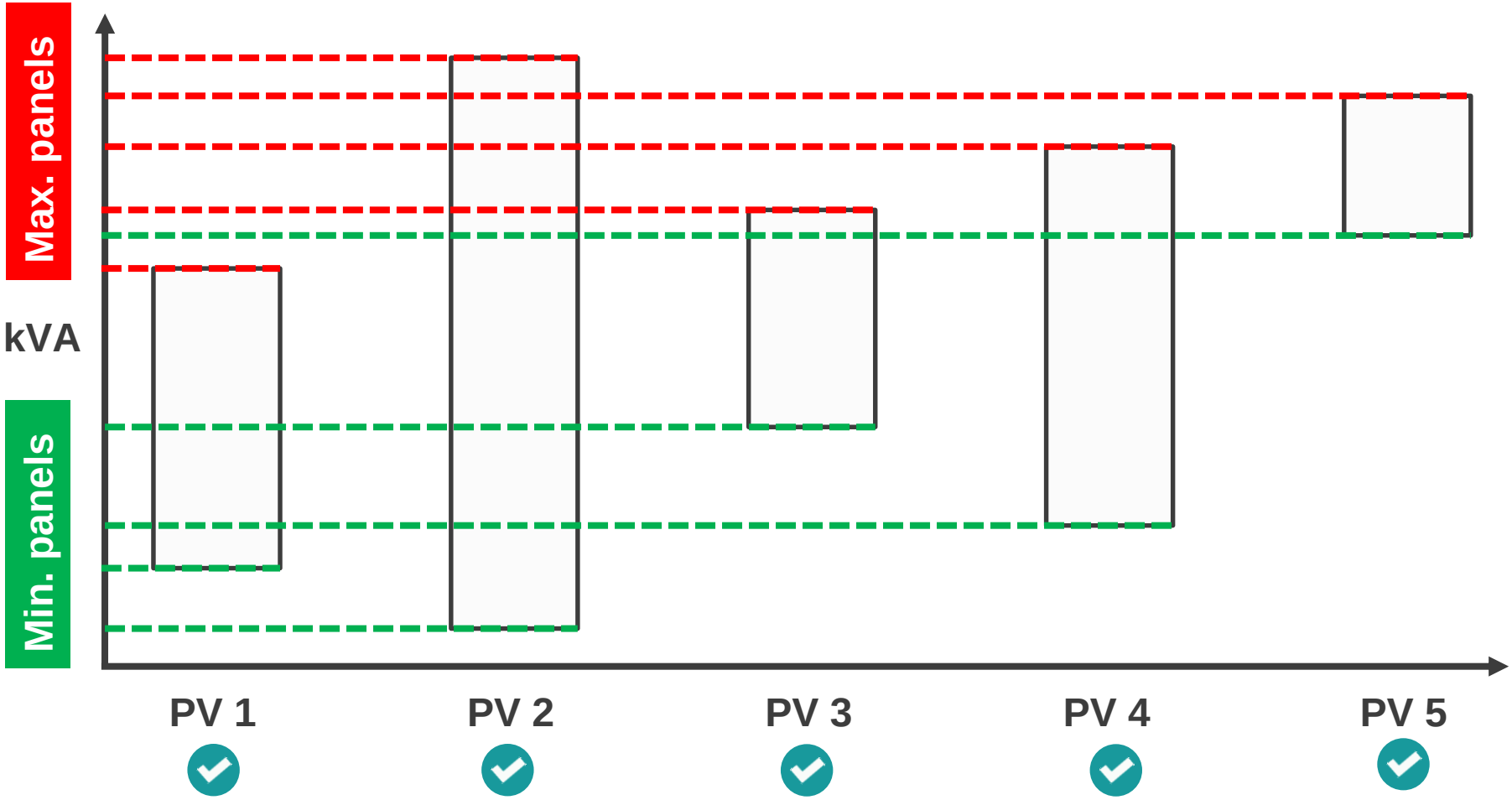
irradiance time series from real measurements

*S. Papathanassiou, *et al*. “A benchmark low voltage microgrid network” [3]

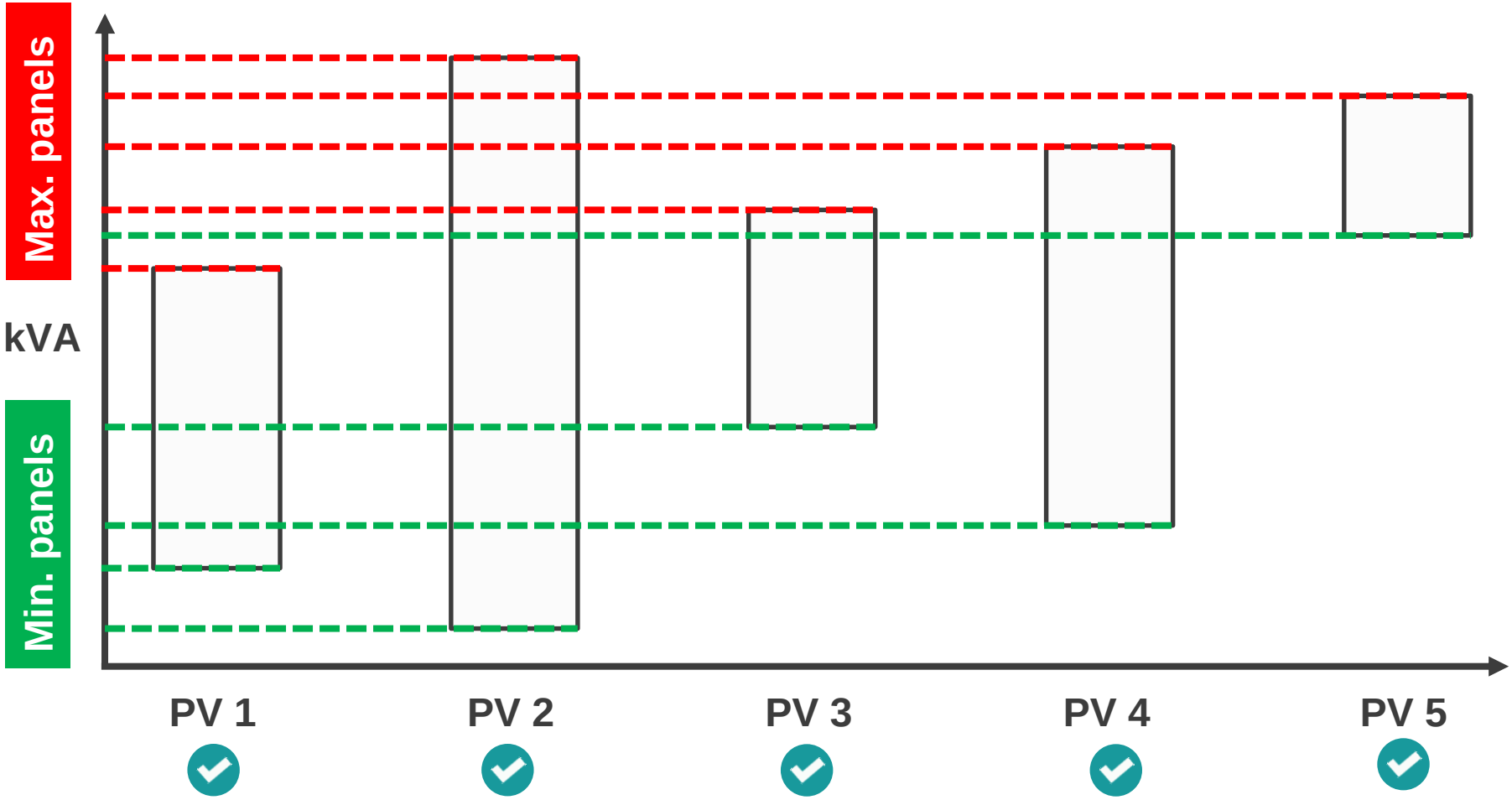
Step 1 – select PV systems



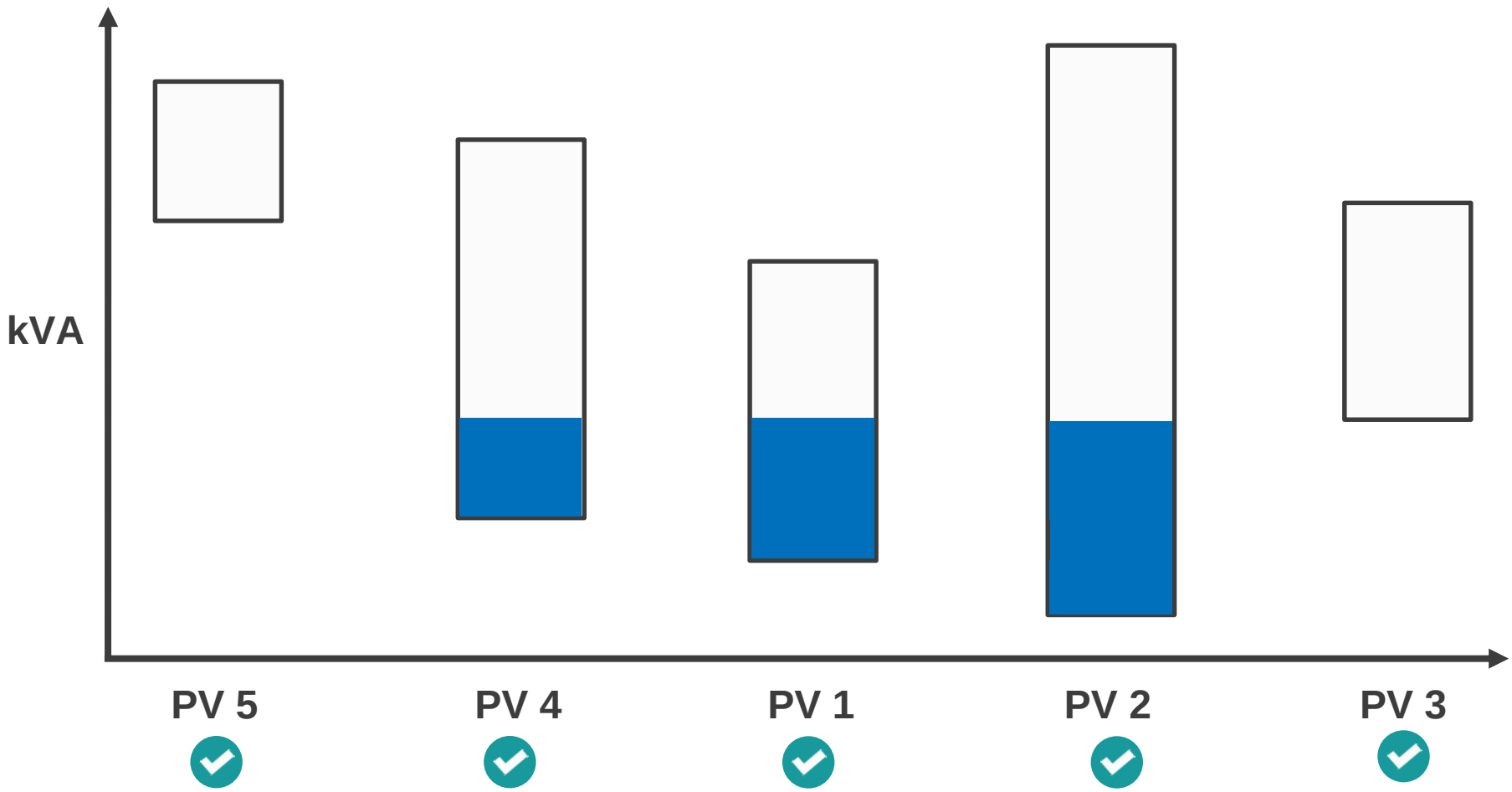
Step 2 – configure PV systems



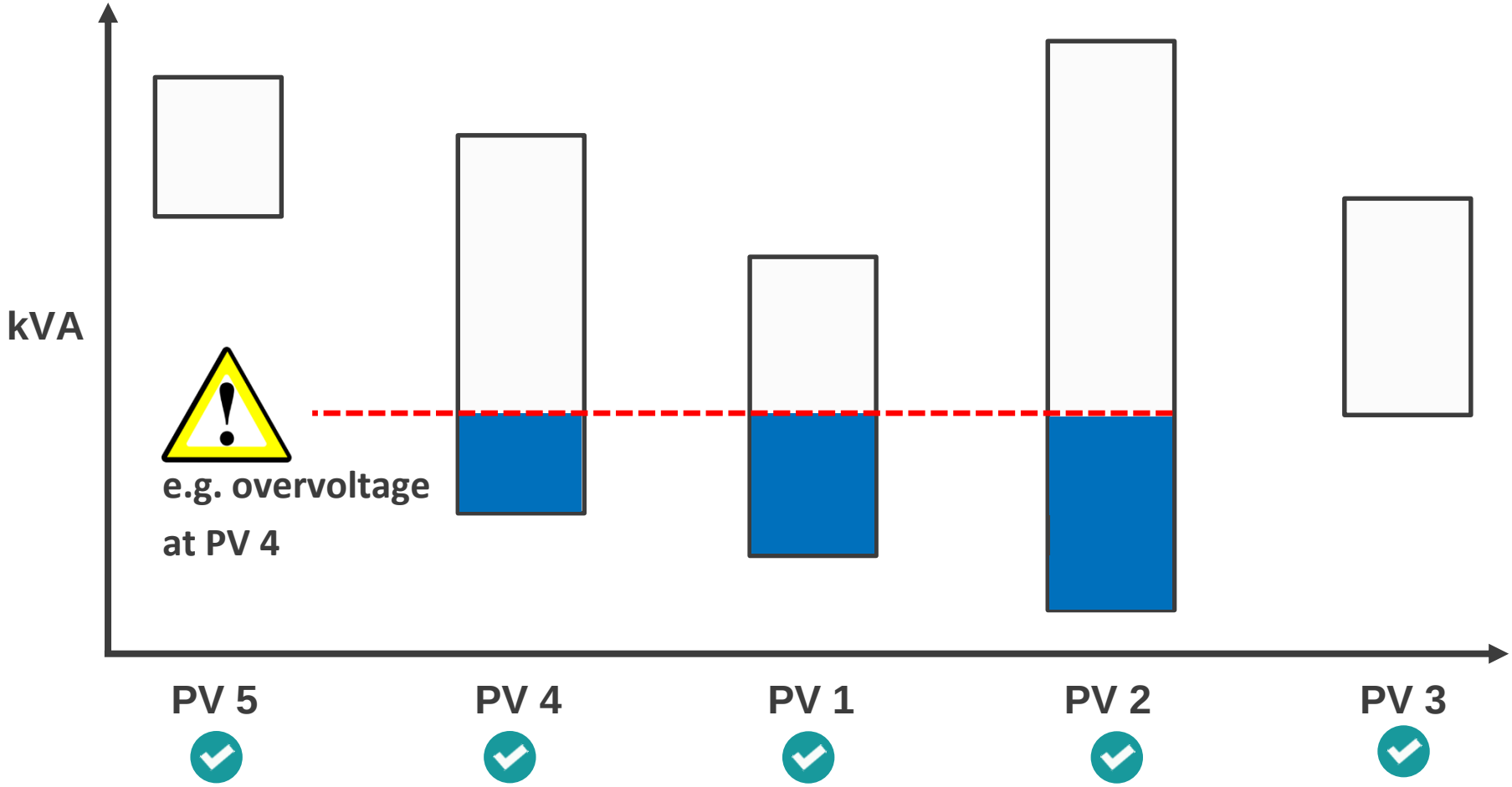
Step 3 – reorder PV systems



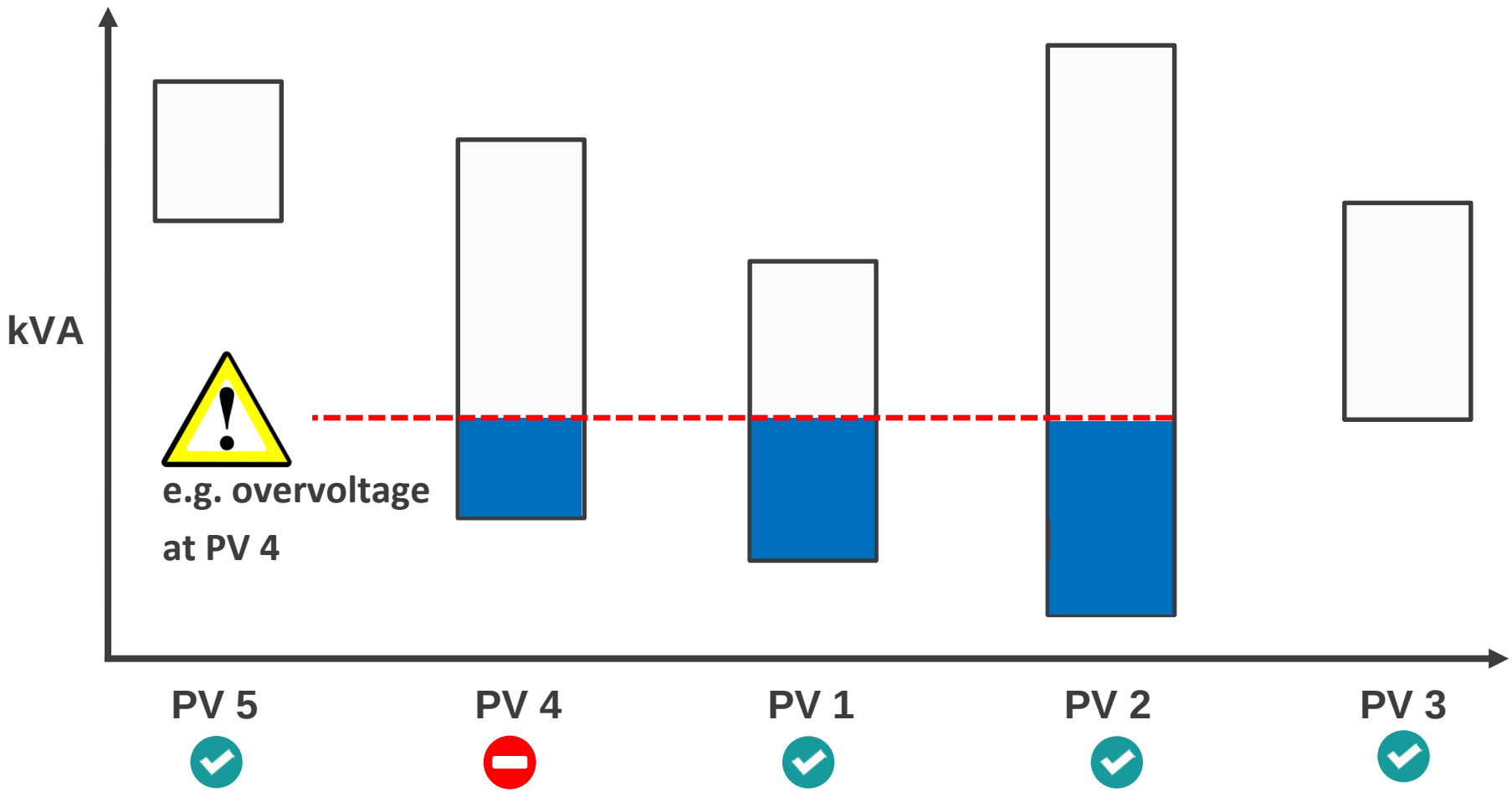
Step 4 – gradually increment power



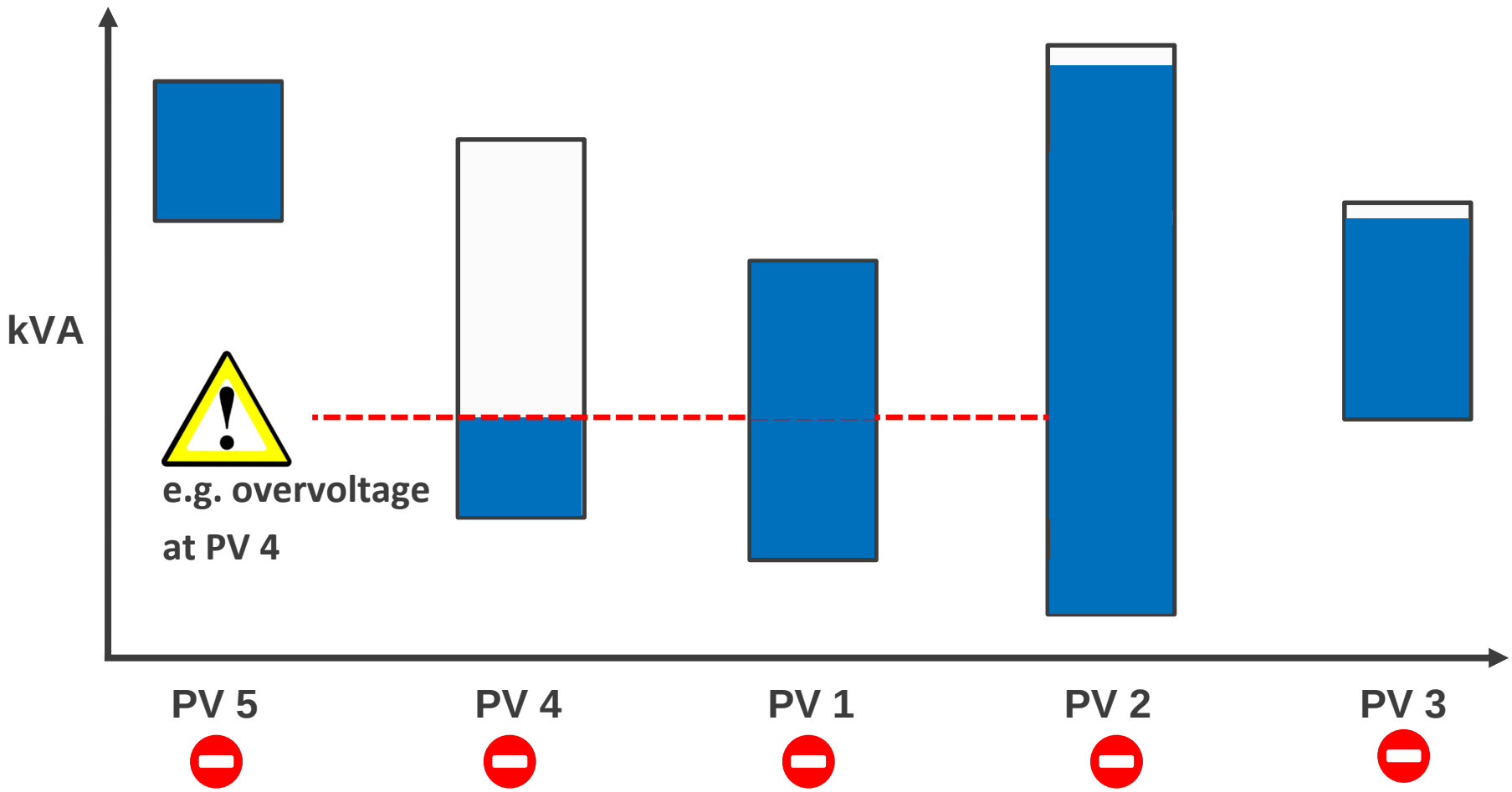
Step 5 – stop at power criterion fail



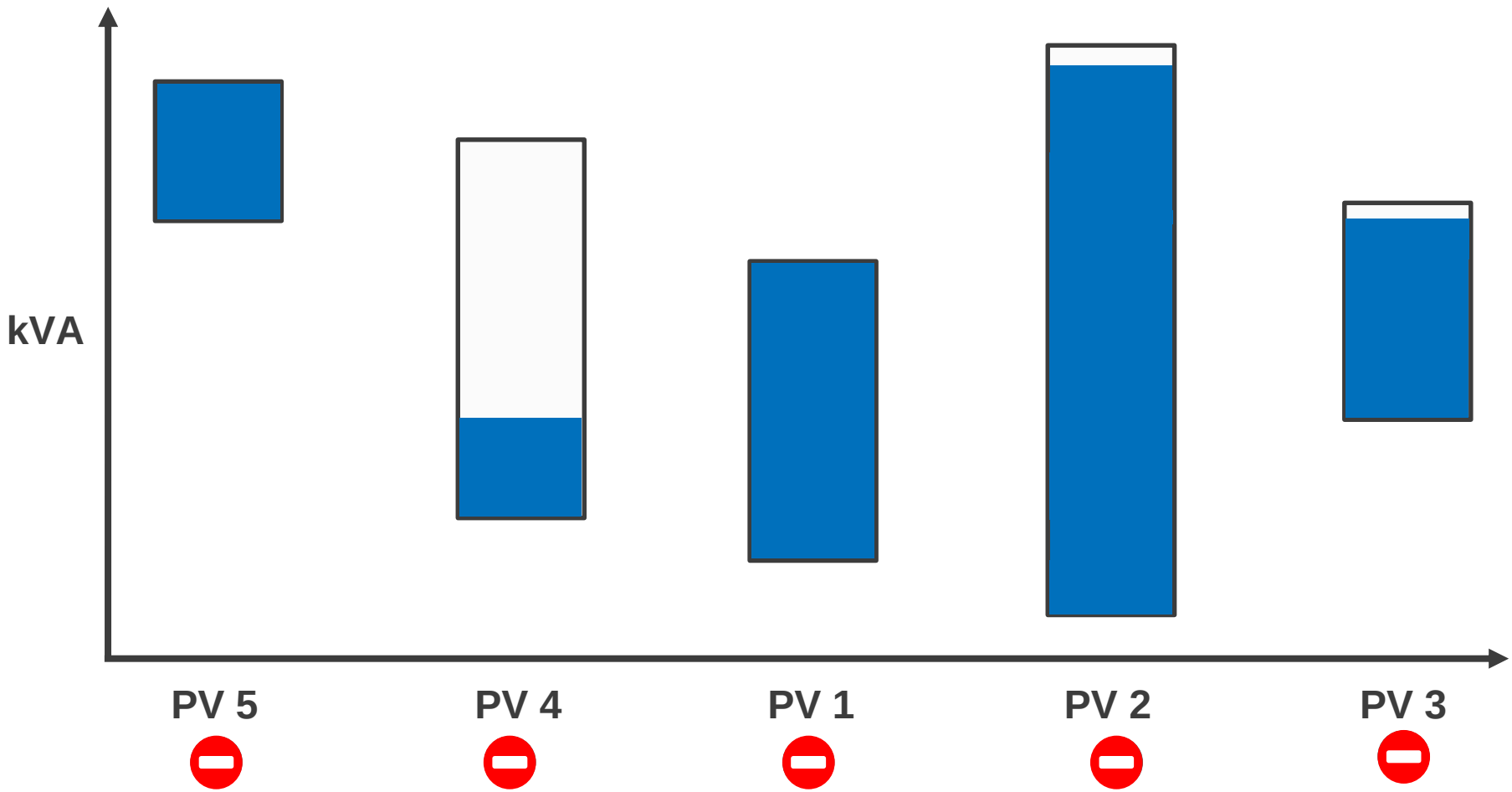
Step 6 – freeze failing PV system



Step 7 – continue incrementing power and freeze PV systems accordingly



1-panel precision convergence



1-panel precision convergence

User input:

- Min. and Max. panel
- Increment step size

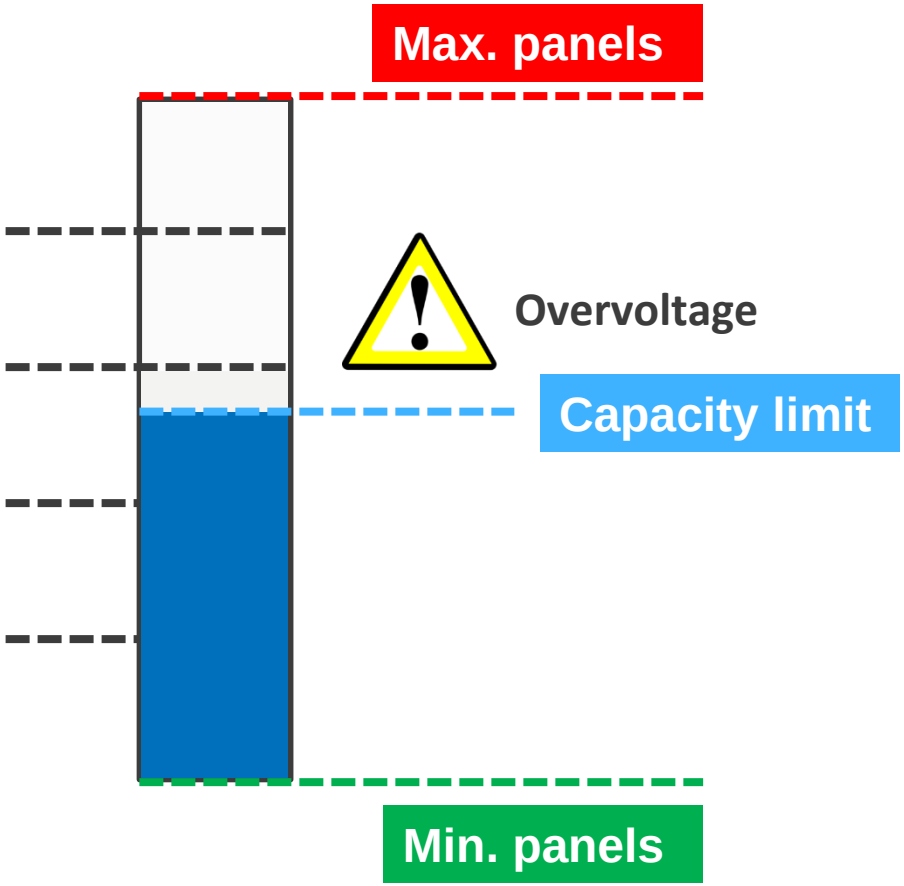
Start incrementing power

Identified failure:

- Stop incrementing
- Apply bisection method

Convergence:

- 1-panel precision



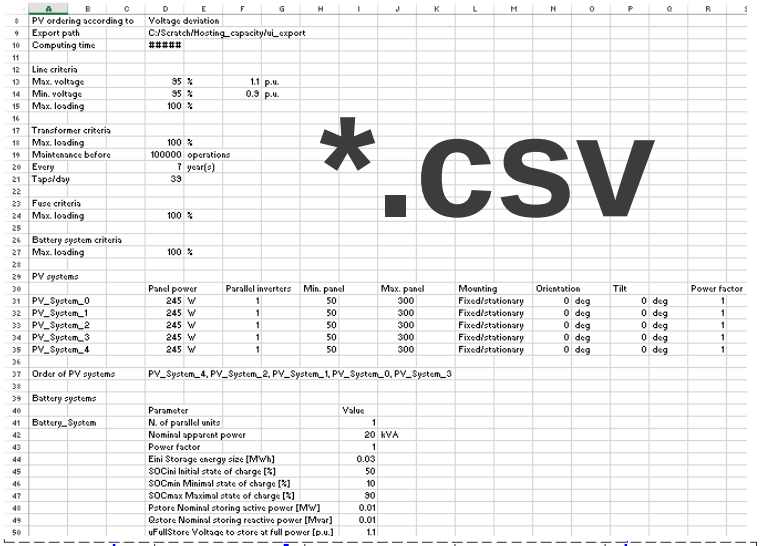
Output and results

Excel sheet containing:

- Recap of program settings and selected network elements
- State of PV systems (panel number, output power)
- Location and cause of failed power criteria
- Total feeder PV generation
- Power quality report (coming soon)

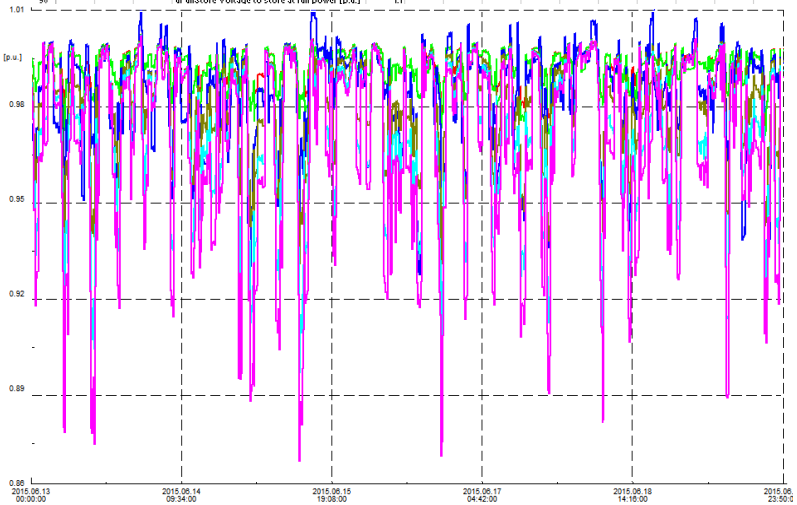
Automatic plotting on PowerFactory:

- Voltage profiles
- Thermal loadings
- Transformer tap changes
- ….

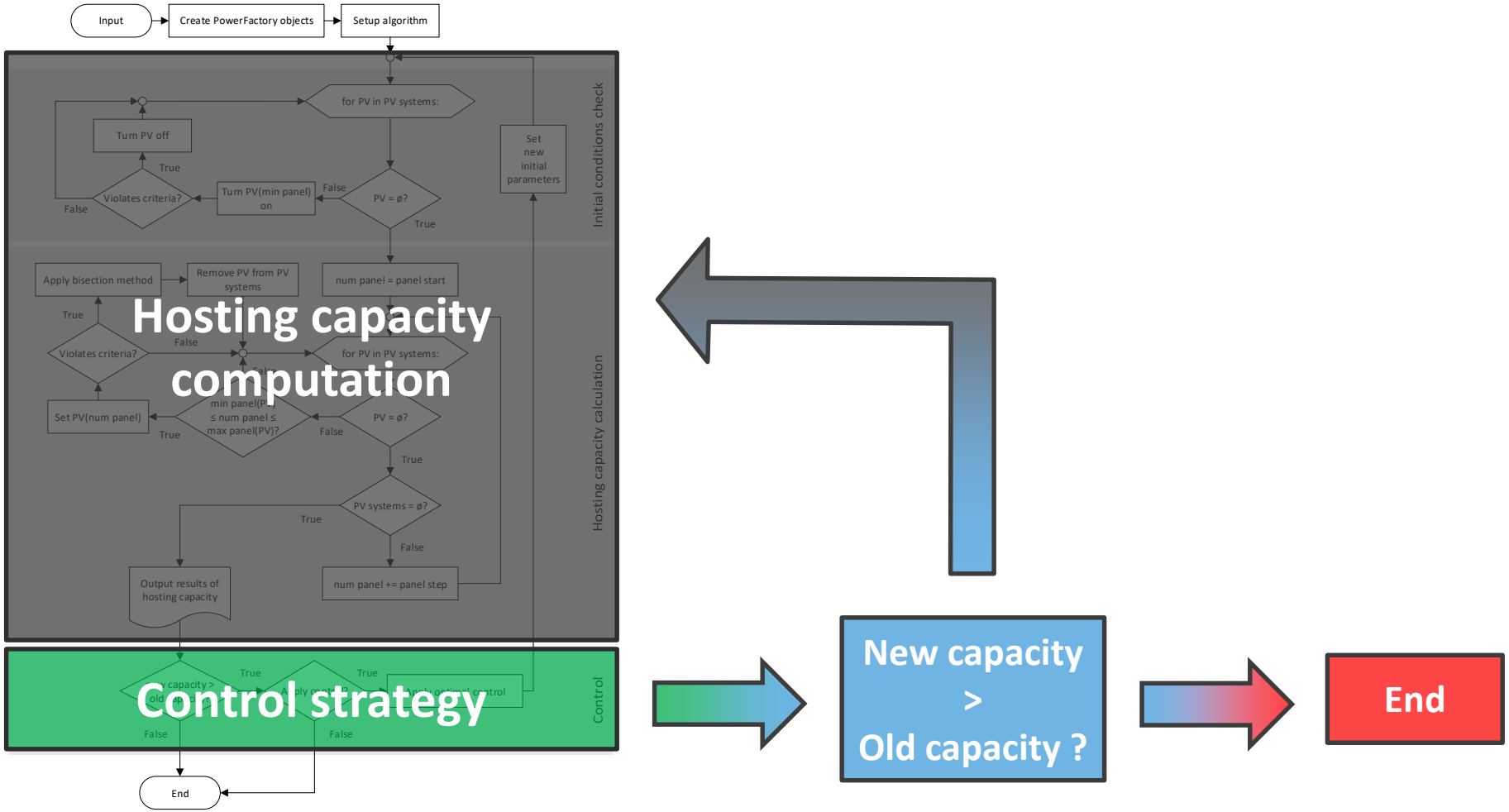


8	PV ordering according to		Voltage deviation																
9	Export path		C:/Scratch/Hosting_capacity/ui_export																
10	Computing time		#####																
11																			
12	Line criteria																		
13	Max. voltage		95	%		1.1	p.u.												
14	Min. voltage		95	%		0.9	p.u.												
15	Max. loading		100	%															
16																			
17	Transformer criteria																		
18	Max. loading		100	%															
19	Maintenance before		100000	operations															
20	Every		7	year(s)															
21	Taps/day		33																
22																			
23	Fuse criteria																		
24	Max. loading		100	%															
25																			
26	Battery system criteria																		
27	Max. loading		100	%															
28																			
29	PV systems																		
30			Panel power		Parallel inverters		Min. panel		Max. panel		Mounting		Orientation		Tilt		Power factor		
31	PV_System_0		245	W	1		50		300		Fixed/stationary		0	deg	0	deg	1		
32	PV_System_1		245	W	1		50		300		Fixed/stationary		0	deg	0	deg	1		
33	PV_System_2		245	W	1		50		300		Fixed/stationary		0	deg	0	deg	1		
34	PV_System_3		245	W	1		50		300		Fixed/stationary		0	deg	0	deg	1		
35	PV_System_4		245	W	1		50		300		Fixed/stationary		0	deg	0	deg	1		
36																			
37	Order of PV systems		PV_System_4, PV_System_2, PV_System_1, PV_System_0, PV_System_3																
38																			
39	Battery systems																		
40			Parameter					Value											
41	Battery_System		N. of parallel units					1											
42			Nominal apparent power					20	kVA										
43			Power factor					1											
44			Eini Storage energy size [MWh]					0.03											
45			SOCini Initial state of charge [%]					50											
46			SOCmin Minimal state of charge [%]					10											
47			SOCmax Maximal state of charge [%]					90											
48			Pstore Nominal storing active power [MW]					0.01											
49			Qstore Nominal storing reactive power [Mvar]					0.01											
50			uFullStore Voltage to store at full power [p.u.]					1.1											

*.csv



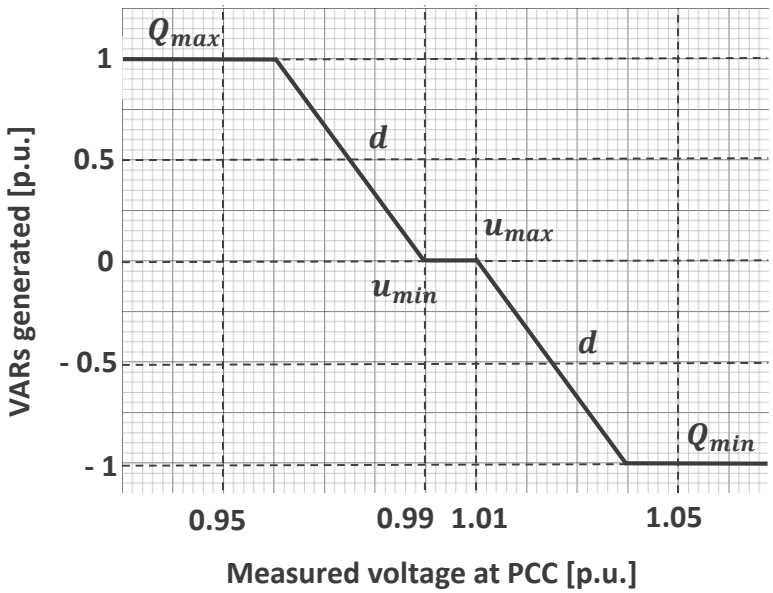
Implementation of user-defined control strategies



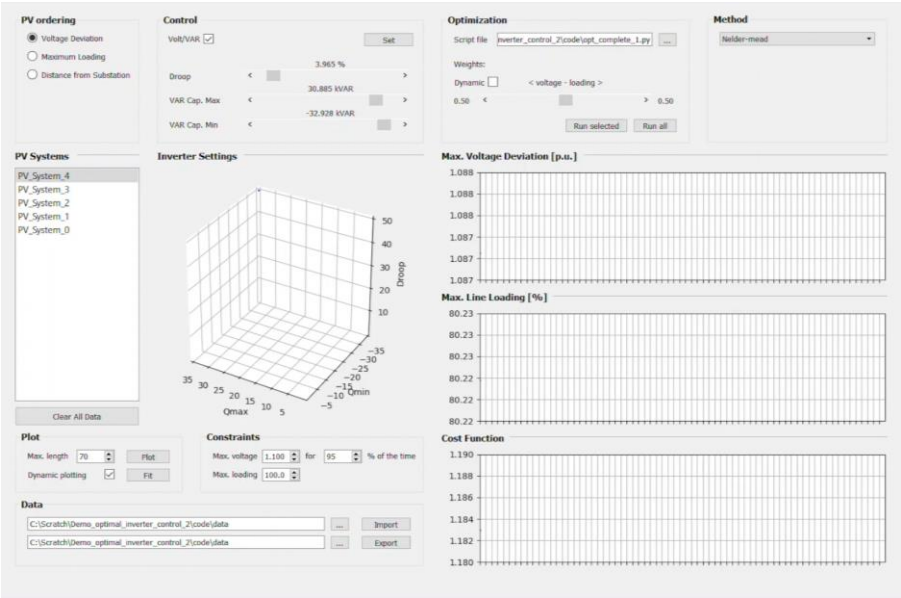
Smart inverter control (I)

Development of a smart inverter control strategy:

- Based on **Volt/VAR control**
- Find **optimal control parameters**
- Based on **regular update** of parameters
- Guarantee grid stability / **power quality**
- Assist in **voltage support**
- Increase **PV hosting capacity**



Smart inverter control (II)



Objective function:

$$min \;\; C(x,\lambda) = \frac{\lambda V^2(x) + (1-\lambda)L^2(x)}{V(x) + L(x)}$$

Trade-off between:

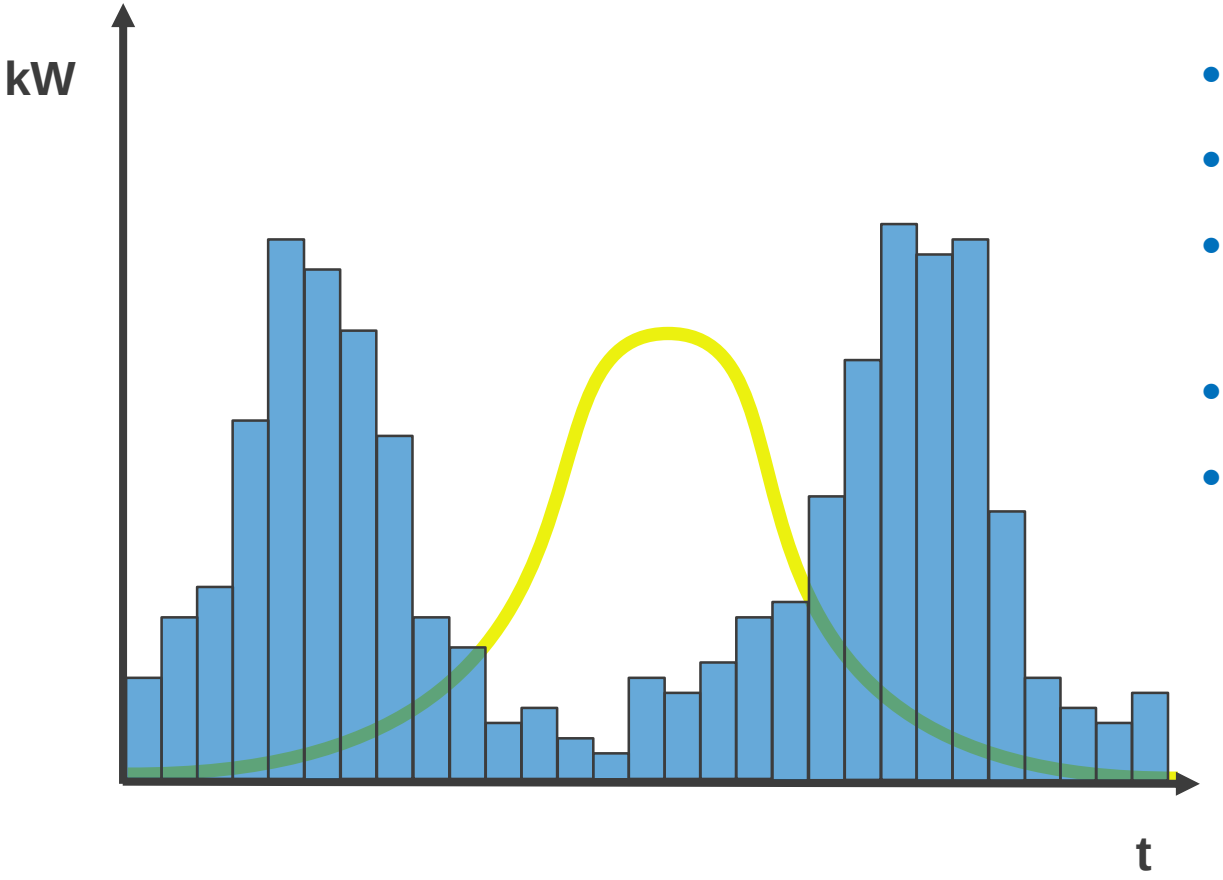
Voltage deviation

$$V(x) = \sum_{n=1}^{N} \sqrt{\frac{1}{K}\sum_{k=1}^{K}(10u_{k,n}(x) - 10)^2}$$

Max. line loading

$$L(x) = \sum_{n=1}^{N} \sqrt{\frac{1}{K}\sum_{k=1}^{K}(0.01l_{k,n}(x))^2}$$

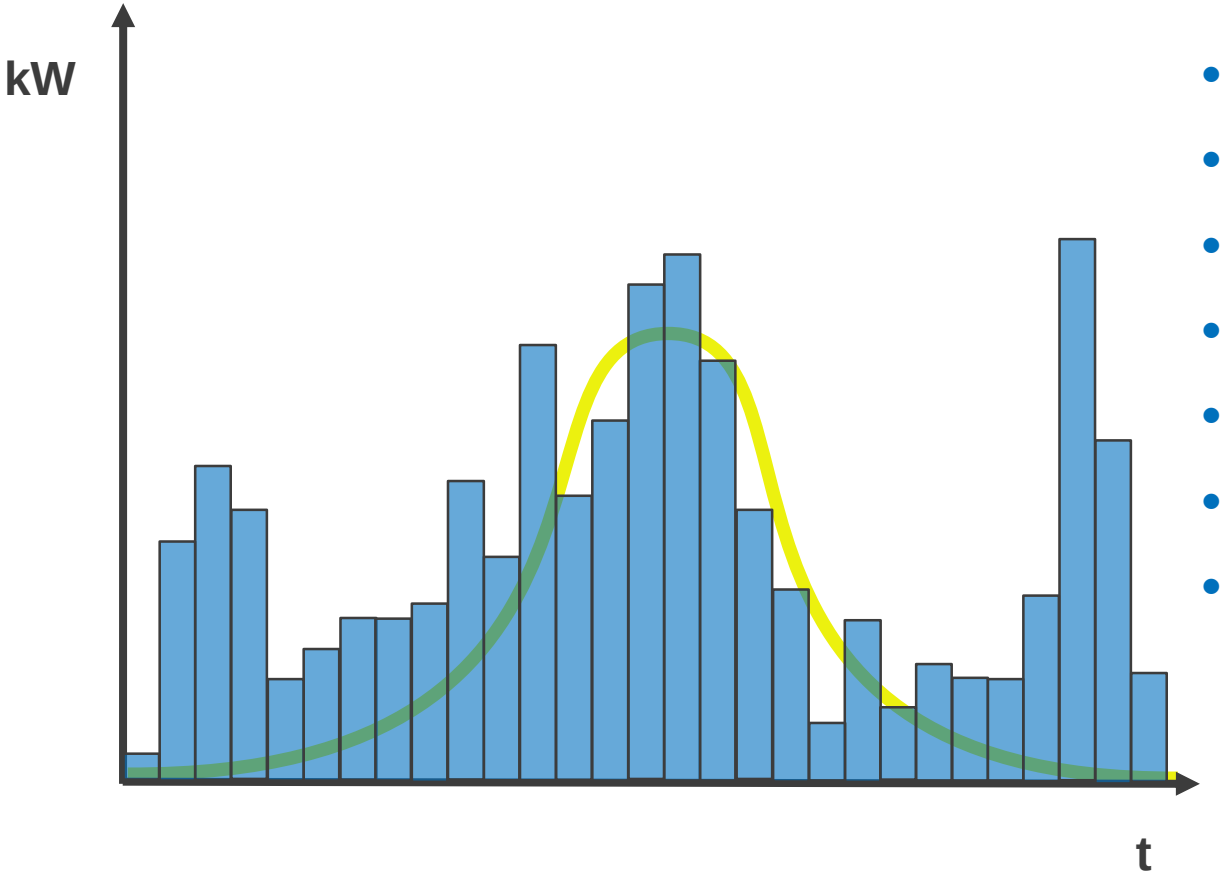
Smart appliance scheduler



No load shifting:

- Suboptimal self-consumption
- Possible reverse power flows
- Possible over-voltages and under-voltages
- Solar leakage
- Expensive storage systems needed

Smart appliance scheduler



Load shifting:

- Done by solving a MILP*
- Self-consumption maximized
- Peak-to-average ratio reduced
- Reverse power flows avoided
- Cost of supply reduced
- Voltage deviation improved
- Possible increase of hosting capacity

*V. Kaczmarczyk, *et al*. "Simulator for optimal scheduling of domestic appliances [4]

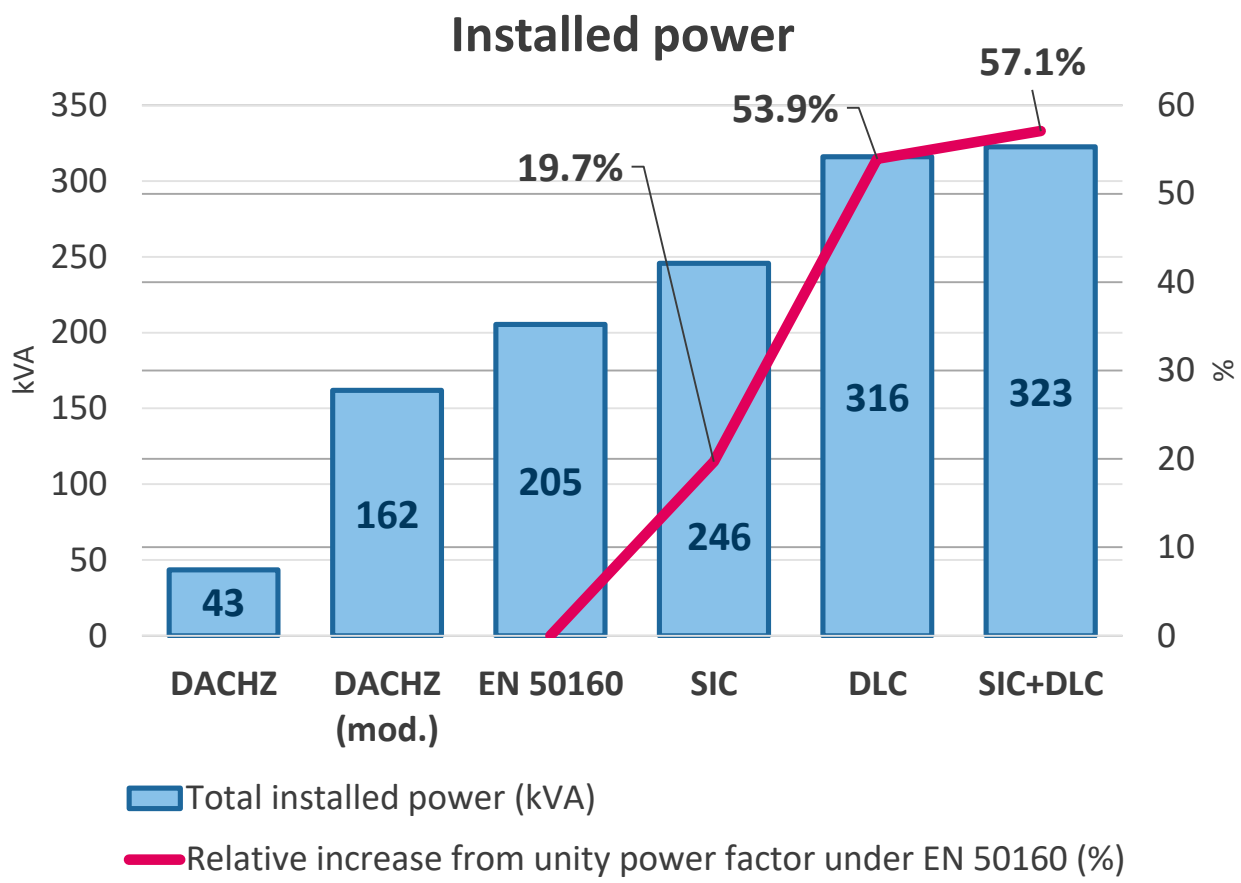
Simulated results

Rules for the sizing of PV systems are **very different from one another**

+ 19.7% hosting capacity with smart inverter control.

+ 53.9% hosting capacity with direct load control.

+ 57.1% hosting capacity with both methods combined



Conclusion

Automated quantification of PV hosting capacity:

- Under specific grid configuration and user-defined settings
- Fast and Accurate
- Easily expandable and portable

Ability to compare, evaluate, and combine various control strategies

Results on CIGRE's benchmark grid show:

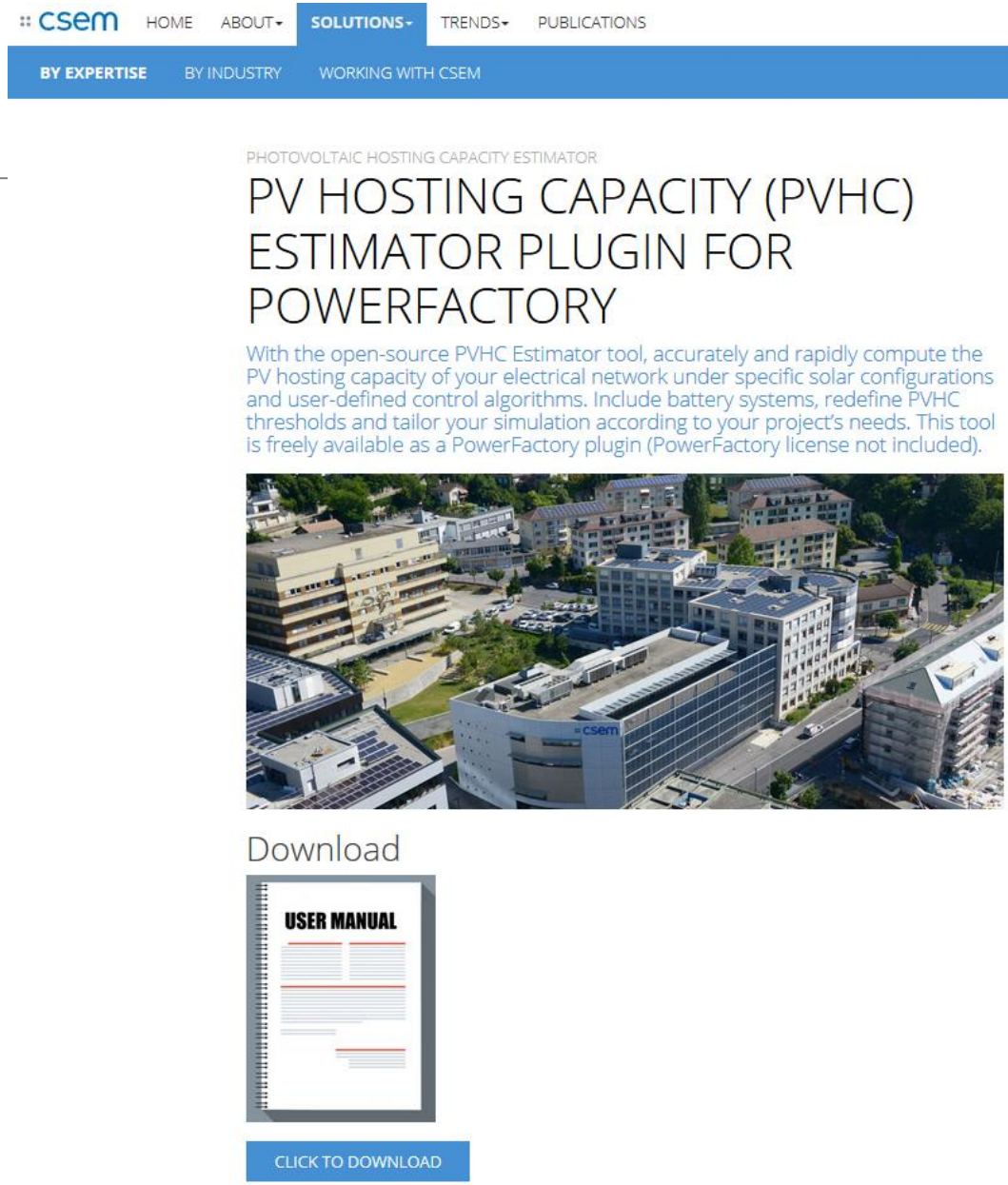
- A 377% difference in hosting capacity between DACHZ and EN 50160
- A total increase of 57.1% in hosting capacity with smart control strategies

Free download

PVHC is an open-source tool.

Access the source code and documentation at:

www.csem.ch/PVHC



Acknowledgements

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