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Fundamentals and processes for photovoltaic devices

III. Energy yield and PV systems

1. Energy yields
2. Inverters and grid
3. Applications of PV

1. Energy yield of PV systems

- What counts primarily, if you purchased a certain number of “Watts”, is the **energy yield** over a certain duration, e.g. one year. Typically the Energy yield in given in **kWh produced/W installed** !
- The nominal efficiency does not count for energy yield: it can be the same for a 10 or 20% module

- Typically the AC injected power will be **70-90%** of the nominal power after correction by the irradiance in the plane of the module.
  Temporarily, it can also be higher (e.g. sun with thin clouds around), going even up to 160%. With bi-facial modules (collecting light from both sides) it can also go above 100%.

- There are multiple “losses” which impact a PV system efficiency !

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1. Energy yield of PV systems

Typical losses of a grid connect system

Compared to the ideal STC conditions of the modules,
losses occur in a real system up to the injection in the grid or self-usage.

- **Heating effect (T > 25°C)** 3-15% losses (varies over the year)
- **Lower irradiance** 1-3% losses (Voc goes down, diodes are not ideal)
- **Dust, soiling** 3-10% (or more)
- **Module mismatch /shading** 1-10% (difference in current produced by the modules)
- **Connections cables** 1-2% (low quality connectors or too thin cables → series resistance)
- **Inverter/transformer losses** 2-10%
- Module degradation 1% (beginning) to 12 to 25% after 30 years
- **Others** 1-5% (system failure, snow, inverter failure, three growing, …)

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Temperature losses

Solar cell: some features

In practice, the operating temperature is up to 20-30° above the ambient temperature

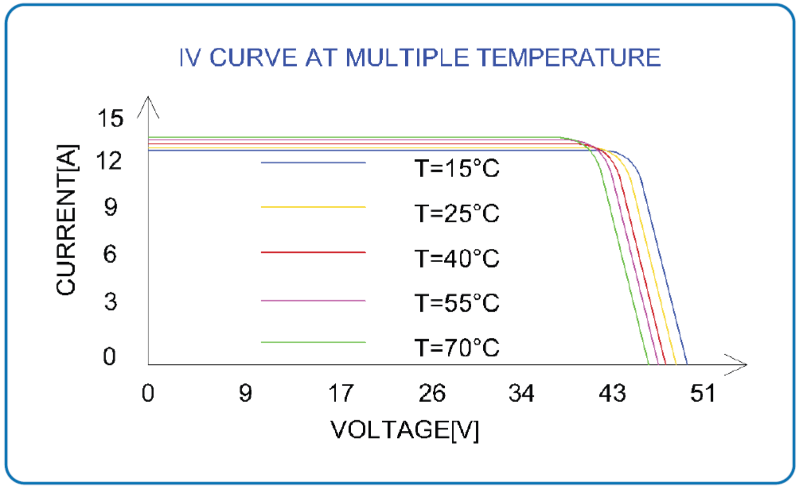
→ The ***coefficient of temperature of the power*** $dP_{max}\ /dT$ is important!

- -0.25 to – 0.45 %/°C for c-Si module (from the best to the worst technology)
- -0.2% for a-Si:H (amorphous silicon)

Example:

c-Si module at 65° → 40x0.4% = **16%** relative losses compared its nominal power

a-Si:H module at 65° → 40x0.2 % = 8 % losses



For silicon and most semiconductor, Voc goes down and current increases a little with temperature.

From datasheet
TP540HG10TB (Glass - Transparent Backsheet)

Temperature losses

In real use, both the type of installation and thermal properties of the module are important

To quantify the thermal behavior of modules in typical operating conditions:

800W/m^2, T_a=20°C, free mounting, wind 1 m/s.

NOCT = **Nominal Operating Cell Temperature given** 61215:2005 (old approach)
in V_{oc} conditions. Typical NOCT value is around 45 °C

NMOT: nominal module operating temperature T (Test procedure IEC 61853-2:2016)
Module at MPP. It extracts part of the impeding energy
Typicall NMOT **are in the range of 43°C**

Under operation (Mpp) the module will be slightly cooler by a few degrees, because energy is extracted, contrarily to Voc conditions. The optical properties of the cells/module, and its efficiency will impact the NMOT… Of course modules can also be cooled actively (e.g. with water)

Tcoefficient, NOCT, NOMOT of C-Si modules

TATA POWER SOLAR

TP540HG10TB (Glass - Transparent Backsheet)

MONO PERC BIFACIAL SOLAR MODULE

Temperature Coefficient Characteristics

NOCT(°C)	45±1
Module efficiency (% / °C)	-0.06 ± 0.01
Temperature Coefficient of Pmax (% / °C)	-0.36
Temperature coefficient of Voc (% / °C)	-0.28
Temperature coefficient of Isc (% / °C)	0.05

PERC

Q.TRON BLK M-G2+ SERIES

415-440 Wp | 108 Cells
22.5 % Maximum Module Efficiency

TEMPERATURE COEFFICIENTS							
Temperature Coefficient of I_{SC}	α	[%/K]	+0.04	Temperature Coefficient of V_{OC}	β	[%/K]	−0.24
Temperature Coefficient of P_{MPP}	γ	[%/K]	−0.30	Nominal Module Operating Temperature	NMOT	[°F]	109±5.4 (43±3°C)

TOPCON

Meyer Burger Panel+ White XL

Product type: MB_WG144Cyz_XXX

540 – 560 Wp

For ground-mounted solar power plants: Bifacial heterojunction high-performance solar module with SmartWire Connection Technology (SWCT®).

Temperature coefficients

Temperature coefficient of I_{SC}	α	[%/K]	+0.033
Temperature coefficient of V_{OC}	β	[%/K]	-0.234
Temperature coefficient of P_{MPP}	γ	[%/K]	-0.259
Nominal Module Operating Temperature	NMOT[3]	[°C]	43±2

The temperature coefficients stated are linear values.

HJT

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Degradation rate and warranty of PV modules

- Typical 0.4- 0.5% per year for c-Si
- 0.7-1% for thin film

- Today's typical products offer 25-30 years performance **warranty** with:

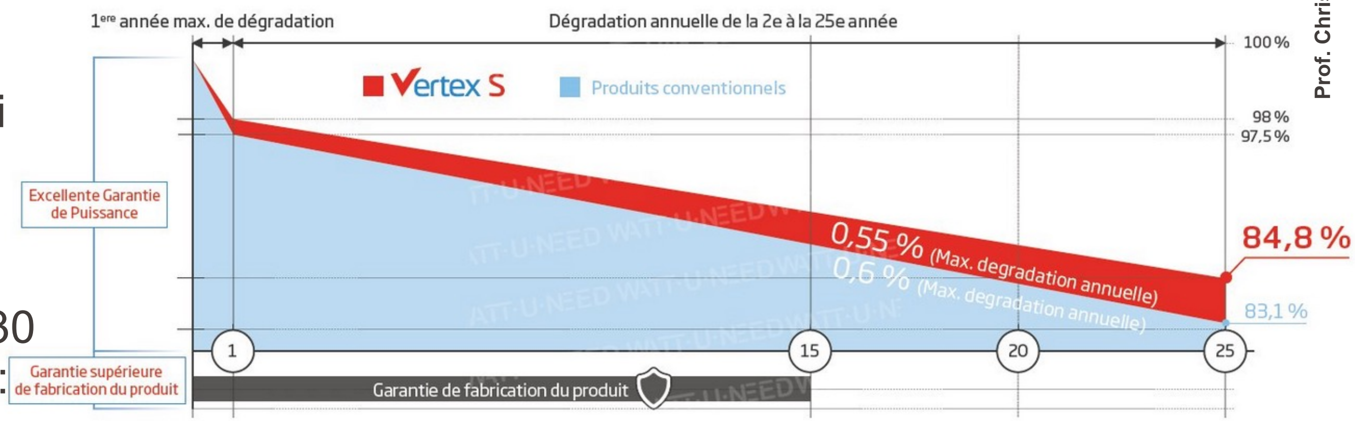
  - 2-3% degradation in the first year

  - Then 0.3-0.6% per year

- **Typically warranty of 84-90% of nominal power after 25 years**
- One company offers up to 40 years performance warranty.
-

TrinaSolar Vertex S DE09.08
Trina Solar

Vertex S Warranty Extension



SunPower Maxeon Panel
40-Year Warranty

Welcome to the solar industry's longest warranty: the SunPower Maxeon 40-Year Warranty.[1] It's as exceptional as our quality solar technology.

Only in selected countries

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The report included both sub-module and system-level anomalies and defects.

PV module underperformance is costing US$2.5 billion globally, says Raptor Maps

By Will Norman

February 28, 2023

Power Plants, Cell Processing, Financial & Legal, Modules, Projects

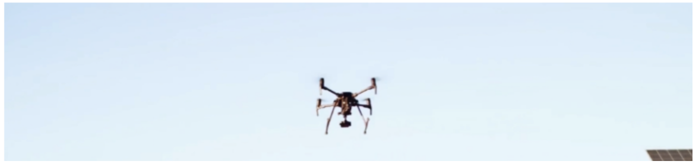
[PV module underperformance is costing US$2.5 billion globally (pv-tech.org)]

US solar facilities lost $5,720 per MW to equipment issues in 2024

US solar facilities lost $5,720 per megawatt in 2024, with global losses from equipment failures and extreme weather reaching $10 billion. Raptor Maps says 193 GW of projects recorded rising power losses, primarily from inverters, strings, and combiners, with regional weather risks varying significantly.

MARCH 6, 2025 RYAN KENNEDY

BALANCE OF SYSTEMS | COMMERCIAL & INDUSTRIAL PV | GRIDS & INTEGRATION | INSTALLATIONS | INVERTERS | MANUFACTURING | MARKETS | MARKETS & POLICY | MODULES & UPSTREAM MANUFACTURING | POLICY | TECHNOLOGY | TECHNOLOGY AND R&D | UTILITY SCALE PV | UNITED STATES



In practice, modules are good products but some surprises can occur with all types of products (and industries adapt). Modules and systems can show anomalies if not properly designed/tested and maintained !

The higher the efficiency, the more sensitive the modules become to «electronic defects» creation !

Inverters, strings, trackers can all fail down as well

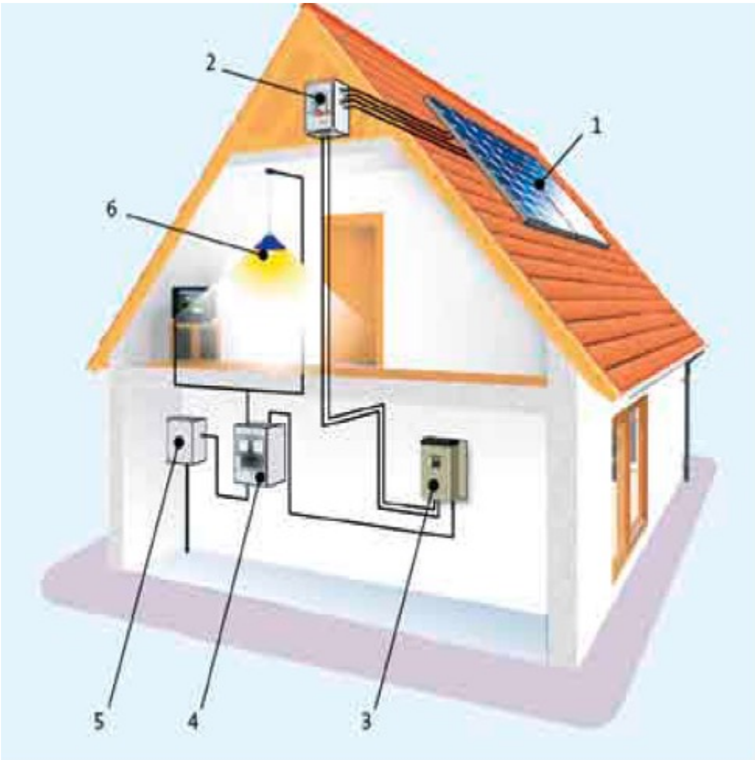
Energy yield: how to get the maximum energy out of a PV system

- Choose product with good warranties and reliability testing, pay attention to the module performance degradation (~ 0.2 to 1%), ideally make it test (for large powerplants)
- Select a place with good irradiation (or accept to loose, e.g. on a façade, it might still be economical or help the energy transition)
- Select a place with a good ventilation !!! (up to 20°-30°C less VS thermal insulation)
- If integrated into a roof of façade, also ensure sufficient ventilation
- Pay attention to the coefficient of temperature of dP_{max} /dT of the modules (typ -0.25 to -0.4% relative per degrees)
- Beware of partial shading (chimneys, threes, buildings) and of possible current mismatch of modules, or of snow coverage
- Soiling of the system has to be controlled (usually no need to clean in Switzerland and losses in the 5% per year compared to “daily cleaning… but not the case everywhere….)

→ All impact the kWh/year produced

Performance ratio (PR) of PV systems

What matters is the energy yield! To compare systems performance, independently from irradiation, one can use the concept of **performance ratio or PR**



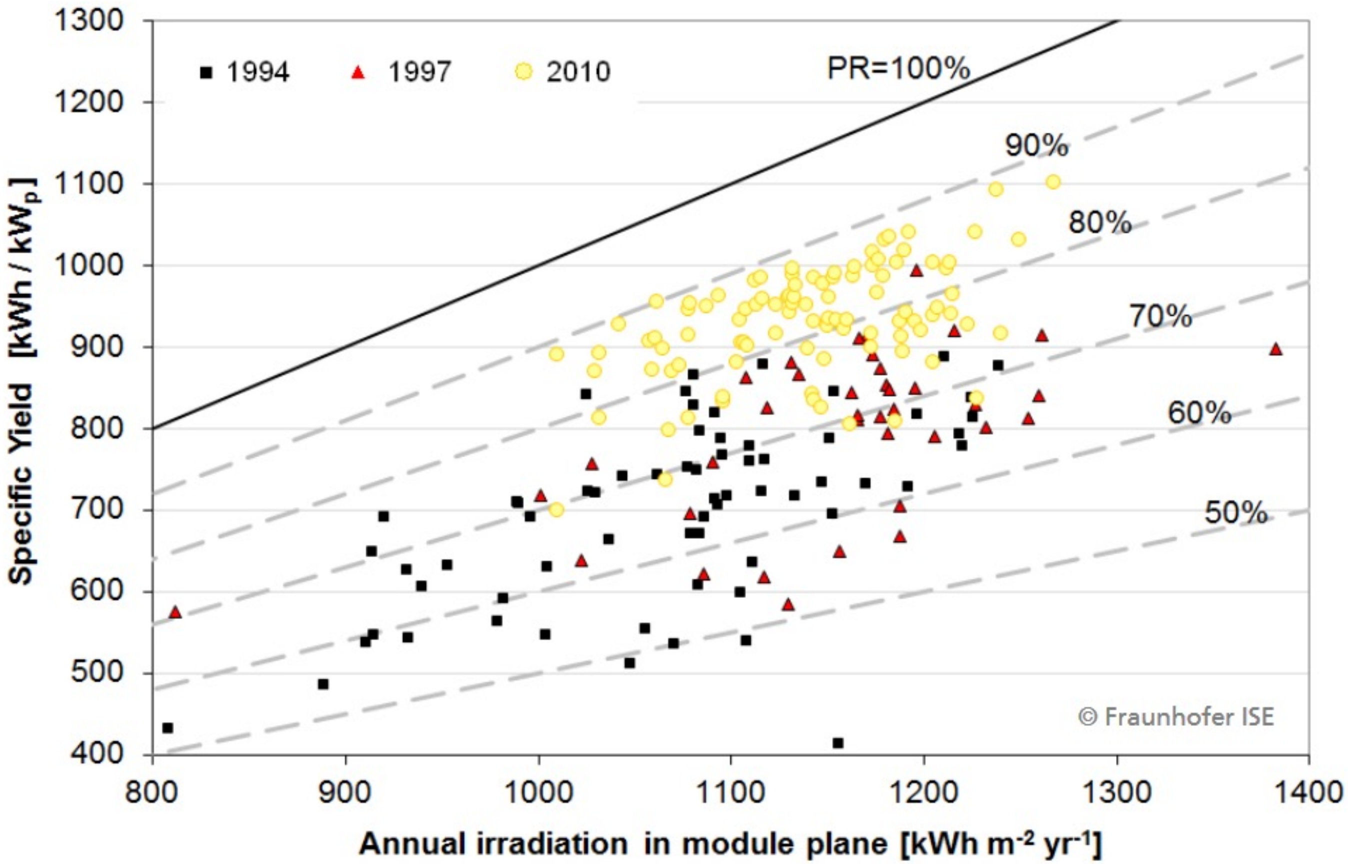
1 PV array
2 PV array combiner / junction box
3 Grid-tied inverter
4 Import / Export meter
5 Connection to the grid
6 Load

The performance ratio **PR[%]** is the annual system efficiency divided by the nominal module efficiency at STC

$$PR = n_{av}/n_{STC} = Yf/Yr \quad (1.11)$$

- n_{av}= average system efficiency (with respect to light impinging on module plane)
- n_{STC}= module STC efficiency
- *Yf*: production yield in [kWh/kWp] (usually measure at the inverter exit
- *Yr*: reference yield production: energy theoretically attainable by kWp measured in [kWh/kWp] at nominal STC conversion efficiency **in module plane**.

Increasing performance ratio over time (German case)



Close to 80-90% already for 2010 systems: it has improved over time thanks to better:

- Inverter efficiency
- System design
- Temperature coefficient

Comparing performance ratio evolution over time allows one to:

- Identify systems problems
- Extract degradation rate of PV modules (but not so easy in practice !)

Prof. Christophe Ballif

EPFL

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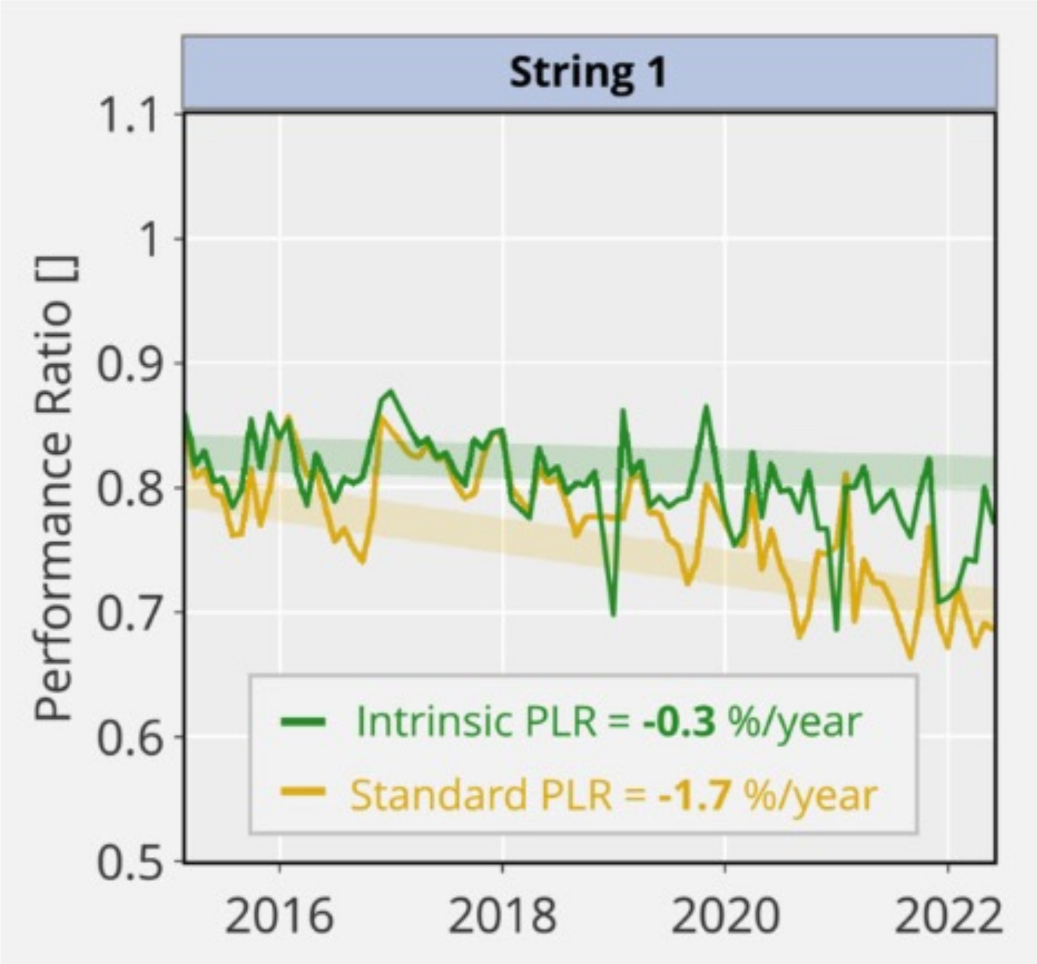
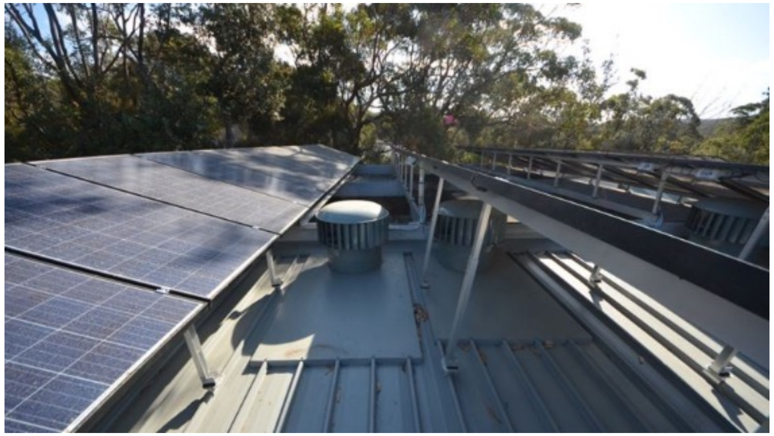
Analyis of performance ratio Not a trivial task !



Various types of filtering allows, e.g. One to differentiate between intrinsic module Performance loss ratio (Intrinsic PLR) and losses induced by external sources such as shading from growing threes (Standard PLR).
At some points shading could also induce



Hugo Quest et al. Intrinsic performance loss rate: Decoupling reversible and irreversible losses (2024 Progress in Photovoltaics)

Prof. Christophe Ballif

EPFL

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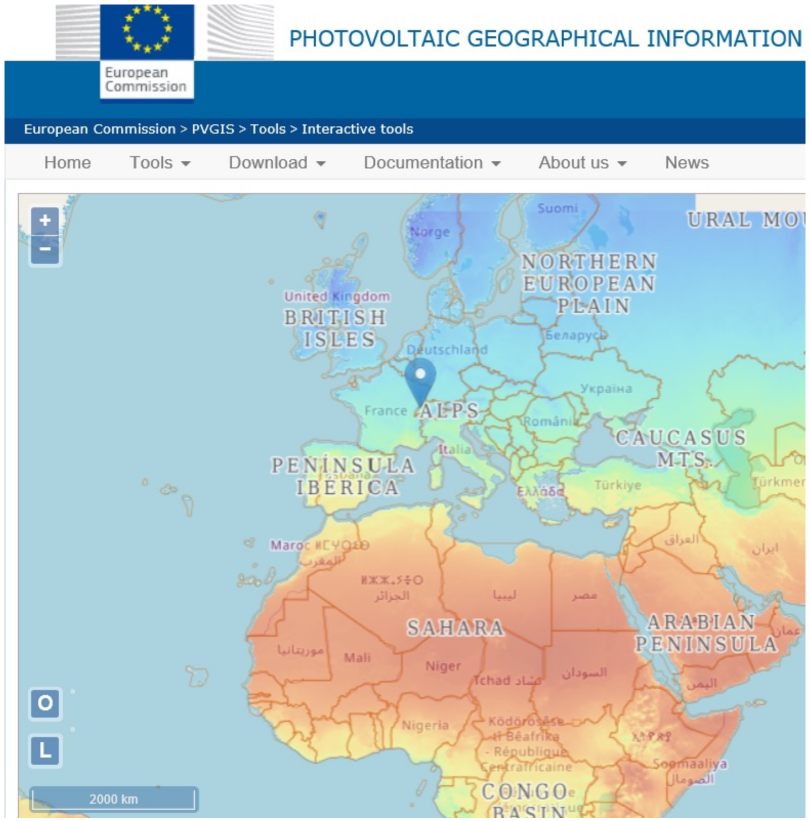
Estimation of Energy yield

Several commercial software exist to estimate energy yield/performance ratio.
A leader in Software is PVSYST (Geneva), which includes module datasheets, SR,….

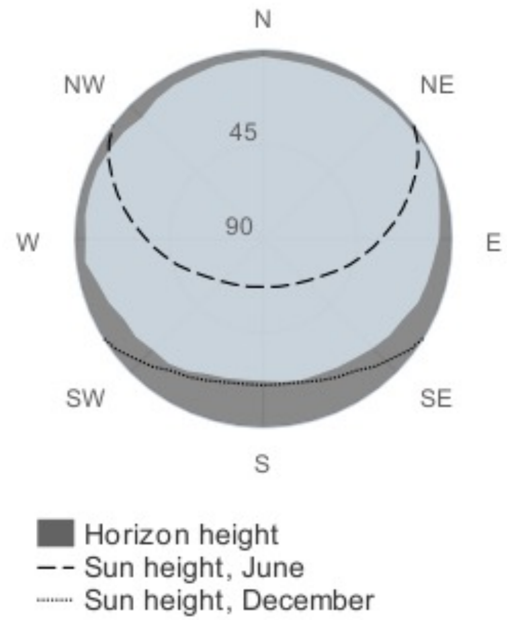


https://re.jrc.ec.europa.eu/pvg_tools/en/

For a quality and free estimation: PVGIS:

Web page for simulation of irradiation and energy yield of PV installation with adjustable parameters:

- locations worldwide; provides horizon profile
- technology (c-Si, CdTe, CIGS)
- mounting and inclination angle
- performance ratio
- tracking



Example: near Madrid

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Fixed slope:
1653 kWh/kW

One-Axis tracking
2223 kWh/kW

Two axis traking
2290 kWh/kW

PERFORMANCE OF GRID-CONNECTED PV: RESULTS

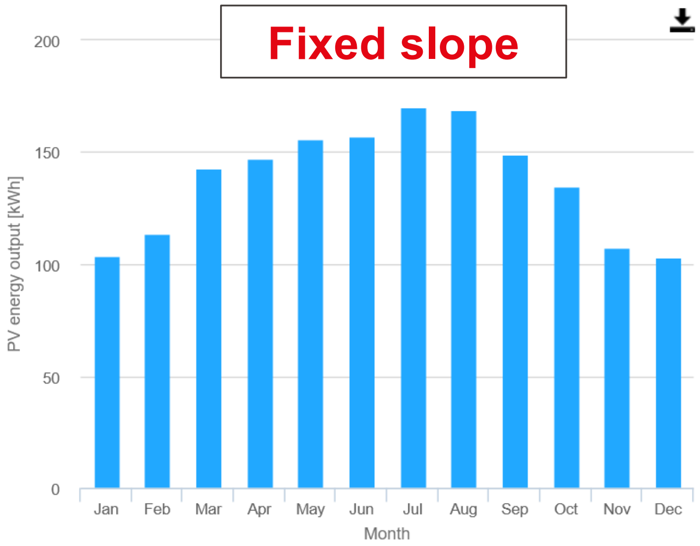
PV output | Radiation | Info | PDF

Summary

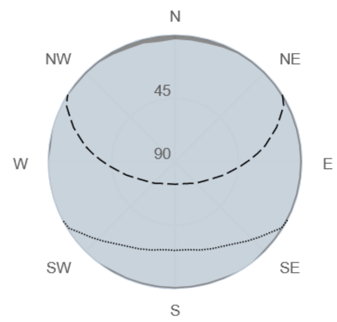
Provided inputs:	
Location [Lat/Lon]:	39.167, -3.669
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	35 (opt)
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	1653.89
Yearly in-plane irradiation [kWh/m²]:	2125.28
Year-to-year variability [kWh]:	60.21
Changes in output due to:	
Angle of incidence [%]:	-2.58
Spectral effects [%]:	0.48
Temperature and low irradiance [%]:	-7.56
Total loss [%]:	-22.18

Monthly energy output from fix-angle PV system



Outline of horizon

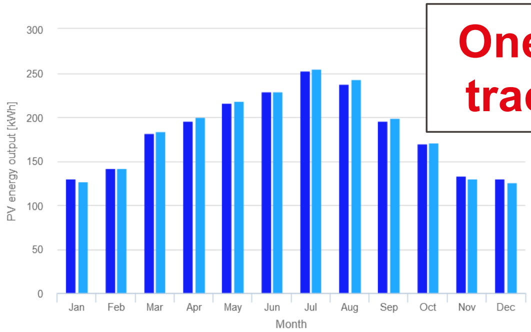


Summary

Provided inputs:		
Location [Lat/Lon]:	39.167, -3.669	
Horizon:	Calculated	
Database used:	PVGIS-SARAH	
PV technology:	Crystalline silicon	
PV installed [kWp]:	1	
System loss [%]:	14	

Simulation outputs	Vertical axis	Inclined axis
Slope angle [°]:	55 (opt)	37 (opt)
Yearly PV energy production [kWh]:	2214.95	2223.51
Yearly in-plane irradiation [kWh/m²]:	2826.33	2838.4
Year-to-year variability [kWh]:	85.6	84.5
Changes in output due to:		
Angle of incidence [%]:	-1.32	-1.32
Spectral effects [%]:	0.44	0.43
Temperature and low irradiance [%]:	-8.05	-8.09
Total loss [%]:	-21.63	-21.66

Monthly energy output from tracking PV system



Tracking mounting options
(Click on series to hide)
● Vertical axis ● Inclined axis

PERFORMANCE OF TRACKING PV: RESULTS

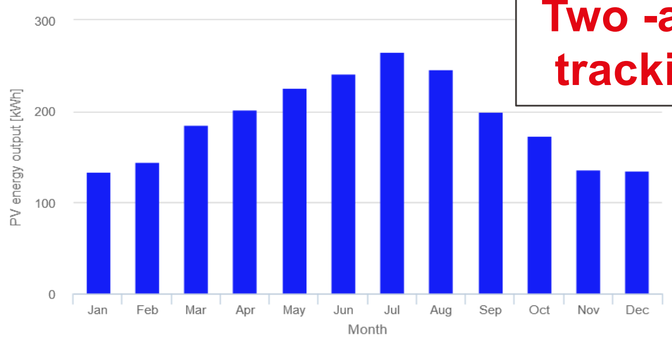
PV output

Summary

Provided inputs:	
Location [Lat/Lon]:	39.167, -3.669
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs	Two axis
Slope angle [°]:	-
Yearly PV energy production [kWh]:	2290.74
Yearly in-plane irradiation [kWh/m²]:	2932.01
Year-to-year variability [kWh]:	88.7
Changes in output due to:	
Angle of incidence [%]:	-1.25
Spectral effects [%]:	0.43
Temperature and low irradiance [%]:	-8.39
Total loss [%]:	-21.87

Monthly energy output from tracking PV system



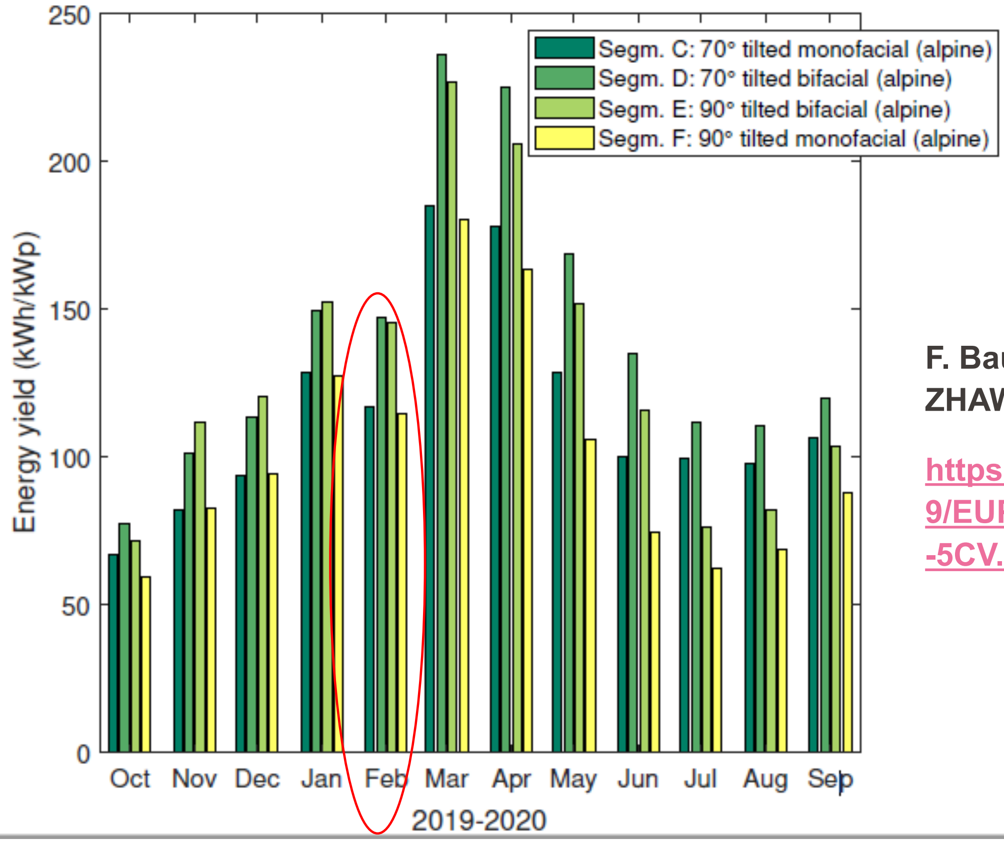
Tracking mounting options
(Click on series to hide)
● Two axis

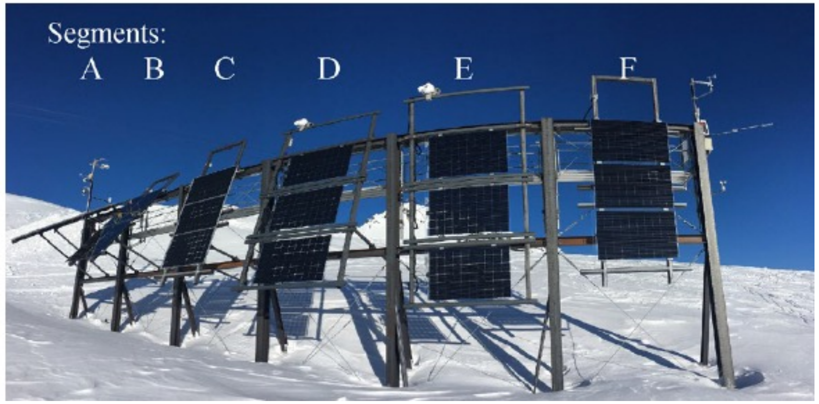
Bifacial PV systems

- Most modern c-Si solar cells can be made **«bifacial»,** with 70% to 93% of the efficiency when illuminating the back compared to the front. A small lost of power (2-3%) occurs at STC (there is no rear reflector behind the solar cell to reflect IR photons)
- But ground reflection (**Albedo**) can add 5 to 30% (typ. 7-15%) annual energy per Watt.
  In the ideal case close to 100% (isolated modules, at maximum height on top of snow or or a perfect white reflector, e.g.white paint)
- Can be combined with 1-axis tracking (+ 20-40% energy)
- Many large parks use these two features to increase the yield and reduce the LCOE
- **PR can be larger than 1**, but is strongly system dependent (height and spacing of modules rows, albedo of the ground,…..)

Surface	Sky Condition	Mean of Albedo
Grass	OV	0.19
	POV	0.19
	CL	0.21
Sand	OV	0.35
	POV	0.37
	CL	0.36
White pebbles	OV	0.55
	POV	0.56
	CL	0.58
Cement slabs	OV	0.13
	POV	0.16
	CL	0.17
White tiles	OV	0.70
	POV	0.70
	CL	0.70
White board paint	OV	0.59
	POV	0.60
	CL	0.65
Aluminium foil	OV	0.73
	POV	0.75
	CL	0.72

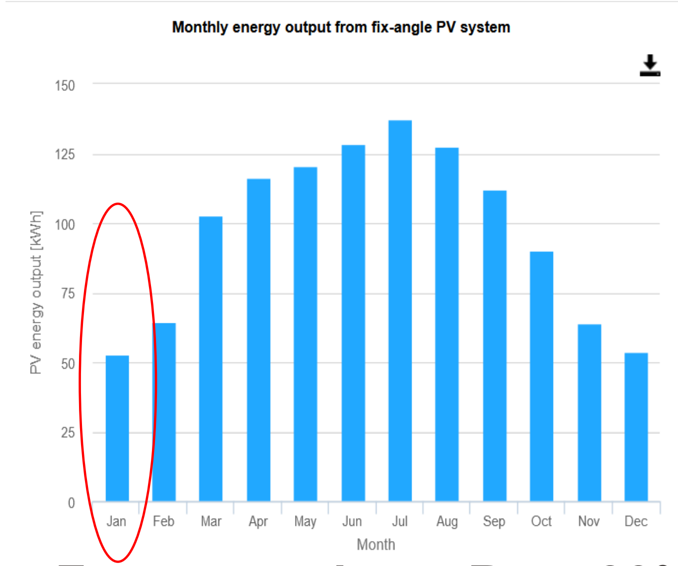
EPFL Alpine with snow reflection





F. Baumgartner et al. ZHAW,

https://doi.org/10.4229/EUPVSEC20212021-5CV.2.6



Alps, 70°-90°. Bifacial up to 150 kWh/kWp in January (1800 kWh/kW annually). A boost for electricity in winter (explains the Alpine park)

For comparison: Bern 30°

50 kWh/kWp in January

Exercise

- Find out difference between horizontal, optimally inclined and façade in Switzerland

Example/impact of orientation at EPFL

optimally inclined system (35°south) yields
→ 1.23 kWh/W
Flat roof it (0°) → 1.03 kWh/W (83%)
South facade (90°) → 0.85 kWh/W (65%)

North roof (35° North) → 622 kWh/W
North façade (90° North)→ 190 kWh/W

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QUIZ

Question 5: a well oriented PV system of 7x7 m^2 with 20% module will provide annually in Switzerland (approximately)?

a) 1100 kWh
b) 22000 kWh
c) 11000 kWh

Question 6: If this system is placed on a south facade, without shading, by how much will the annual energy yield be reduced?

a) by 10% b) by 35% c) by 50%

Question 7: The Performance ratio of a standard Si system will be higher …

a) in Qatar
b) In North Pole
c) In Germany

Question 8: The energy yield of a PV system will be higher …

a) in Qatar
b) in North pole
c) In Germany

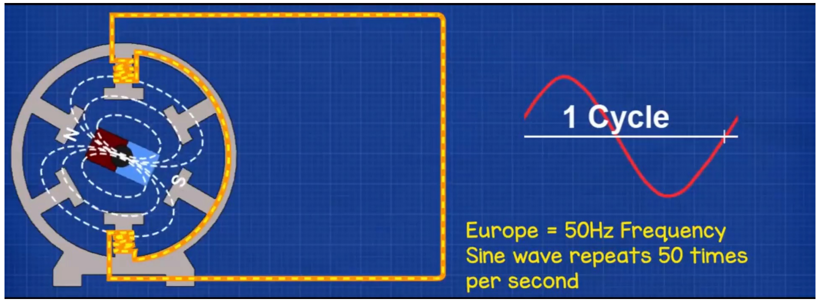
2. Connecting PV modules to the outside world

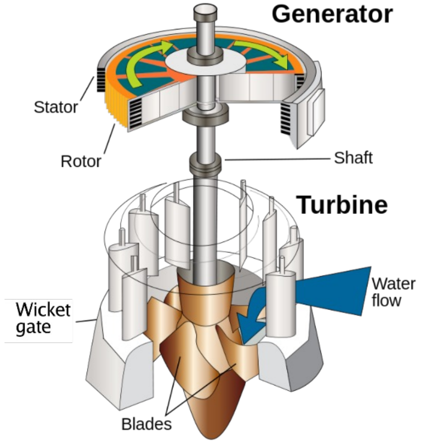
Direct current (DC)

$$V(t) = V_p$$

Alternative current (AC)

$$V(t) = V_p \sin(2\pi f t + \phi)$$

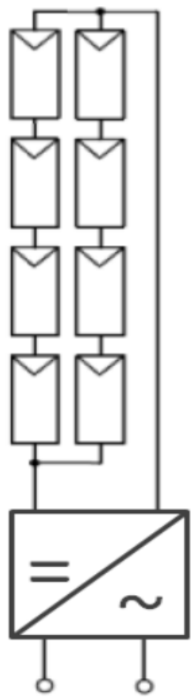




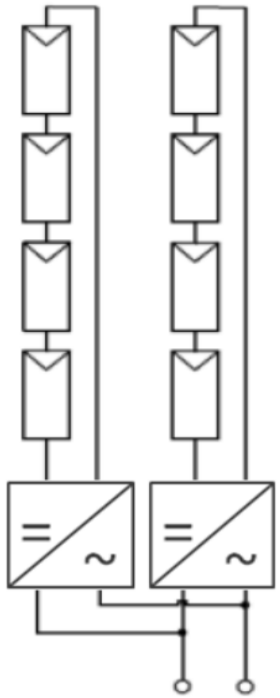
https://www.youtube.com/watch?v=iIqhAX0I7lI

Inverters types

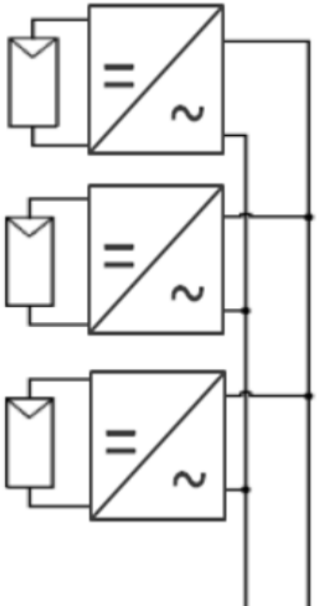
Module level electronics



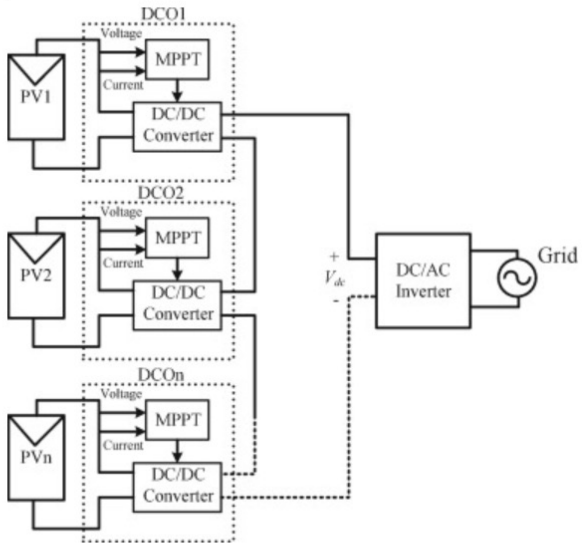
Central inverters Large



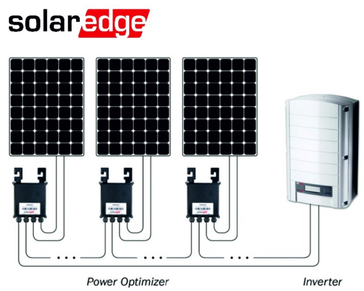
String: distributed
n.b. typically entrance for three strings
on a «home inverter»



Micro-inveters



Power optimiser



Fraunhofer ISE : Photovoltaics Report, 2020

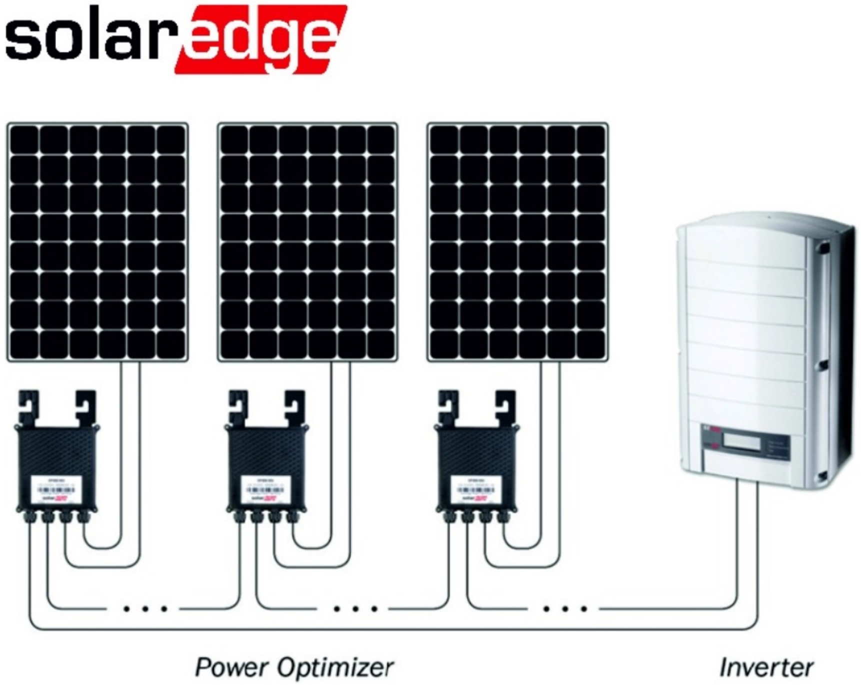
Module level electronics

Controlling MPP at module level

When working with PV systems with frequent shadings of some modules (which could block the current) → use of MPPT at module level.

Approach 1:
Power Optimiser

DC/DC → same current for all modules, string in series again
Then a large DC/AC inverter



HUAWEI Smart PV Optimizer
Only for selected modules in the chain

Approach 2
Micro-inverter
DC/AC(220 V)

Inverters types; from 3-4 cts/Wp to 20-30 cts/Wp

Inverter / Converter	Power	Efficiency	Market Share (Estimated)*	Remarks
String Inverters	up to 150 kWp	up to 98%	61.6%	• 5-15 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	36.7%	• 3-4 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-97%	1.7%	• 10-25 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 99.5%	5.1%	• 3-10€-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed

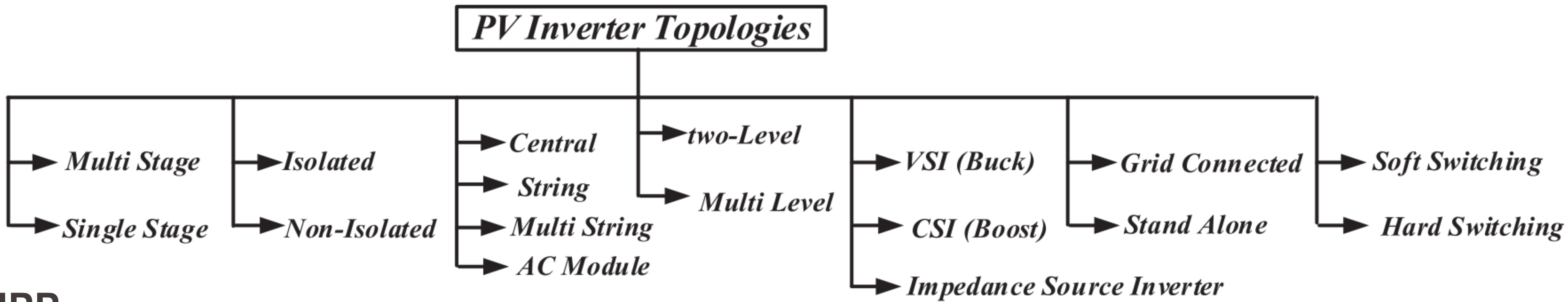
Data: IHS Markit 2021; IRENA 2021. Remarks: Fraunhofer ISE 2021. Date of data: Jun-2021
inverters

Fraunhofer ISE : Photovoltaics Report, 22

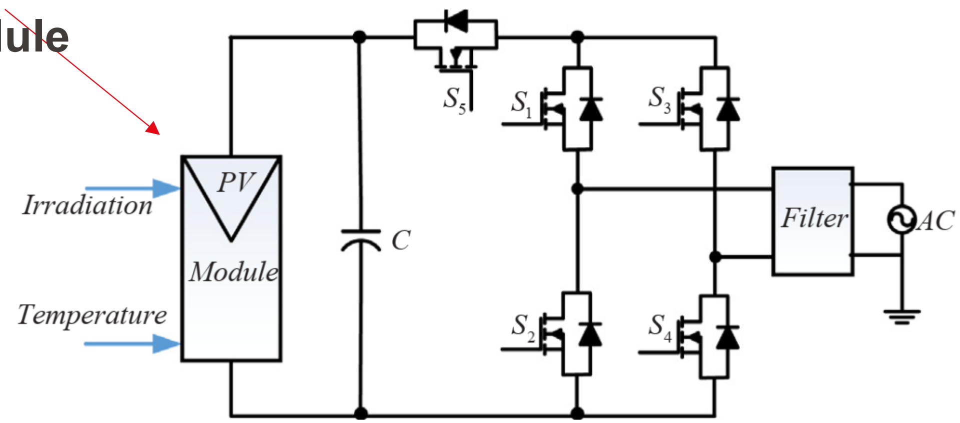
Price estimates in Europe 2025
Market share estimates 2021

Inverter topologies

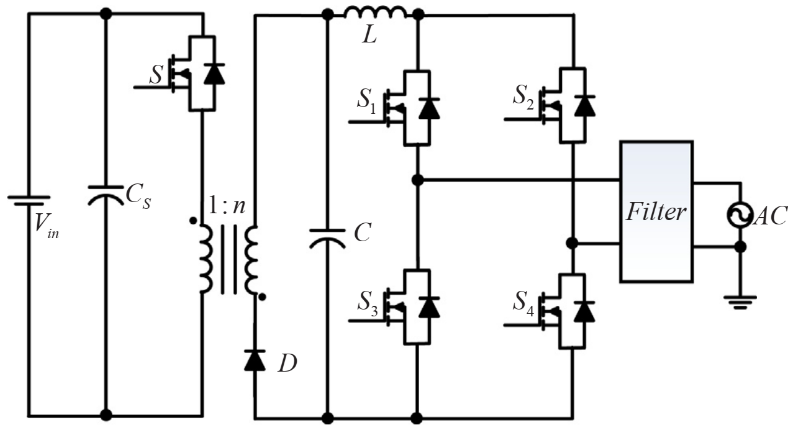
Just for information



Here MPP included in module



H5 topology from SMA, not isolated

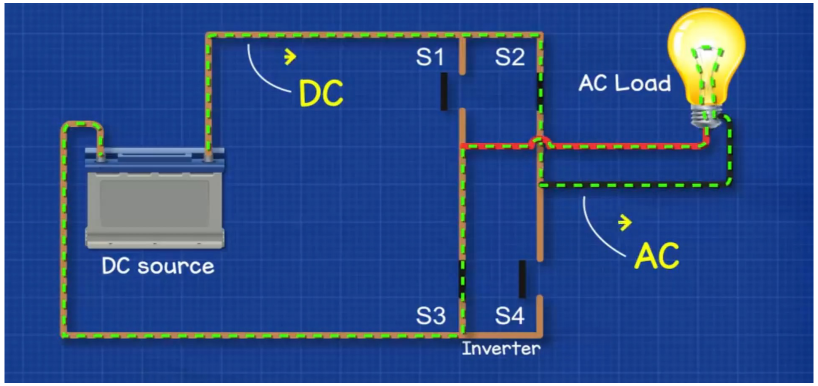


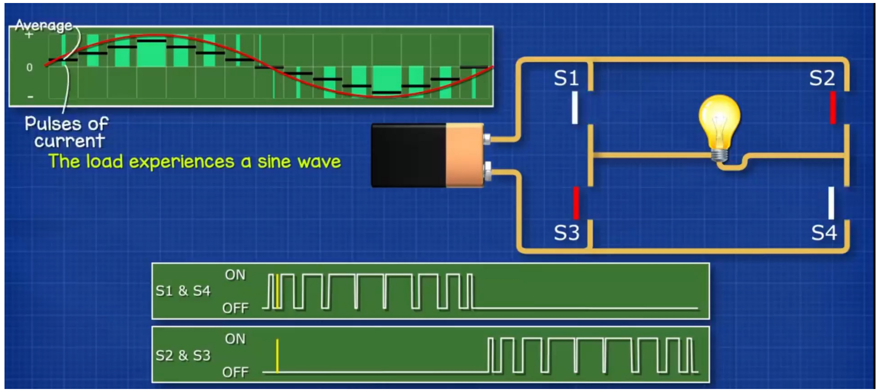
Two-stage isolated buck-boost inverter

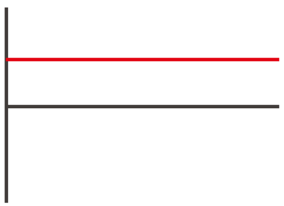
Dogga, Raveendhra, and M. K. Pathak. 2019. "Recent Trends in Solar PV Inverter Topologies." Solar Energy 183 (May): 57–73. https://doi.org/10/gh4w22.

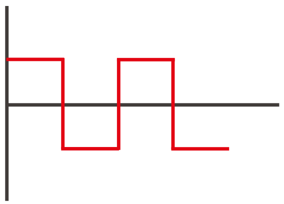
Inverter operating principles

AC can be generated with 4 switches (MOSFET/IGBT)









Constant DC

Square wave

Pulse width modulation (PWM) can be used to transform a square wave into an average sine

Inverter operation principles

Monitor AC grid for voltage, frequency, and phase

Injection <=> produce voltage $V > V_{grid}$

Most efficient (96-99%) at nominal power
(3-phase may switch to 1-phase for low-light conditions)

Inverter types:

Galvanically separated	Not galvanically separated
high level of security (grounding)	often more efficient (high frequency electronics)
contains transformer (bulky)	more complicated circuitry

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Inverters properties

Just for information

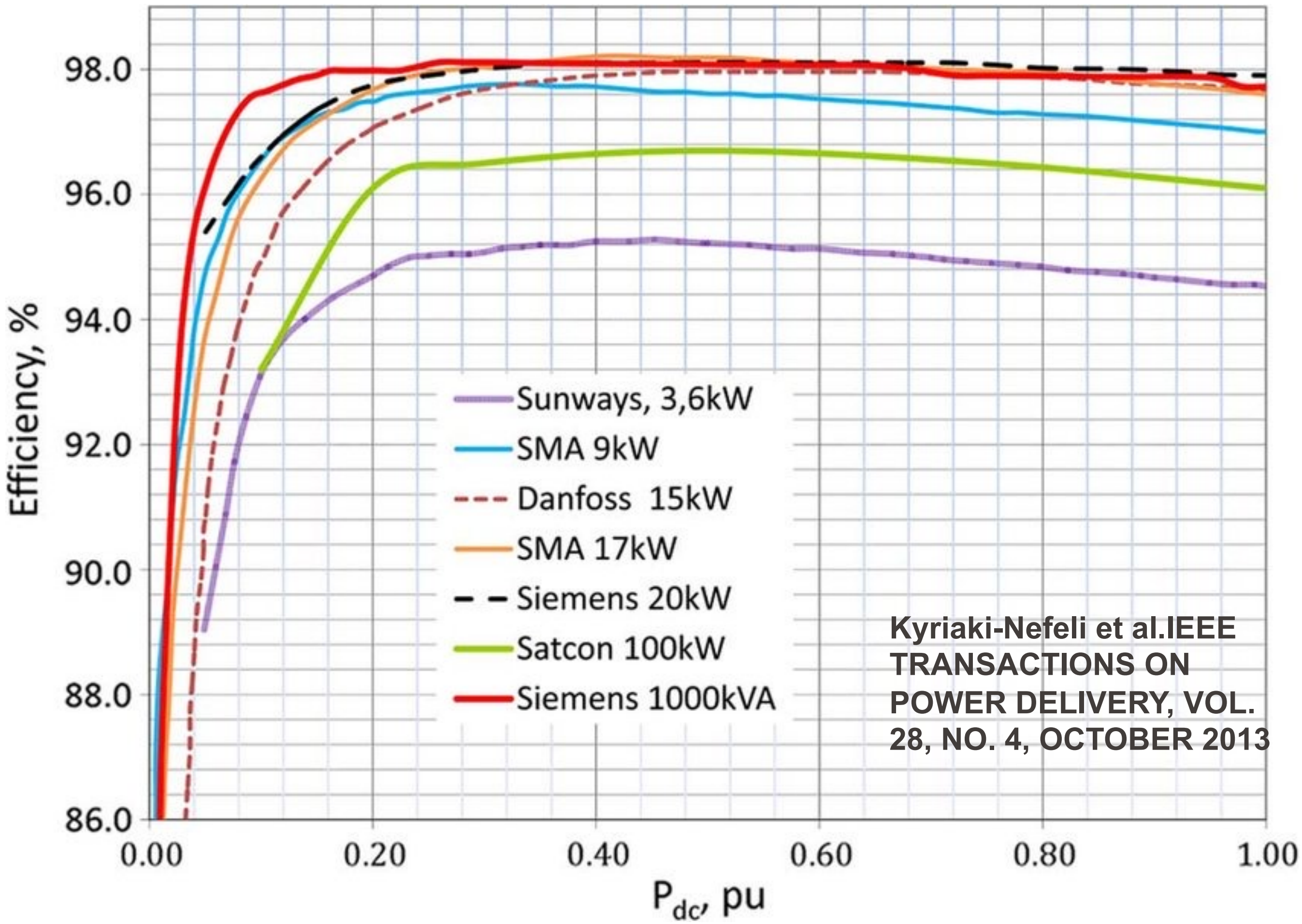
Basic properties

- Input DC voltage **(typ 1000-1500 V)**
- Output waveform
- Total hamonic distortion (THD)
- Frequency
- AC voltage (typ. from 240 V, 1 to 3 phase up to typically 35 KV (medium voltage level)

Advanced features

- Intrisic boost capabilities (voltage boosting)
- Isolation
- High efficiency with higher voltage and SiC components
- Good power decoupling (higher power quality, noise effect from one element on the rest of the circuit is limited)
- Dual grounding function (fewer components with two grounding)
- Compact design
- Grid supporting functions (see later)

Inverters efficiency



Typical generic inverter efficiency curve

$$\eta_{inv} = \frac{P_{AC,output}}{P_{DC,input}}$$

Right «sizing of inverter important».
Sometimes inverter selected with Max power smaller than nominal PV power plant. Some energy is lost but allows more PV installation and smaller grid connection capactiy

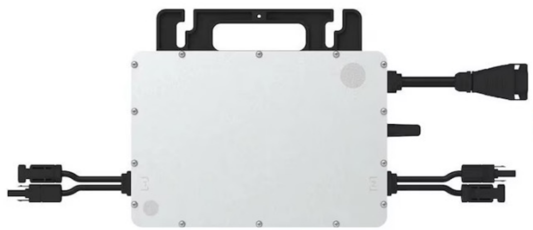
https://www.e-education.psu.edu/eme812/node/738

From small PV systems

System Plug&Play with integrated micro-inverter and a simple 230V plug. The generation should be 100% self-consumed.

MPPT converter for small PV and battery systems

- Power < 500 W
- Cost $ 20 – 200
- 12V or 24V supply



114.–
Hoymiles HMS-800W-2T
Microinverter

Bewertungen
★★★★ 6

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To large scale : 4 MW or more inverters

MEDIUM VOLTAGE POWER STATION
4000-S2-US / 4200-S2-US / 4400-S2-US / 4600-S2-US

SMA

Robust
- Complete station is UL listed for higher safety and lower risk
- Station and all individual components type-tested for maximum reliability
- Optimally suited to extreme ambient conditions

Simple Integration
- Plug and play concept
- Completely pre-assembled for easy set-up and commissioning

Cost-Effective
- Fully integrated transformer and switchgear simplifies logistics
- Minimun O&M requirements create lowest cost of ownership

Flexible
- One product for all markets and applications
- Ideally suited for PV applications, PV plus storage (DC coupled) and storage applications (AC coupled)

MEDIUM VOLTAGE POWER STATION
4000-S2-US / 4200-S2-US / 4400-S2-US / 4600-S2-US
Turnkey solution for PV, storage, and PV plus storage power plants

Larger power plant: > 1 MW
Example SMA «medium voltage power station»
With efficiency of inverter > 98.5% (according to various cycles)

Inverter efficiency

Max. efficiency[3] / European efficiency[3] / CEC weighted efficiency[4]
98.7% / 98.6% / 98.5%

Note: thanks to improvements in power electronics → higher efficiency → decreased heating → more compact, and more reliable inverters → reduced costs !

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Famous companies

- SMA, Fronius in Europe
- Huawei, Sungrow in China

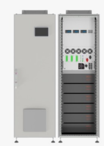
SMA

SMA Sunny Boy | SMA Sunny Tripower | SMA Sunny Boy Storage

- Note: if the grid is down, normal inverter stop working (and modules are in open circuit-voltage)

- You need a special system with batteries and an «islanding mode» to be able to be autonomous

Une infrastructure énergétique intégrale



infra nx3

Solution énergétique tout-en-un plug-and-play
Next3 rack, gestion intelligente de l'énergie
Jusqu'à 30 kWh de stockage d'énergie
Jusqu'à 24 kW d'énergie solaire intégrée avec 2 MPPT
Bypass, infra outdoor, infra battery en option

Studer in Switzerland,
Specialised in « islanding system »

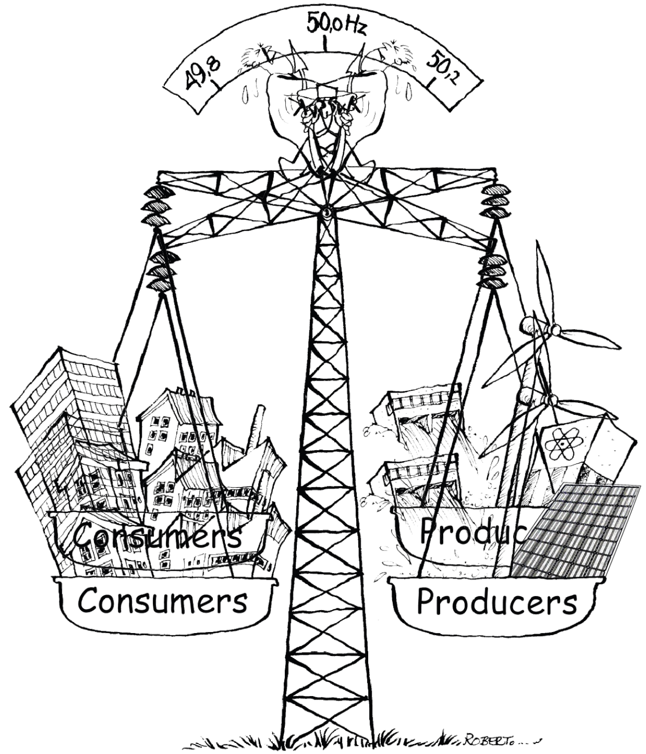
Note:

- Chinese electronics start to be predominant in Europe (low cost, good software)…. But data exchanges, and software upgrade taking place via China ! Possible risk for the grid, if large portion of inverters « fail » at the same time .

Grid integration: Consumption & production balance

Challenges

- Protection system malfunction
- Poor power quality
- Islanding
- Over/under voltage
- Reverse power flow exceeding transformer capacity
- Inertia (no rotating mass)*



* Cf for an introduction: Inertia and the Power Grid: A Guide Without the Spin

Grid connection: additional inverter functions

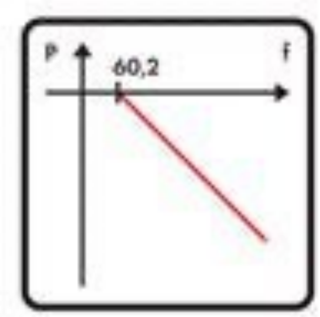
Inverter control approaches

1. Centralized control by the DSO (either on-off or multi-level curtailement, i.e. production reduction)
2. Local control, based on local monitoring (curtail, phase)
3. Distributed optimal control with communication between all agents (others inverters, substation transformer, ..)

Grid connection: additional inverter functions

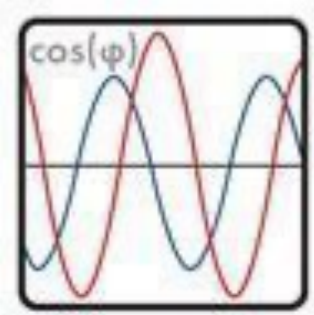
Curtailing: limit injected power P to avoid overload

- required by some grid operators, usually if $P_{PV} > 10\ \mathrm{kW_p}$
- Can be costly if applied often (e.g. peak shaving at noon)
- useful to compensate frequency peaks (grid stabilisation)
- Can be controlled by grid system operator



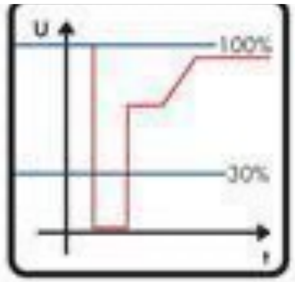
Provide reactive power Q: modify the injected phase angle

- recommended/tolerated up to $\cos\phi = +0.9$ (inductive)
- This allows to keep local grid voltage within limit
- new: provide Q also during the night (grid stabilisation)
- Can be controlled at distance…



Low voltage ride-through

- normally: immediate disconnect when $V_{grid} = V_{norm} - 10\%$
- new: inverter stays connected through short voltage dips



for more information: SMA knowledgebase

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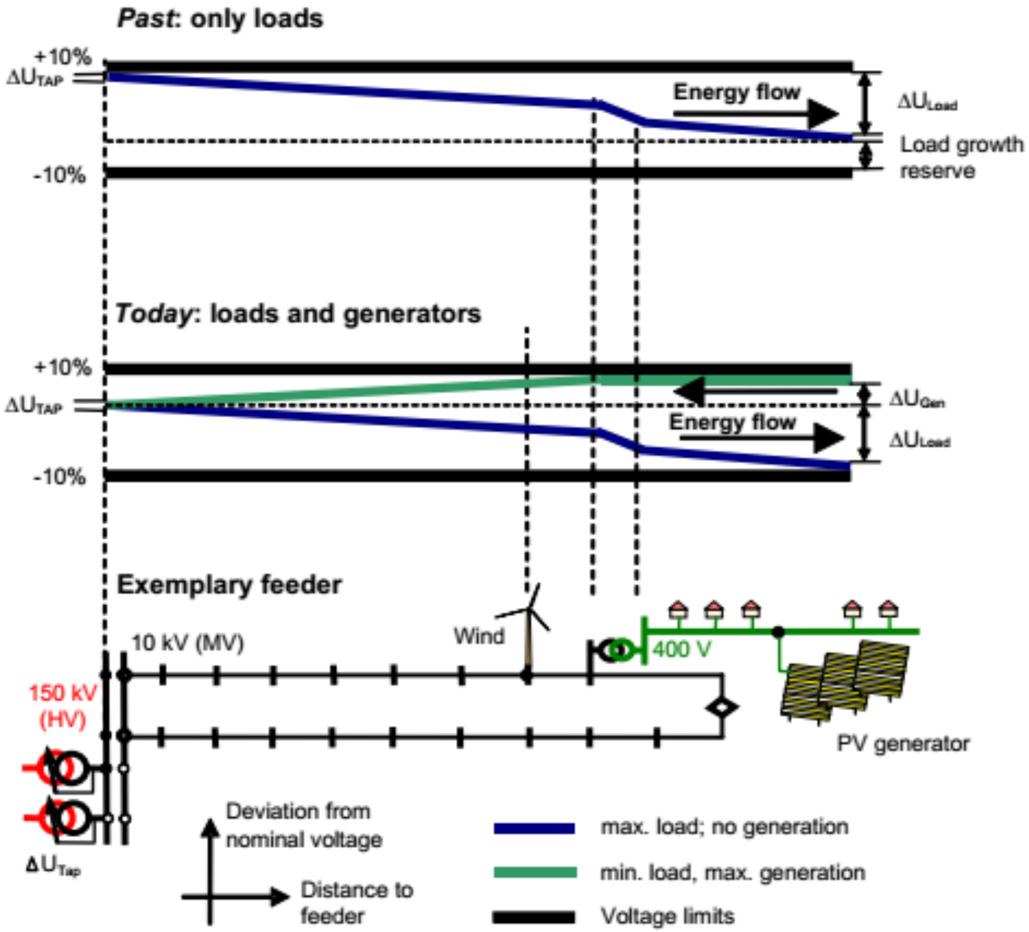
Grid connection: potential issues



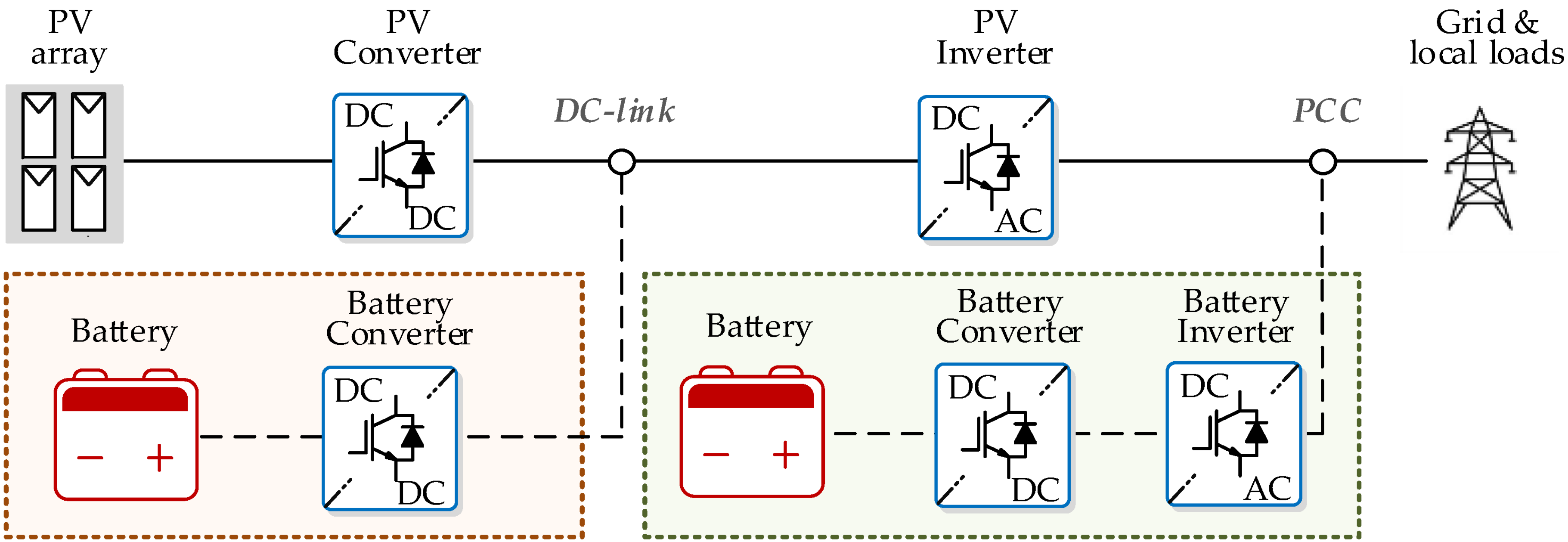
Typically allowed tolerance:
$V_{grid} = V_{norm} \pm 10\%$

In large grids: voltage drop between node and client

Tolerance limit is easily surpassed for bi-directional transport

Bletterie, EU-PVSEC (2010)

PV systems with batteries



Battery connection in **DC coupled configuration**

Battery connection in **AC coupled configuration**

DC coupled :
- Higher efficiency
- Only one inverter
- More compact

AC coupled :
- Battery can be added later

PV systems with batteries

a) DC coupled configuration ?
b) AC coupled configuration ?
c) I don't know..

Current Tesla Powerwall 2 price : ~$500/kWh

Typical residential system
4-15 kWh
- < 10 years warranty

Systems with Islanding capabilities
(can work in case of grid failure)
See e.g. swiss company Studer-Innotec

STUDER

"Join the solar autarky"

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IEM NEUCHATEL

Summary

- Grid with strong (and even 100%) penetration of renewables can be operated.
- Modern PV inverters can support grid functions, can be controlled by various agents.
- Coupled with batteries can even provide inertia and various kind of electricity reserve (primary, secondary, tertiary)
- As for the panels, large improvement in efficiency, costs and reliability of inverters (down to 3 cts-4 cts/W for large string or central inverters)
- Can also be operated as micro-grid systems (usually with storage), with power electronics of the largest unit dictating frequency and phase. It can be for small microgrid (master and slave concepts, see e.g Powerblox CH (power-blox.com)) or large grid with large storage system

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3. Major applications of PV

- Emerging country
- Residential and commercial, sometimes with **integrated PV (BIPV)**
- Power plants
- Stand-alone PV (not grid connected or microgrid), IOT,….

- **Floating PV**
- **Agri PV**
- **Carports**
- **Special space usage**
- **Vehicle integrated PV**
- …..
- …..

What was the 4th largest country installing in p

'The Solar Blitz': How crisis-ridden Pakistan is leading the world on the 'Solar March'

Karl-Heinz Remmers examines Pakistan's startling growth in solar energy use, which could serve as an inspiration not only for developing countries but also for Germany and the EU.

MARCH 4, 2025 PV MAGAZINE

['The Solar Blitz': How crisis-ridden Pakistan is leading the world on the 'Solar March' – pv magazine International]

In 2024, Pakistan will have installed as much new photovoltaic capacity as rich Germany? **Over 16 GW?**

"Anyone can get involved — the technology forgives many mistakes and is largely "plug and play". The Pakistanis are also used to bridging their grid problems with diesel generators or batteries of all kinds, and now both solar modules and batteries are cheaper than ever and available in large quantities. Thanks to the good relations with China, there are no tariffs standing in the way of taking advantage of the low prices in Pakistan."

Le panneau solaire, symbole d'un Proche-Orient en ruine

À Gaza, au Liban, en Syrie, le panneau solaire photovoltaïque est devenu omniprésent dans les paysages d'immeubles en ruines, de routes en terre défoncées, de tentes et de centres d'accueil où se pressent des réfugiés épuisés et privés de tout. Il est le symbole de la précarité de vies et d'infrastructures soumises aux caprices de la météo et à la violence.

ENVIRONNEMENT > **ÉRIC VERDEIL** > 22 JANVIER 2025

[Le panneau solaire, symbole d'un Proche-Orient en ruine - Éric Verdeil]

[(4) Le solaire à la conquête du monde | Géopolitis – YouTube]() 2025 . Don't miss it !

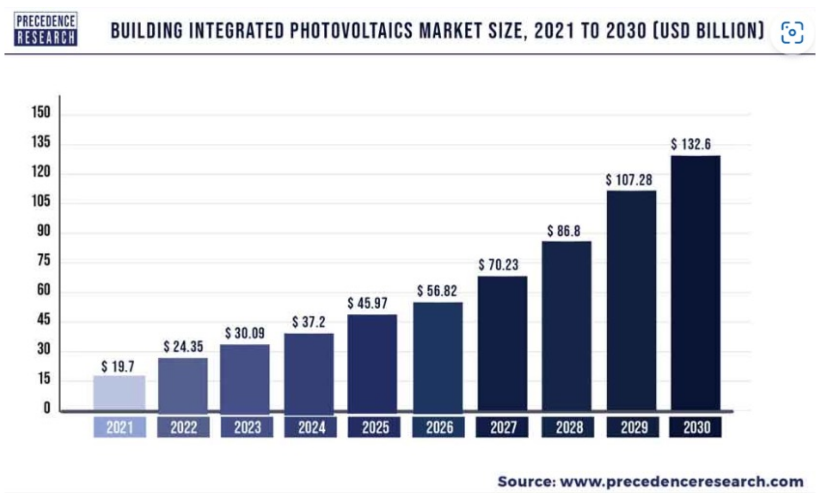
Building integrated PV (BIPV)

A BIPV module is a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV product is dismounted, it would have to be replaced by an appropriate construction product.

A BIPV system is a photovoltaic system in which the PV modules satisfy the definition above for BIPV products. It includes the electrical components needed to connect the PV modules to external AC or DC circuits and the mechanical mounting systems needed to integrate the BIPV products into the building.

Market growing from ~ 20 billions To 100 billions dollars by 2030

International Energy Agency
Photovoltaic Power Systems Programme

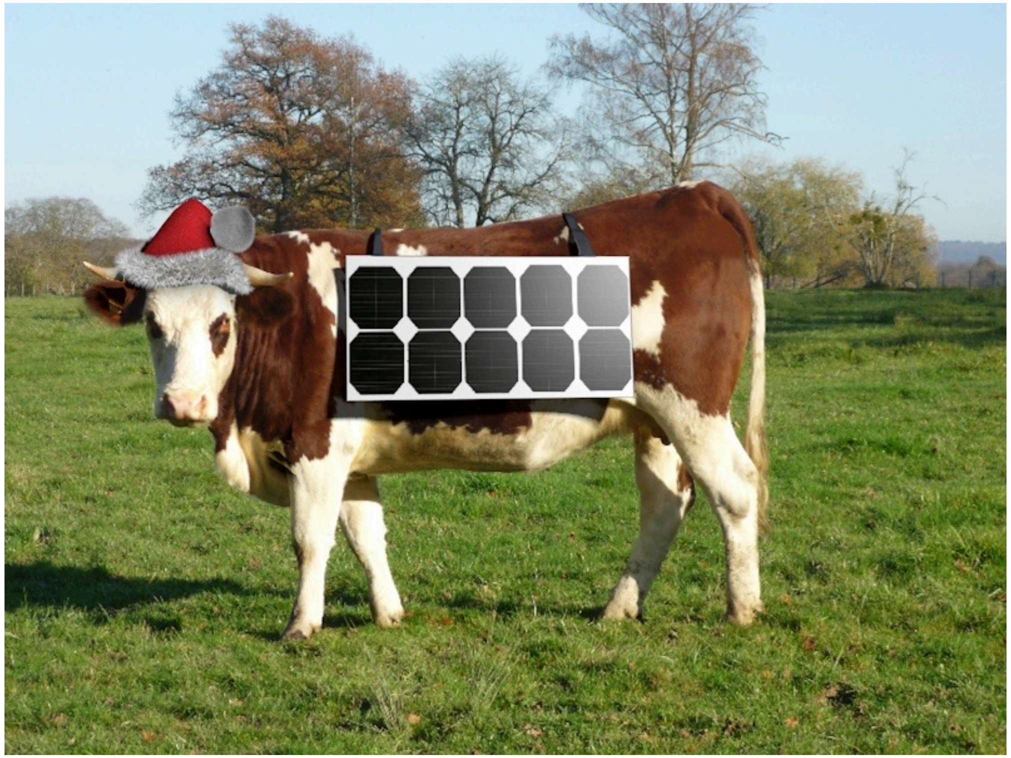


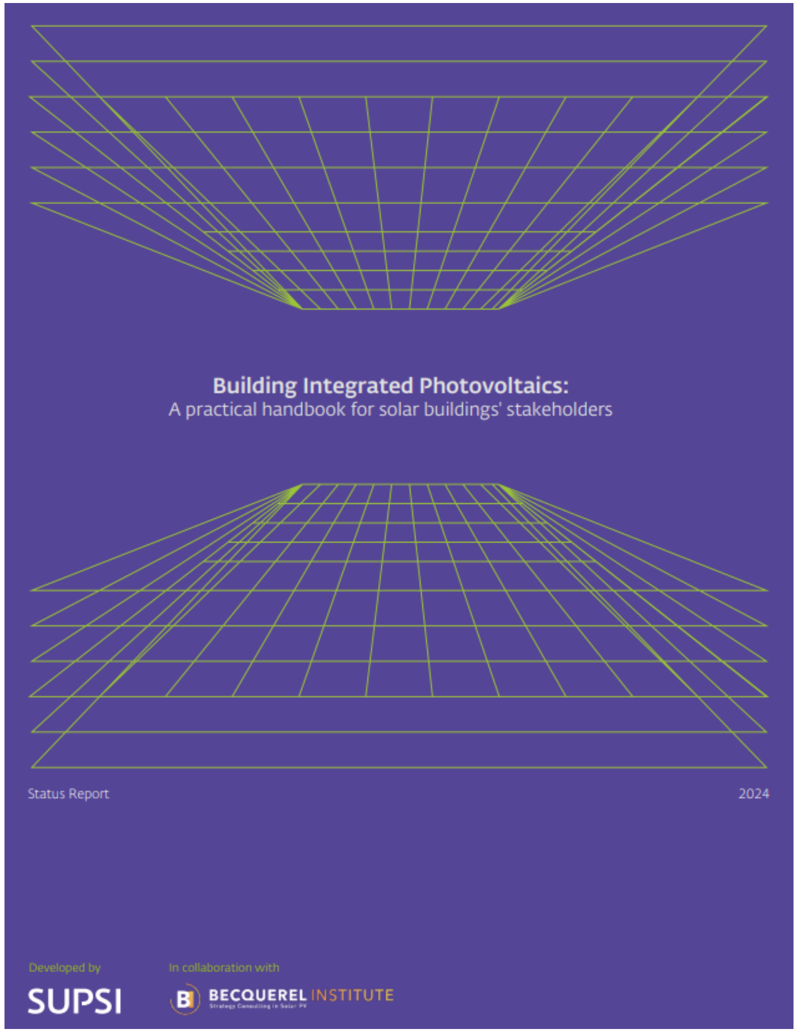
Conventional BIPV roofs

Integration of quasi-standard (or standard) modules

Switzerland, sensitive to acceptance in Rural and Urban Environment

Sensitive to aesthetics





2024_report_BIPV_web-1.pdf

A lively European ecosystem with BIPV product manufacturing and ~50 companies active,

Including equipment builders, components suppliers

University of Applied Sciences and Arts of Southern Switzerland
SUPSI
BECQUEREL INSTITUTE

3S, Freesuns, Solaxess, Megasol, Climacy Schweizer, Sunstyle, Eternit, Glass Troesch, Gasser/Panotron, …
+ all installers for «standard BIPV»

- **Neuchâtel, maison des associations, Swiss Solar Award 2015 «renovation category»**
- **Over 20’000 “megaslates roofs” from 3S” installed**

Prix solaire

Suisse 2015

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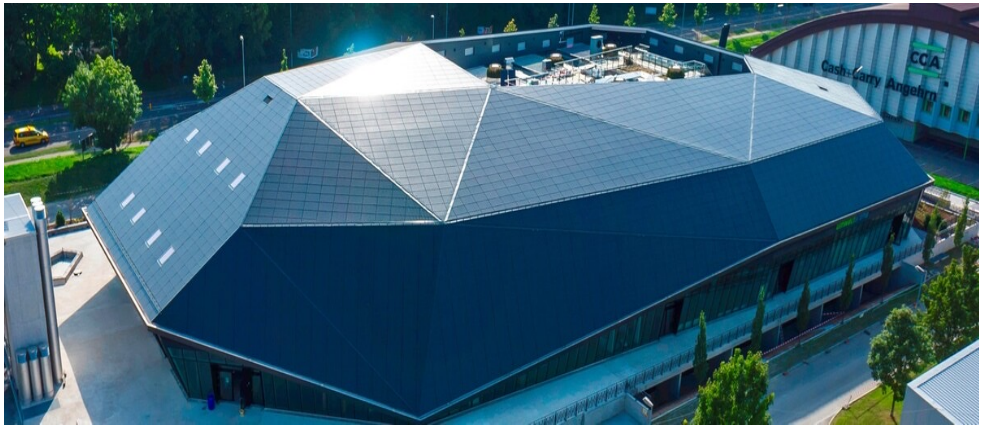


Spreitenbach Arena

3S Solar Plus

Transformative technologies: keep silicon cells but change the look ... acceleration in the last decade !

Elegance and architecture
Transforming building and cities

CSEM as pioneer of transformative technologies for PV panes

Based on low cost c-Si modules, ….

White PV panels,
together with Solaxess

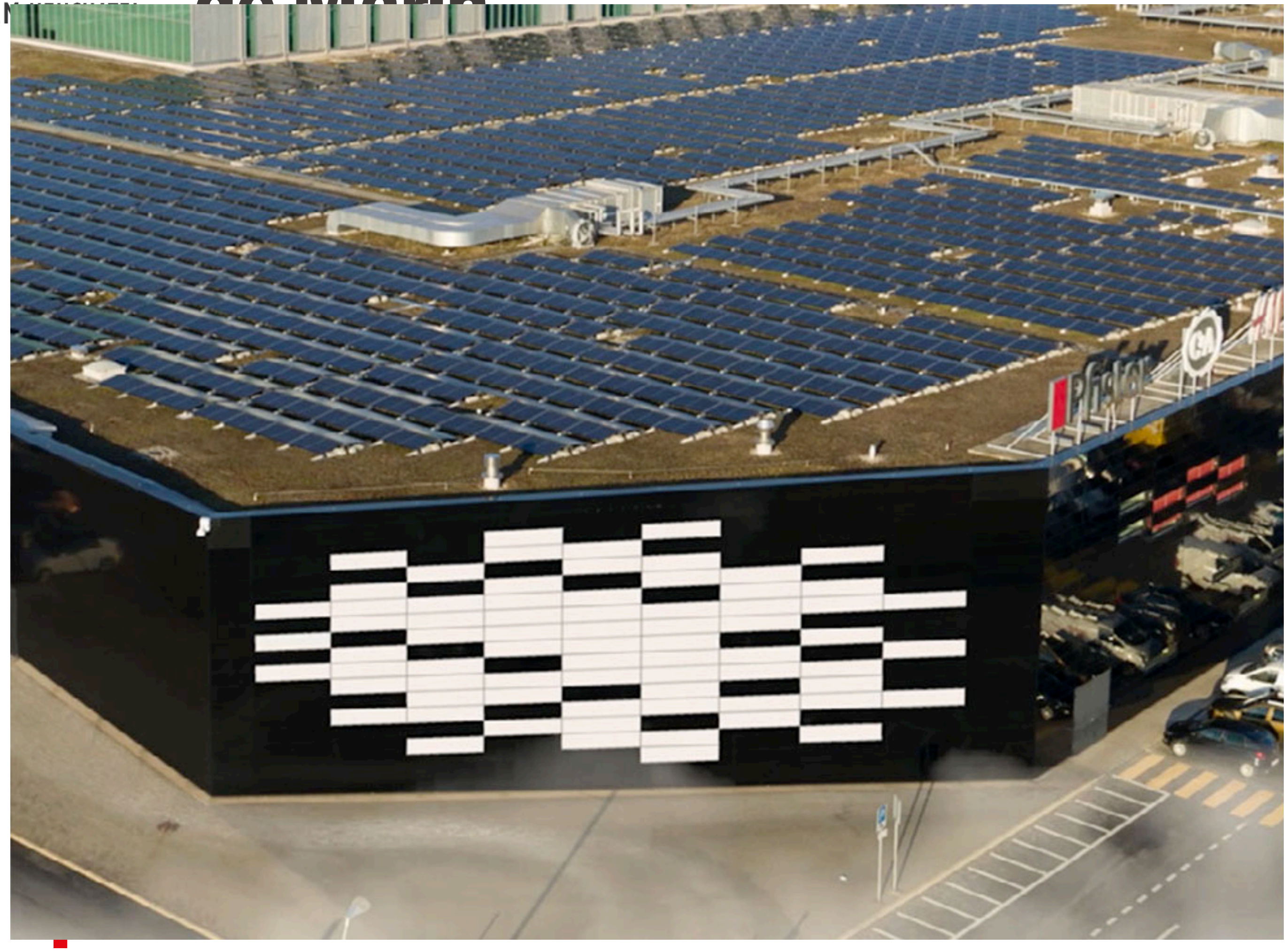

SOLAXESS
WHITE & COLOR SOLAR TECHNOLOGY

SOLAXESS
white solar technology

EPFL

PV-lab

Façade active, Migros de Marin



SOLAXESS

EPFL | csem

BE SMART

La chaux-de-Fonds

SOLAXESS
WHITE & COLOR SOLAR TECHNOLOGY

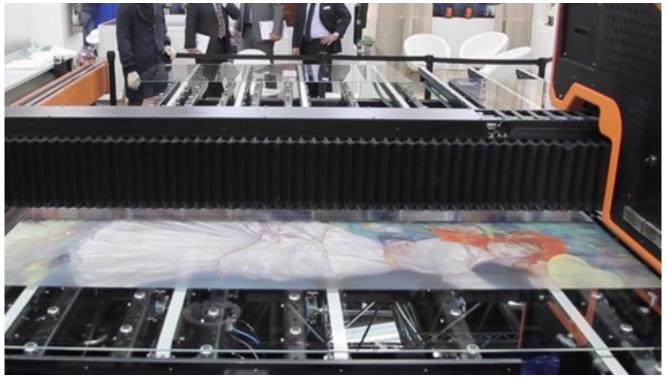
Transformative technologies: keep silicon cells but change the look … acceleration in the last decade !

Digital Ceramic printing (DCP)

Printing on glass

Tempering

shipping



Versatility

Interferential coatings

Multi-layer coating on glass

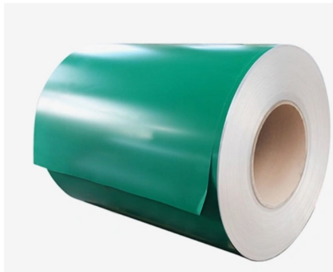
Tempering

Shipping

Efficiency for dark tones

Colored foils

Direct integration at module level



simplicity

Other technologies: low temperature glass printing, photonic structures ,….

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Elegance and architecture

Transforming building and cities, renovating houses

Prix solaire

Suisse 2018

Digital ceramic printing

Ecuvillens
- 27 kWp
- With ISSOL, Solstis, Userhuus, SFOE
- Soutien des Service de l’énergie et des biens culturels de Fribourg

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

csem

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Colored foils

SOLAXESS
white solar technology

3S Solar Plus

csem

EPFL

SOLAXESS
white solar technology

3S Solar Plus

csem

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PV-lab
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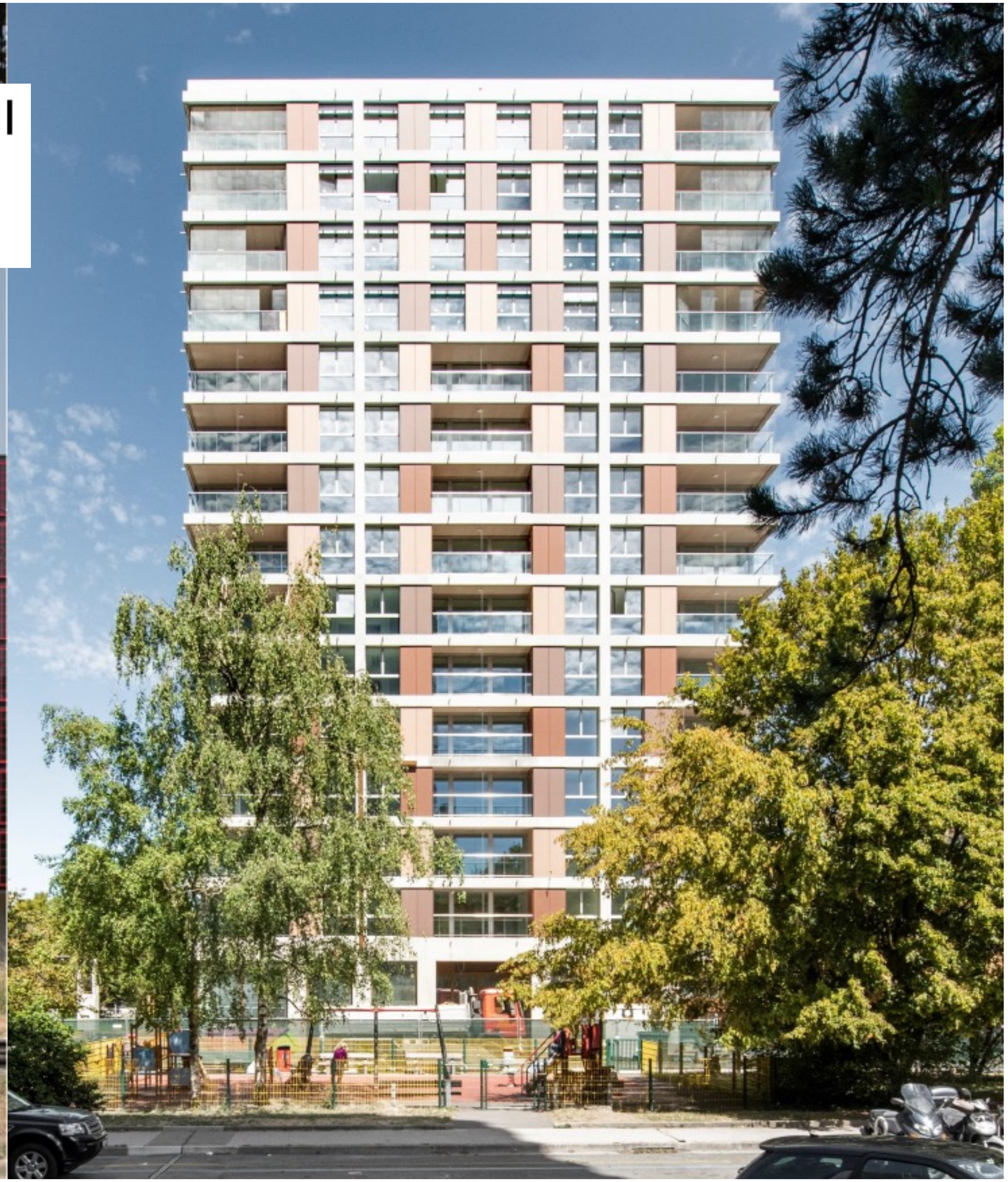
SOLAXESS
white solar technology



Solarwall
Architectural integrated photovoltaics

A Villars-Ste-Croix

Kromatix / Swiss Inso (interference filters, glass structuration)


climacy
New high performance cost-affordable solutions for Roof or indsutrail building
A new company in Bussiny
(see talk this afternoon)
30


Solar tiles
FREESUNS
SOLAR ENERGY


FREESUNS
SOLAR ENERGY


FREESUNS
SOLAR ENERGY
csem


FREESUNS
SOLAR ENERGY
csem

Private house
Neuchâtel

Courtesy L.E.
Perret-Aebi

compáz | csem

Private garden
Neuchâtel

Courtesy L.E.
Perret-Aebi

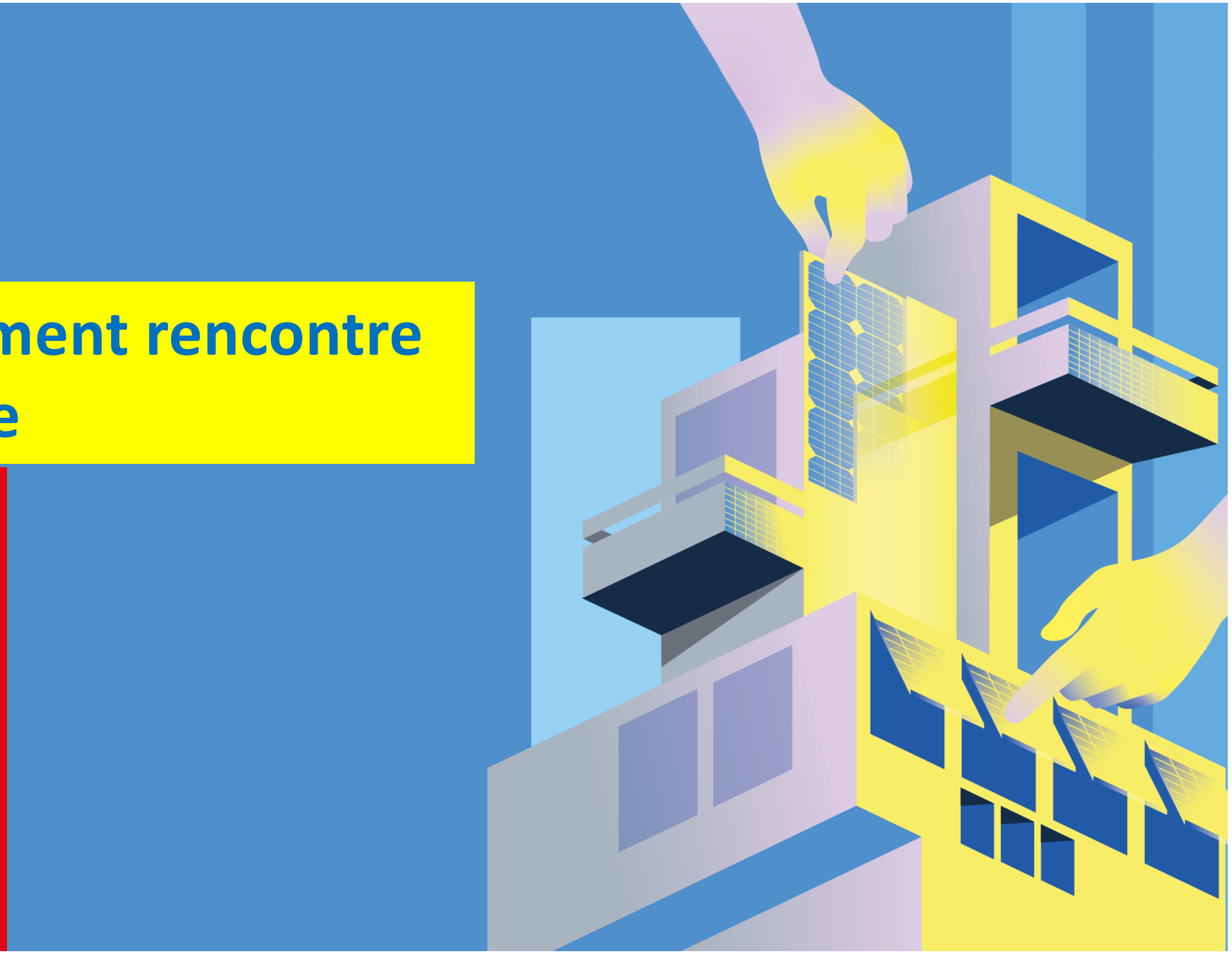
EPFL

formation continue Unil EPFL

Starting 2025

L'élégance du bâtiment rencontre la puissance solaire

CAS Photovoltaïque intégré aux bâtiments (BIPV)



Ce CAS bénéficie du soutien
de diverses organisations, incluant:

suisseénergie

canton de vaud

Scannez pour en savoir plus

CAS Photovoltaïque intégré aux bâtiments (BIPV)

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IEM NEUCHATEL

BIPV

- An infinite number of possibilities.
- Either for standard roofs or façades (ventilated facades),
- or for «Prestige architecture».

Challenge can be the pricing
And the necessity to involve all stakeholders from the beginning of the project !

For a first introduction: check
Christophe, Laure-Emmanuelle Perret-Aebi, Sophie Lufkin et Emmanuel Rey, "Integrated thinking for photovoltaics in buildings", Nature Energy, 8 June 2018

And **Home (bipv.ch)**

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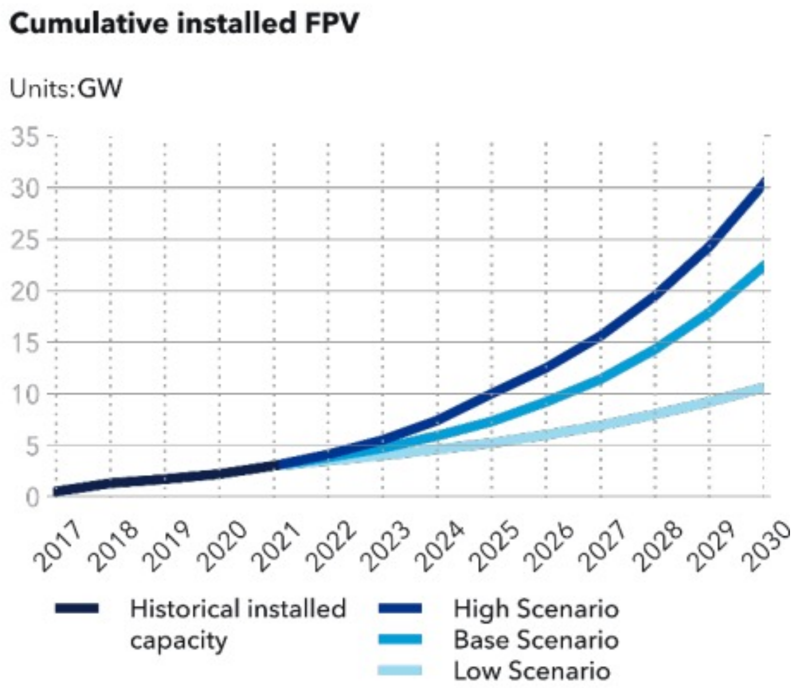
Floating PV



Floating solar to reach 77GW by 2033, led by APAC region - PV Tech ?
1.7 GW in 2024
6 in 2025

Use ponds, water reservoir, or even protected sea/lake areass.
Currently at around 1-1.2$/W capex
Can add benefit of lower water evaporation rate (as high as seveal meters per year)

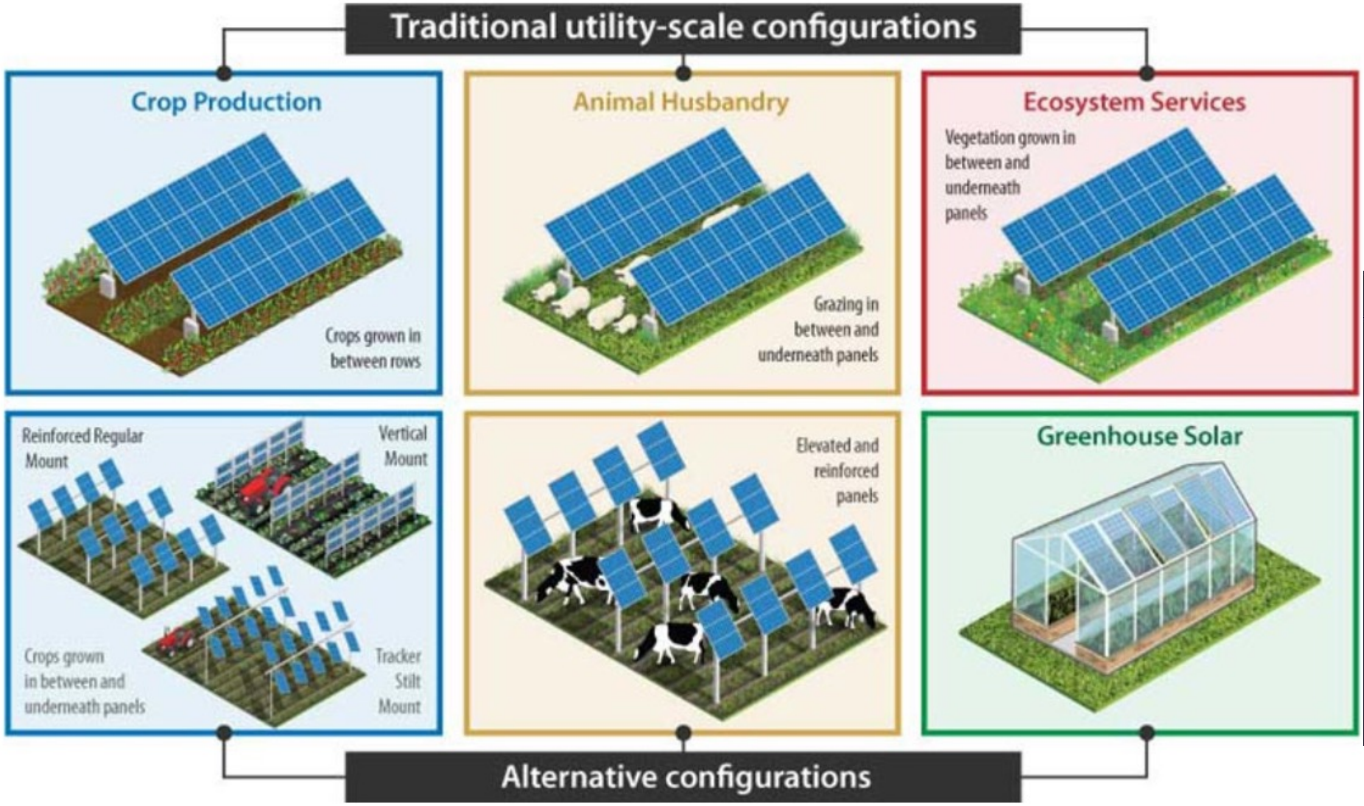
The future of floating solar DNV

Prof. Christophe Ballif

25 MW in Netherlands

92 MW in India
NTPC- Kayamkulam

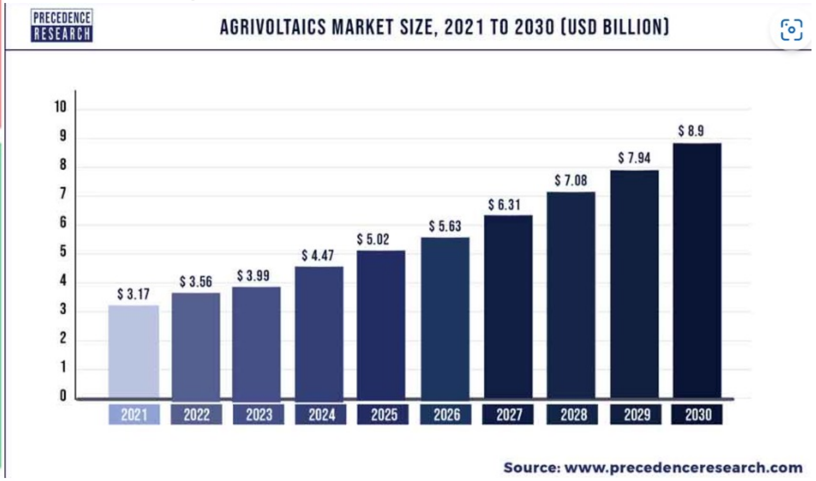
Agri PV: Combine PV and agriculture



Source NREL

Protect from excess heat/Sunry
Keep a good agricultural yield
More stable conditions

Immense potential (many TW)
Many demos,
But strongly site/culture dependant
Growing market (> 10 G$ in 2030?)



Agri PV

Bayware system in Netherlands
(band of c-Si cells)

Bifacial solar modules fence for livestock enclosure Source: Next2Sun

Exemples Agri PV

Sun'Agri agrivoltaism on vines Tresserre
Figure 11: Sun'Agri's viticulture agrivoltaics system

Figure 20: Axial AgriTracker
Source: Axial Structural Solutions[83]

greenhouses

Voltiris (EPFL start-up)

insolight **Another EPFL start-up !**

Product | Projects | Company | Newsroom | Contact

... a dynamic agrivoltaic solution for protecting crops and generating renewable energy

... using an optical layer for adjustable shading

Solar carports

16 MW Corbas solar carport installed by Neoen, in France

Private and commercial solar carports (~1.0/2.5€/W) with shading function
Growing market (500 to 800 millions $ in 2024)

Special solutions

For rough space or above sewage station

Powering ski ressort

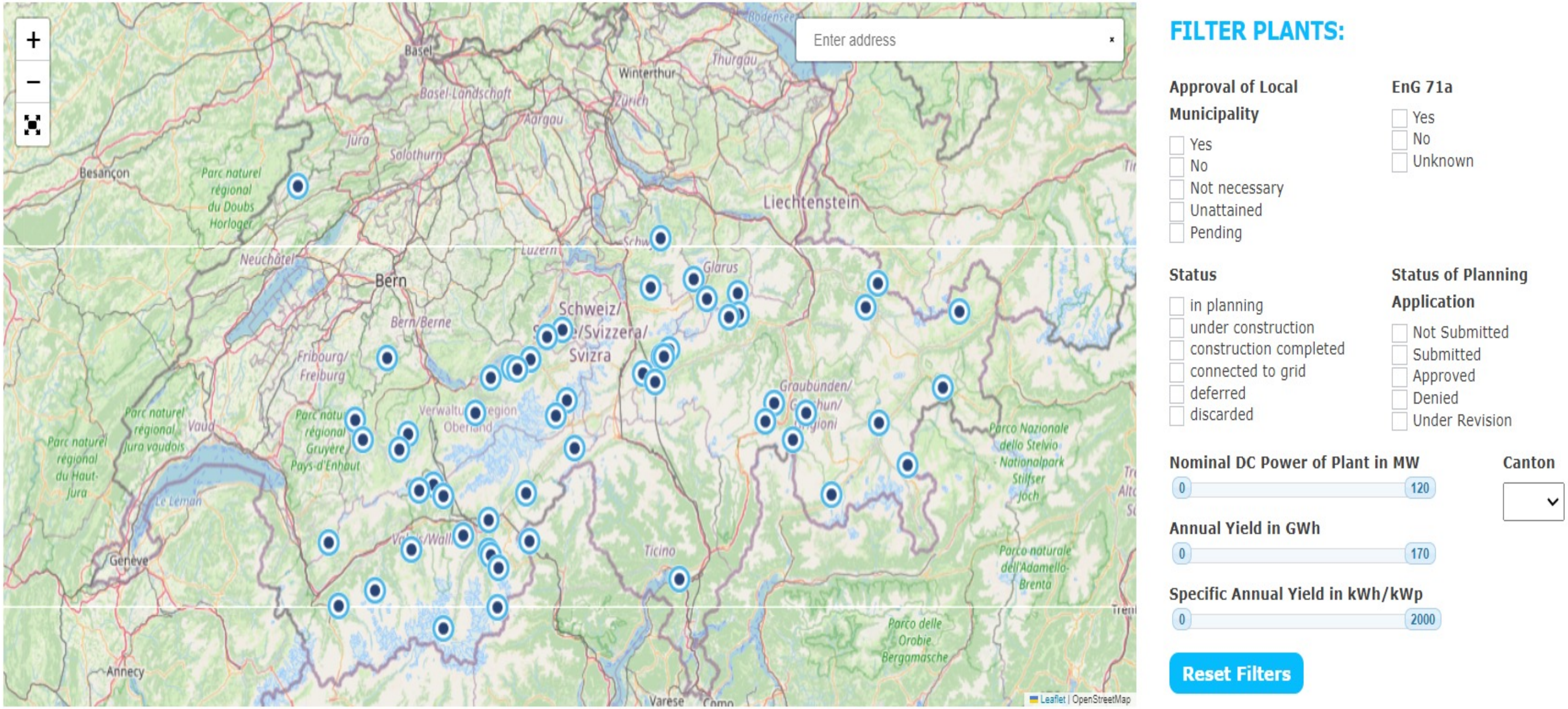
ALPINE PV (nickname triggered by the Swiss Solar express law)
High energy production in winter semester > 500 kWh/kW annual, then eligibeble for 60% investment credit, if 10% of Park installed before end of 2025!

Projet de Morgeten simulation

In construction:Madrisasolar - Alpine PV competence

12 MW, 667 kWh/kW in winter, 70 millions invest (note: very very very high… LCOE at 12 cts/kWh after 60% subsidy….

Christophe Ballif



https://alpine-pv.ch/map/

PV on infrastructure

4 CHF/W, CAPEX
Harsch conditions

2.2 MW PV system on the Muttsee Dam, commissioned by AXPO

Tests on highway

Concept in CH

NO limitation, but possible high CAPEX

Routes solaires

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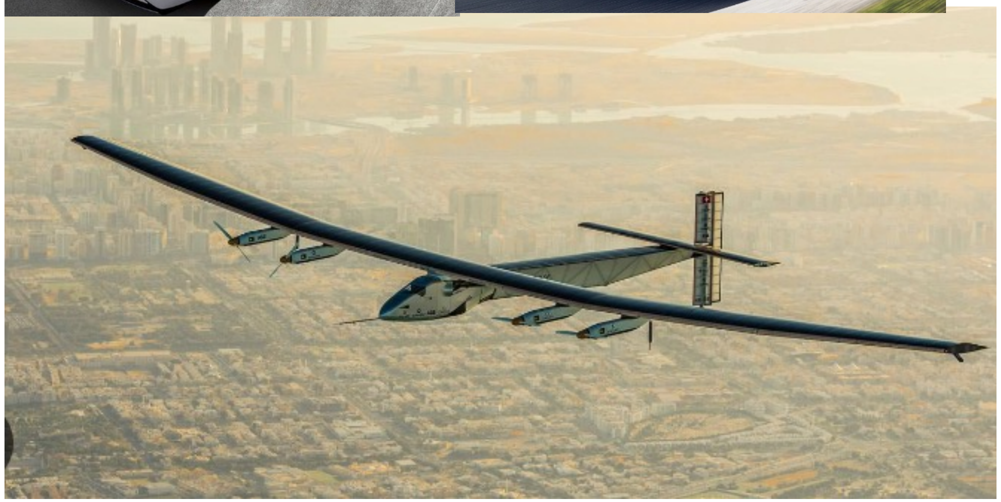
New growing niche markets

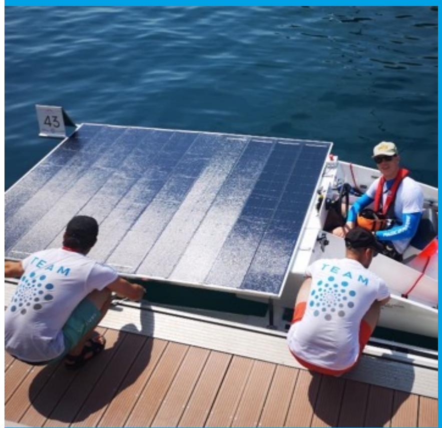
VIPV= vehicle integrated photovoltaics

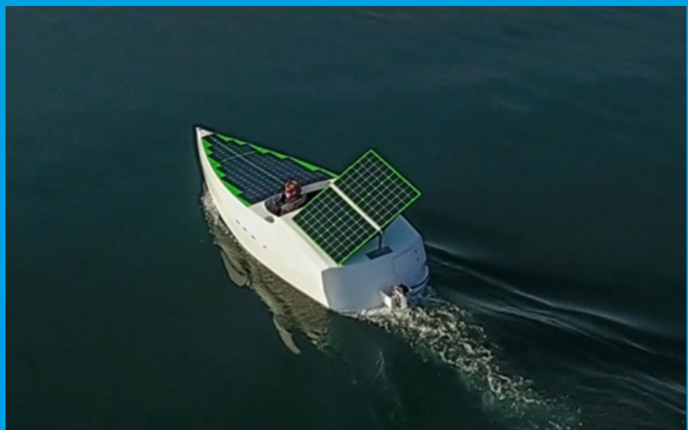
5 m2 of PV on a car in CH → 700 kWh/year → 4000-5000 km per year



Integrated PV to reach the Stratosphere

SOLARSTRATOS TO THE EDGE OF SPACE | csem





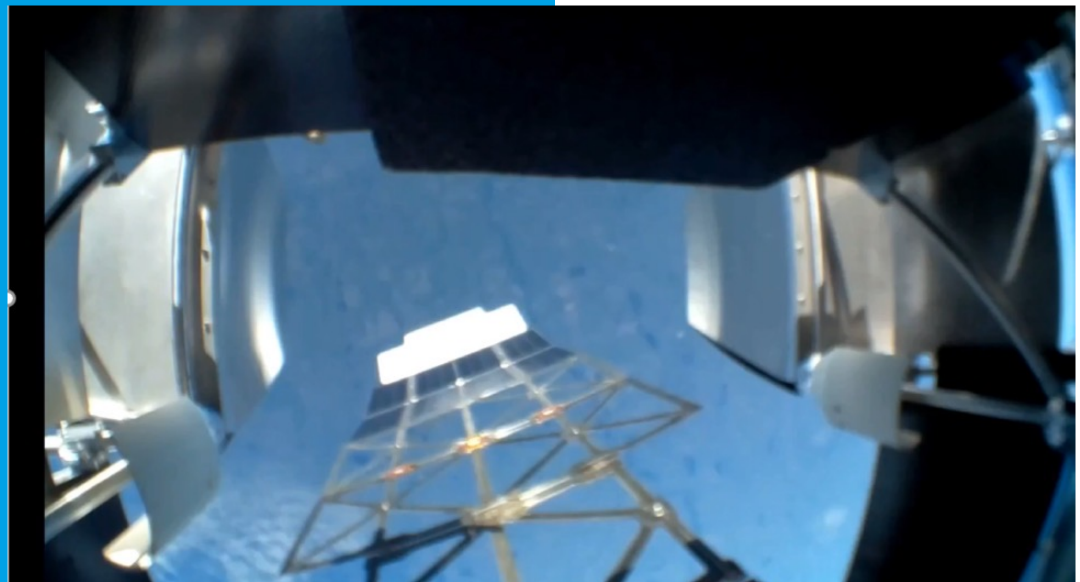
Light weight customized ultra-reliable modules

EPFL csem

SOLAR ROOFS MADE IN NEUCHÂTEL

Strateole:
PV solutions for stratospheric balloons

Deployable lightweight structures and PV modules qualified in stratosphere!
Up to 35‘
000 meters



Multiple Applications
For terrestrial PV

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.... THE T-TOUCH SOLAR CONNECT
Solar dials developped by CSEM,
production fully ramped-up by CSEM
Now production lines at Swatch Group
METEO
NAVIGATION
TISSOT
1853
Welcome


PRC 100 SOLAR
VOM LICHT ANGETRIEBEN
TISSOT 1853
PRC 100 SOLAR


TISSOT 1853
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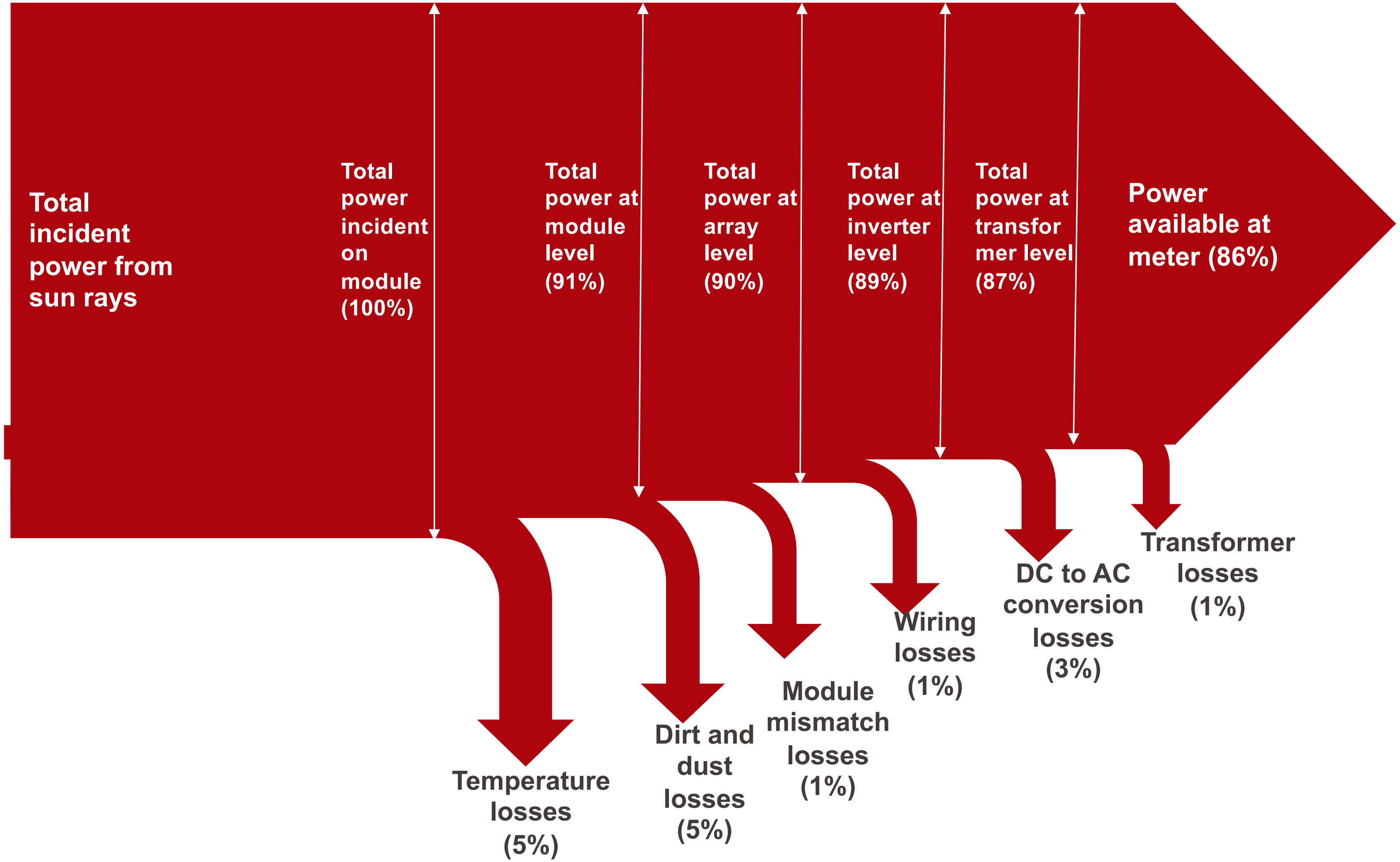
Conclusions, 2nd part

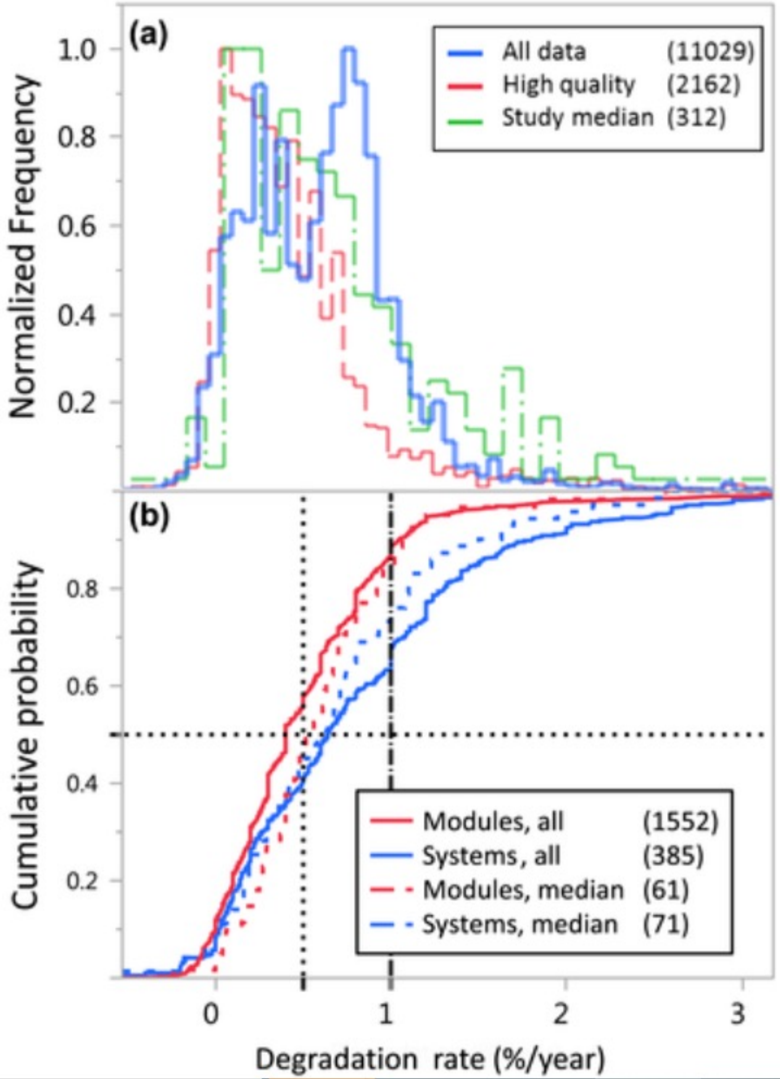
- Many developping markets, in addition to standard residential, commercial and large power plants
- BIPV is a growing market, supported by the trend for aesthetic and green buildings, with a lots of companies active in Switzerland
- Floating PV and Agri PV are gaining traction
- PV can virtually come everywhere. The low cost c-Si solar cells, allows for an infinite number of variations of modules shapes, size and colors
- Many niche applications (and many groups active in CH)

Appendix

Average power available (example)



Additional losses: Module and systems degradation

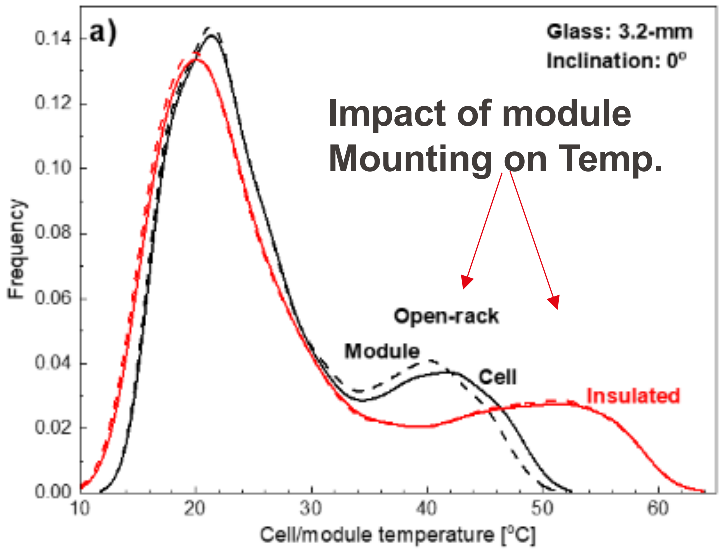


- Modules and systems have «degradation rates» (0.2 to 1% relative per year sometimes even more)
- This can impact the buisness model of large power plant

- Mitigating/preventing degradation is an important research topic ! Reliability of PV products requires a huge R&D work

- Cell type
- Packaging
- System aspect (voltage, heating)
- Climate (T, UV, Humidity)

→ Impact on degradation

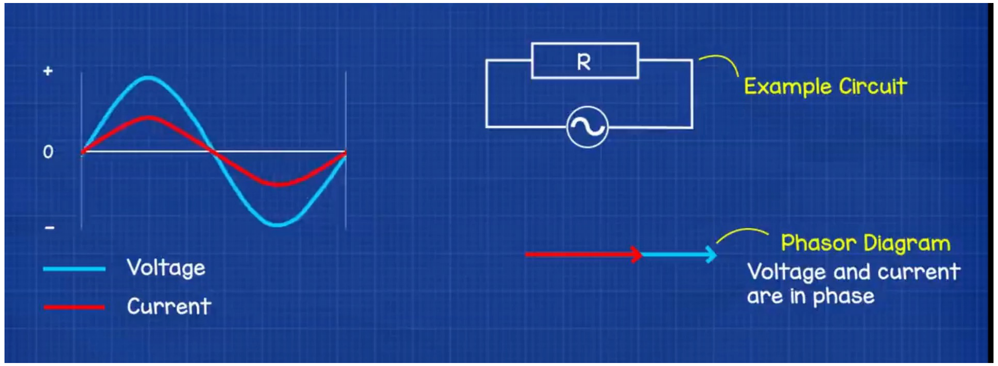


Compendium of photovoltaic degradation rates
Dirk C. Jordan et al. Progress in PV 2016

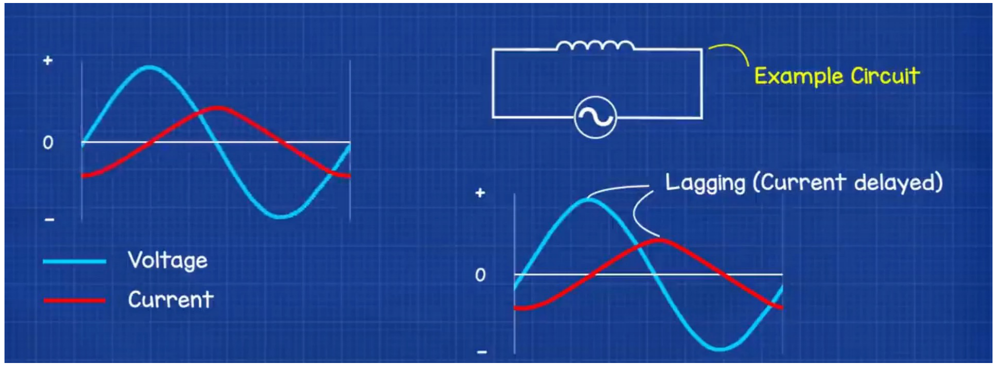
Fairbrother et al. PV-lab

How reactive power is generated

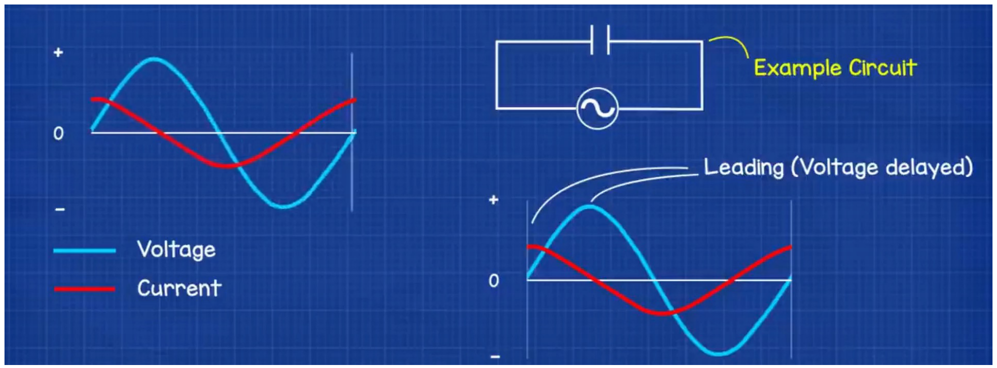
For info only



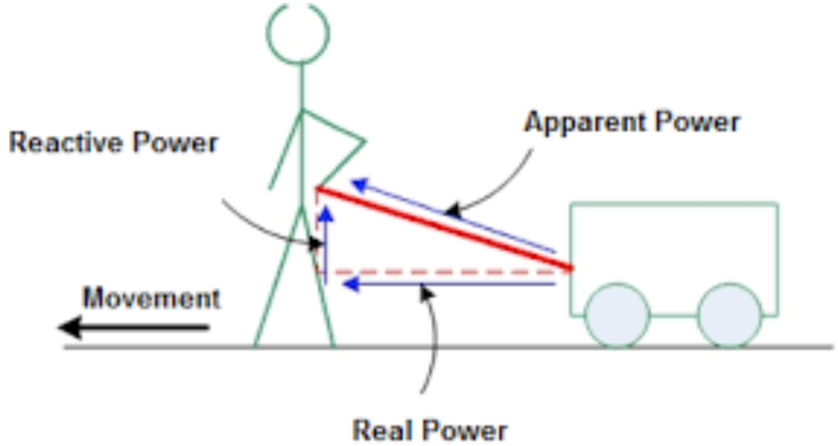
resistive load



inductive load

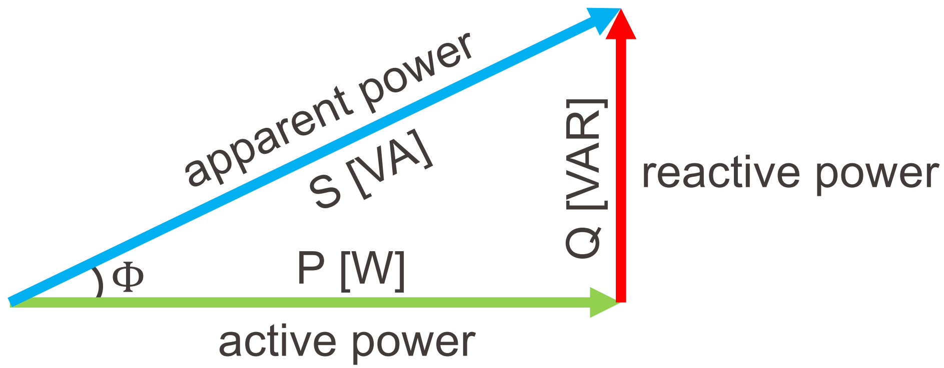


capacitive load



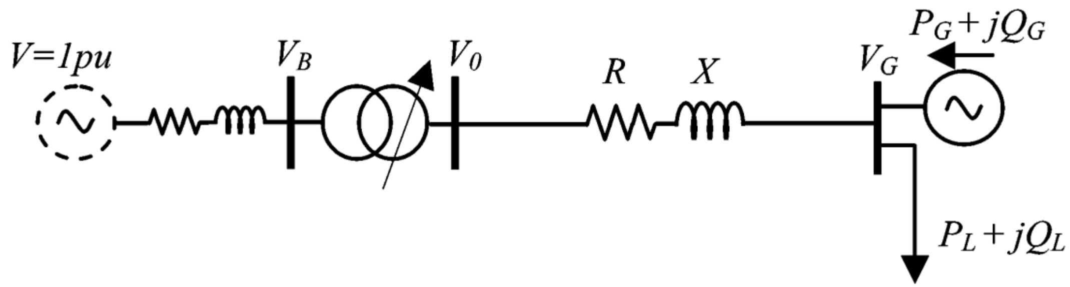
Voltage control with reactive power

For info only



$$\text{power factor} = cos(\phi) = \frac{\text{active power}}{\text{apparent power}}$$

Voltage can be regulated with reactive power, but it is not a very effective solution in low-voltage grid with $R \gg X$



Approximation of the voltage :

$$\boldsymbol{V_G = V_0 + R \cdot P + X \cdot Q}$$

V_G generator voltage

V_0 substation voltage

R feeder resistance

X feeder reactance

Carvalho, P. M. S., P. F. Correia, and L. A. F. M. Ferreira. 2008. "Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks." IEEE Transactions on Power Systems 23 (2): 766–72. https://doi.org/10/fgp4fj.

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Voltage control with reactive power

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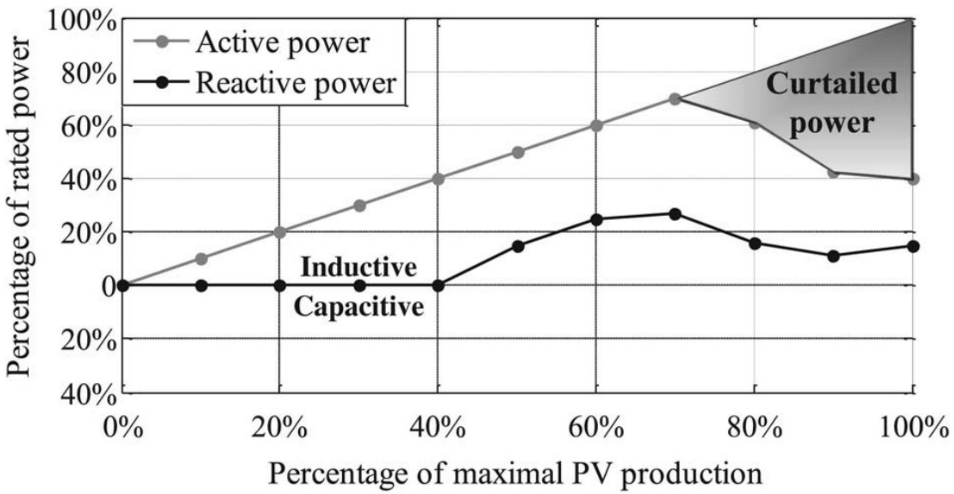

Voltage control with optimal control of reactive power and curtailment is feasible but require high resolution measurements of the local voltage and PV generation.

Enable a decrease of the voltage but increase the current.

Today's solution = grid reinforcement or fixed power factor at best

Weckx, S., C. Gonzalez, and J. Driesen. 2014. "Combined Central and Local Active and Reactive Power Control of PV Inverters." IEEE Transactions on Sustainable Energy 5 (3): 776–84. https://doi.org/10/gh482f.

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Grid-Enhancing Technologies (GETs)

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Renewables are limited to 2.6 GW in Kansas and Oklahoma due to transmission congestion. This limit could be raised to 5.2 GW with :

- Advanced Power Flow Control
  - Injects voltage in series with a facility to increase or decrease effective reactance, thereby pushing power off overloaded facilities or pulling power on to under-utilized facilities.
- Dynamic Line Ratings
  - Adjusts thermal ratings based on actual weather conditions including, at a minimum, ambient temperature and wind, in conjunction with real-time monitoring of resulting line behavior.
- Topology Optimisation
  - Automatically finds reconfiguration to re-route flow around congested or overloaded facilities while meeting reliability criteria.

https://watt-transmission.org/wp-content/uploads/2021/02/Brattle__Unlocking-the-Queue-with-Grid-Enhancing-Technologies__Final-Report_Public-Version.pdf90.pdf