Materials & Chemical Engineering
for nano • bio • sustainable technologies

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dipartimento di Ingegneria e Architettura

Engineering Energy Transition

A.Y. 2026 - 2027

Materials, systems and critical raw materials for the energy transition

Alternative Technologies 1

Vanni Lughi – vanni.lughi@dia.units.it
Alessandro Massi Pavan – apavan@units.it
Nicola Blasuttigh – nicola.blasuttigh@units.it

Structure of the courses

Master Degree in
"Materials and chemical engineering for nano, bio and sustainable technologies"

Materials, systems and critical raw materials for the energy transition

Modules:
- Materials for photovoltaics and energy transition technologies 3 CFU
- **Photovoltaic systems and energy management 3 CFU**
- Strategic and critical raw materials 3 CFU
- Substitution of critical materials 3 CFU

Master Degree in
"Engineering for the energy transition"

Alternative Energy Technologies 1

Modules:
- Materials for the Energy Transition 3 CFU
- **Electrical Systems for the Energy Transition 3 CFU**
- Electrical Energy Storage 3 CFU

Content

You can find the Syllabus in the Moodle page of the Course

1. Photovoltaic systems: Massi Pavan
2. Storage systems: Massi Pavan
3. Energy management systems: Blasuttigh

References

- **Your notes taken during lesson**
- **Slides in Moodle**, the password is: eSfet2320L*
- Books

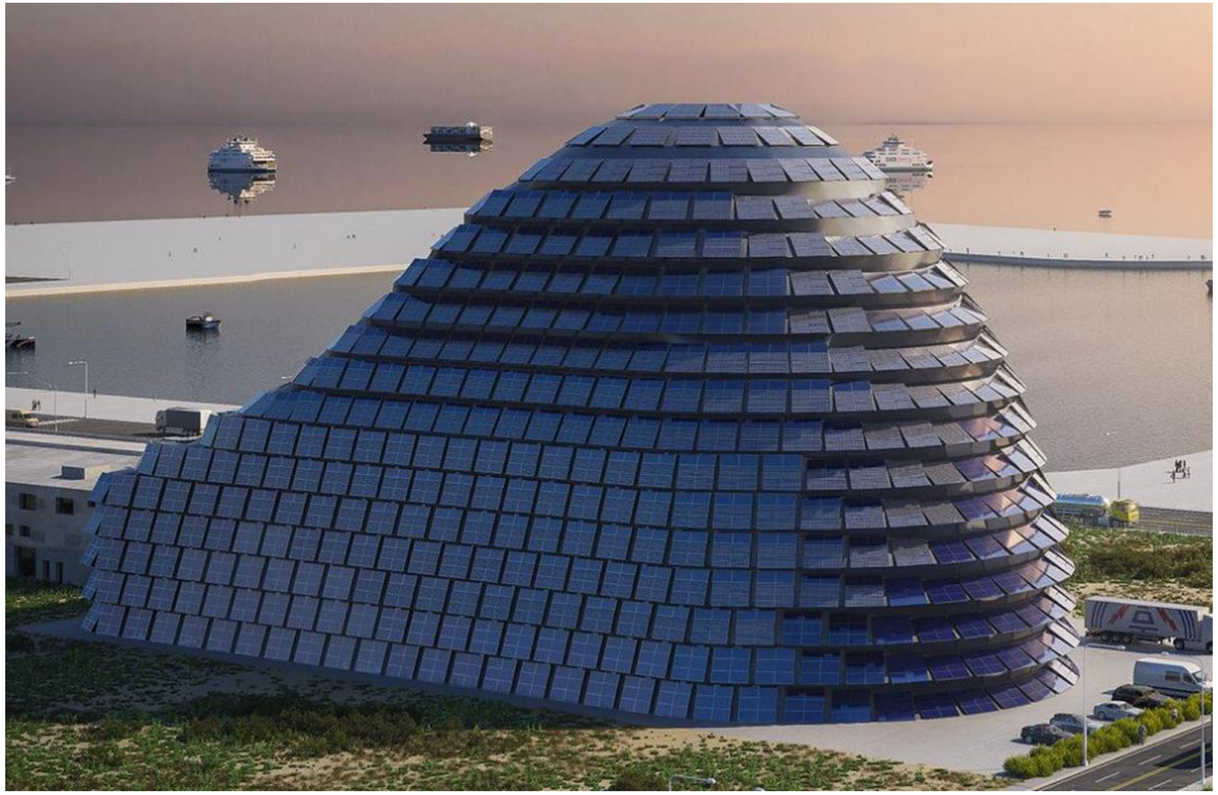
  ✓ V. Bearzi. Manuale di Energia Solare, Tecniche Nuove

  ✓ Photovoltaic Solar Energy: From Fundamentals to Applications Volume 2, Wiley 2024

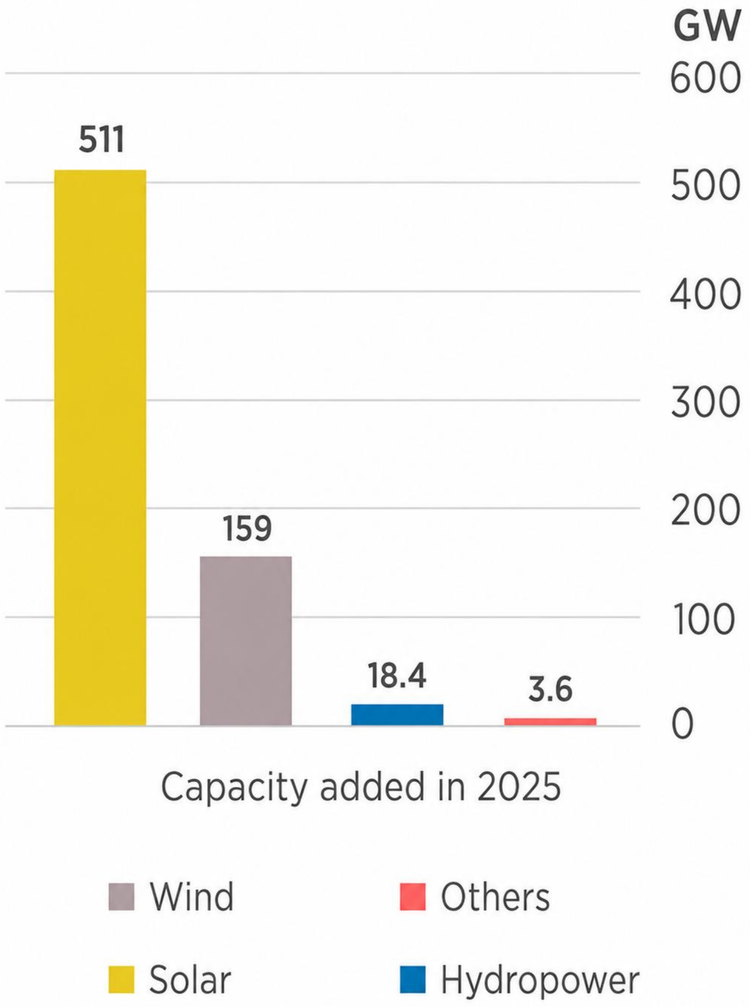
  ✓ Practical handbook of photovoltaics : fundamentals and applications, Elsevier 2011

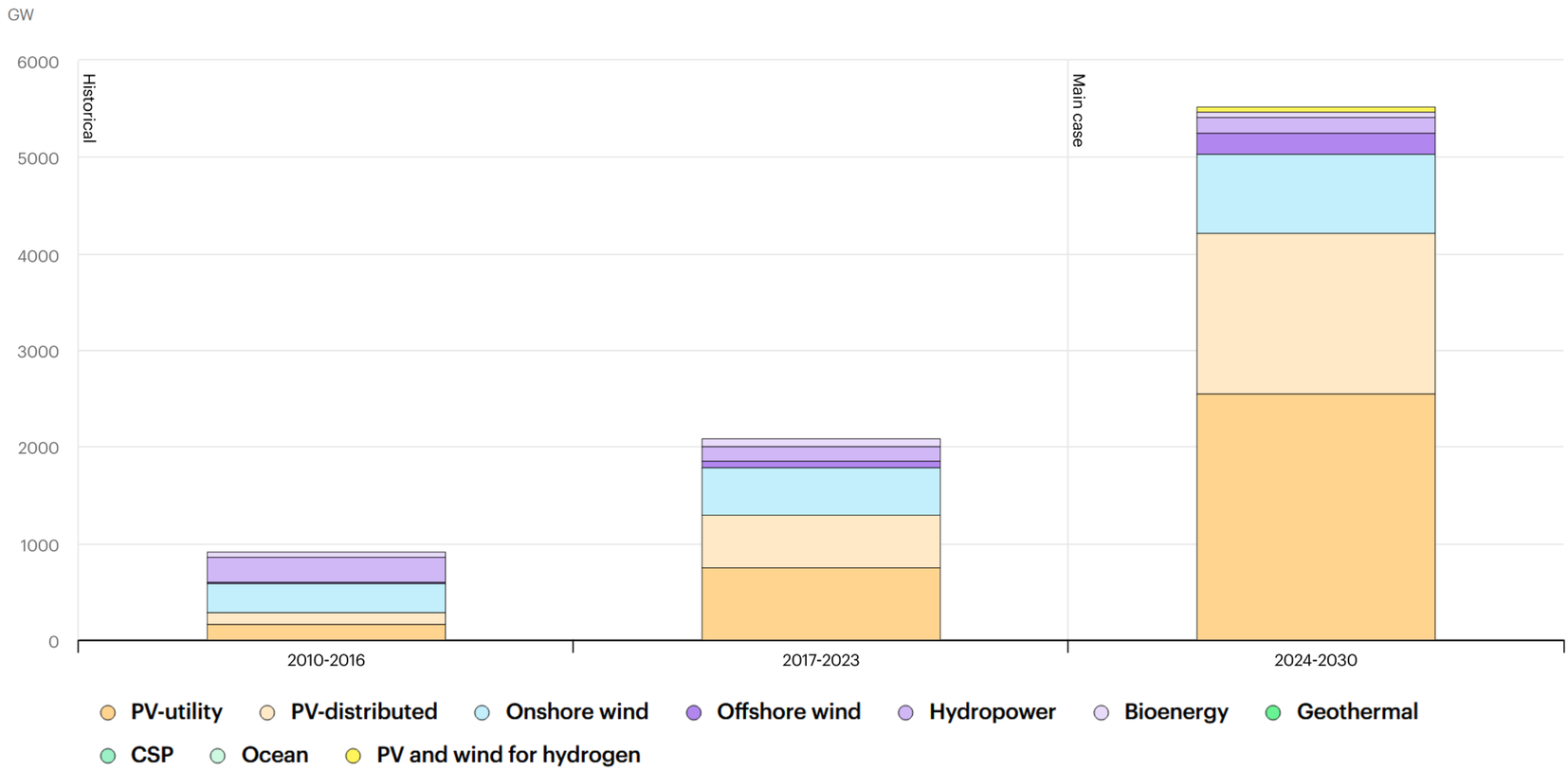
  ✓ Handbook of photovoltaic science and engineering, Wiley 2003

PHOTOVOLTAIC SYSTEMS

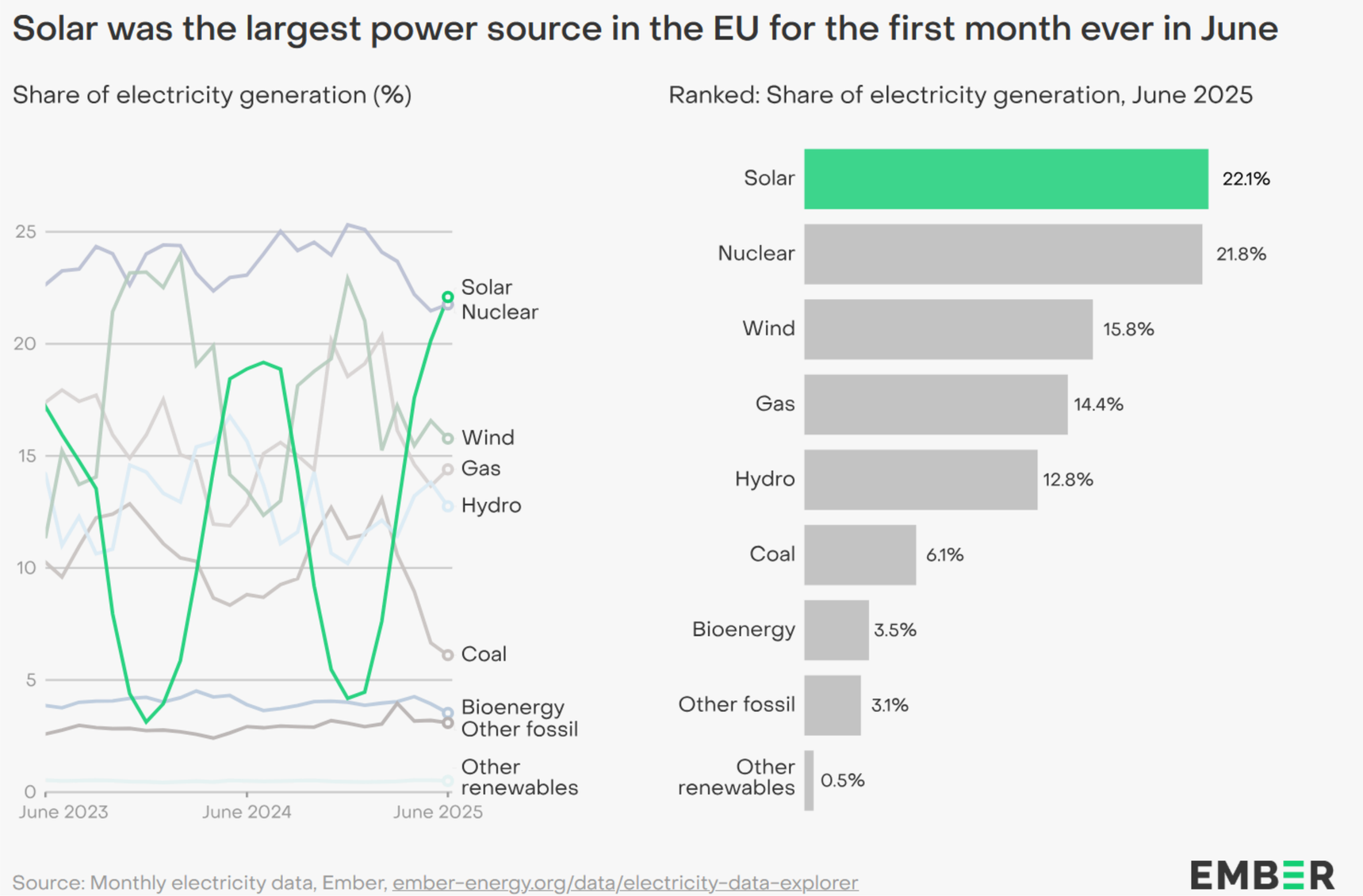


The role of photovoltaics





The role of photovoltaics



A vision from the past



J. Ciamician

SCIENCE

FRIDAY, SEPTEMBER 27, 1912

CONTENTS

The Photochemistry of the Future: PROFESSOR GIACOMO CIAMICIAN 385

The First International Eugenics Congress: PROFESSOR RAYMOND PEARL 395

Industrial Education in the Philippines 396

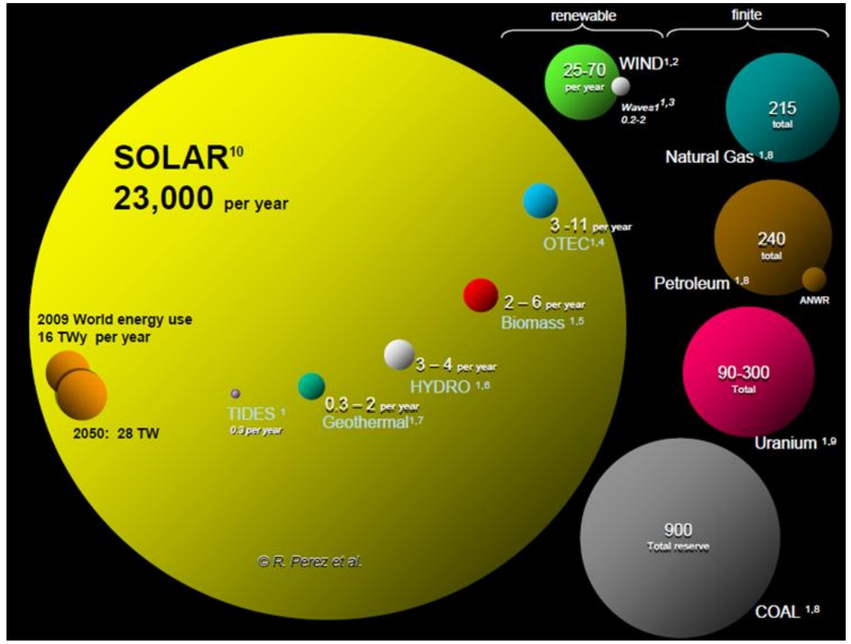
Graduates from American Colleges and Universities 397

THE PHOTOCHEMISTRY OF THE FUTURE[1]

MODERN civilization is the daughter of coal, for this offers to mankind the solar energy in its most concentrated form; that is, in a form in which it has been accumulated in a long series of centuries. Modern man uses it with increasing eagerness and thoughtless prodigality for the conquest of the world and, like the mythical gold of the Rhine, coal is to-day the greatest source of energy and wealth.

"...if our black and nervous civilization, based on coal, shall be followed by a quieter civilization based on the utilization of solar energy, that will not be harmful to progress and to human happiness."

Why photovoltaics?



Solar is now ‘cheapest electricity in history’, confirms IEA



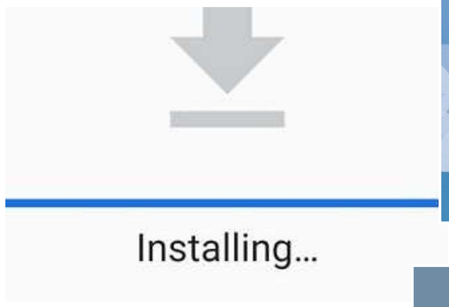


Fuel source is vast and essentially infinite

Low costs

Why photovoltaics?







Reliable and durable

Easy and quick installation

Why photovoltaics?

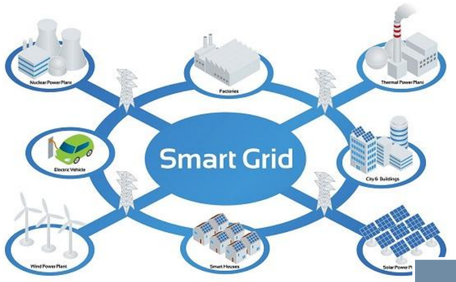


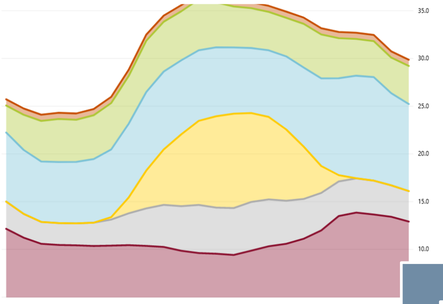


Modular technology

No moving parts, no noise (no emissions)

Why photovoltaics?

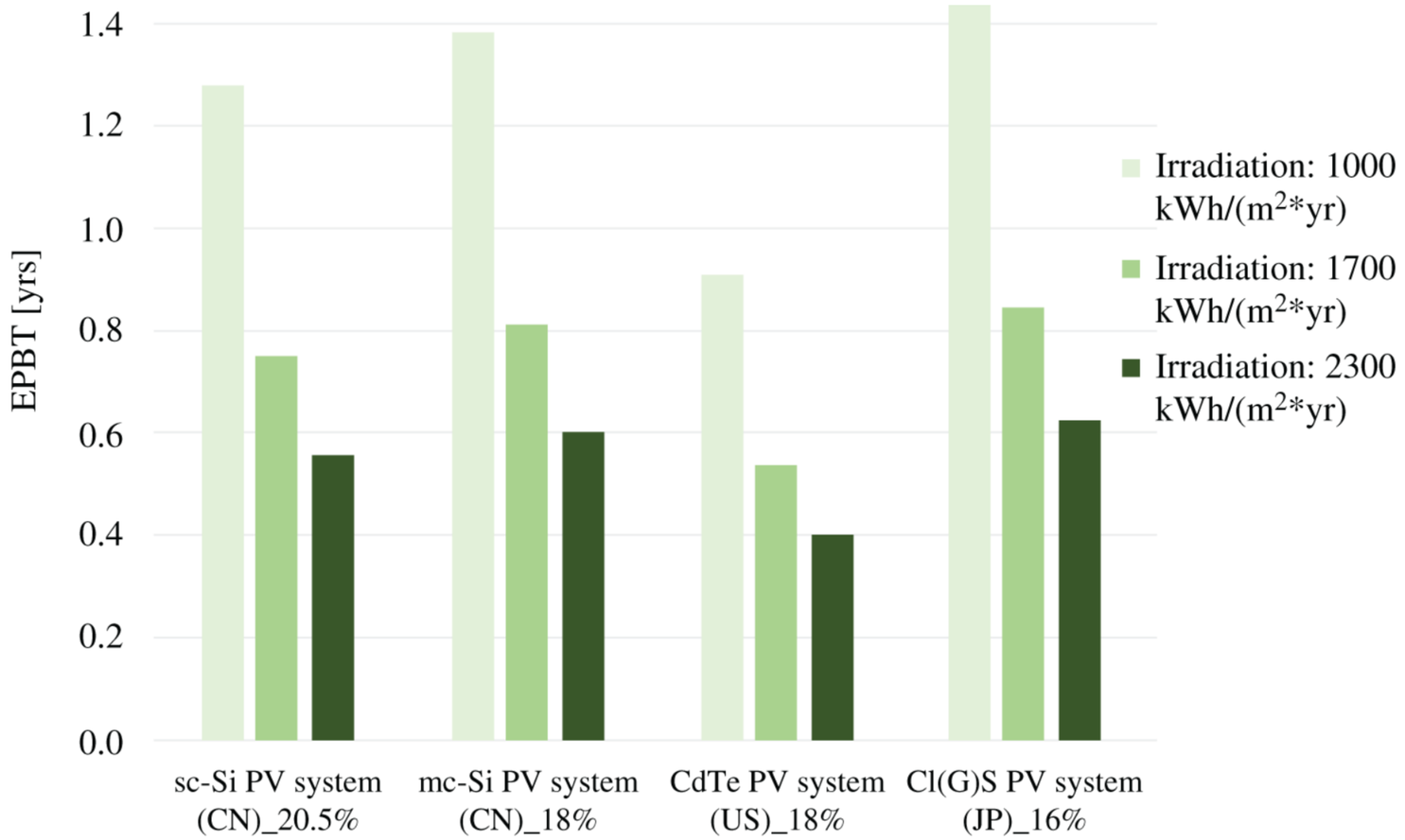




Distributed generation

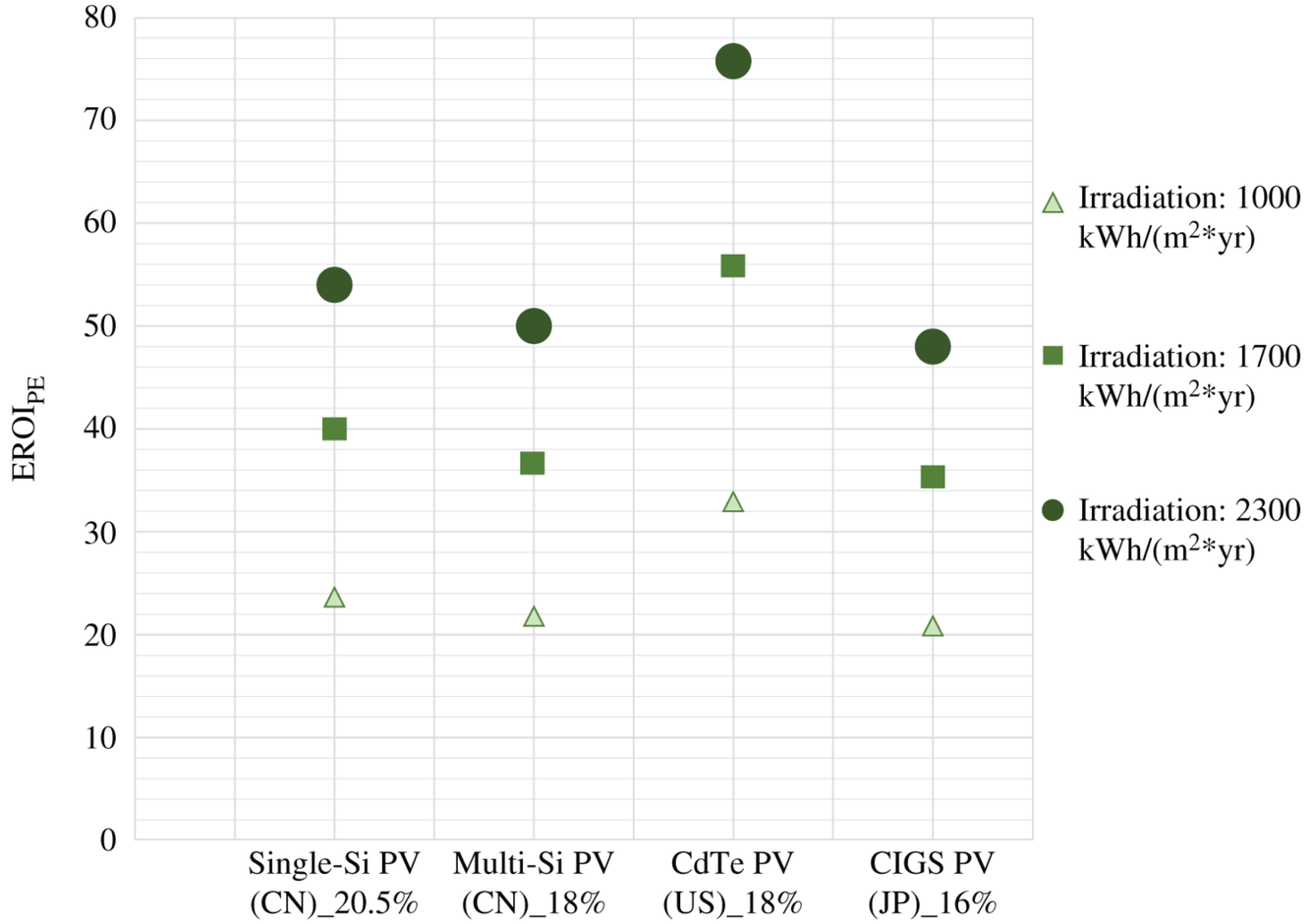
Daily output peak can match the local demand

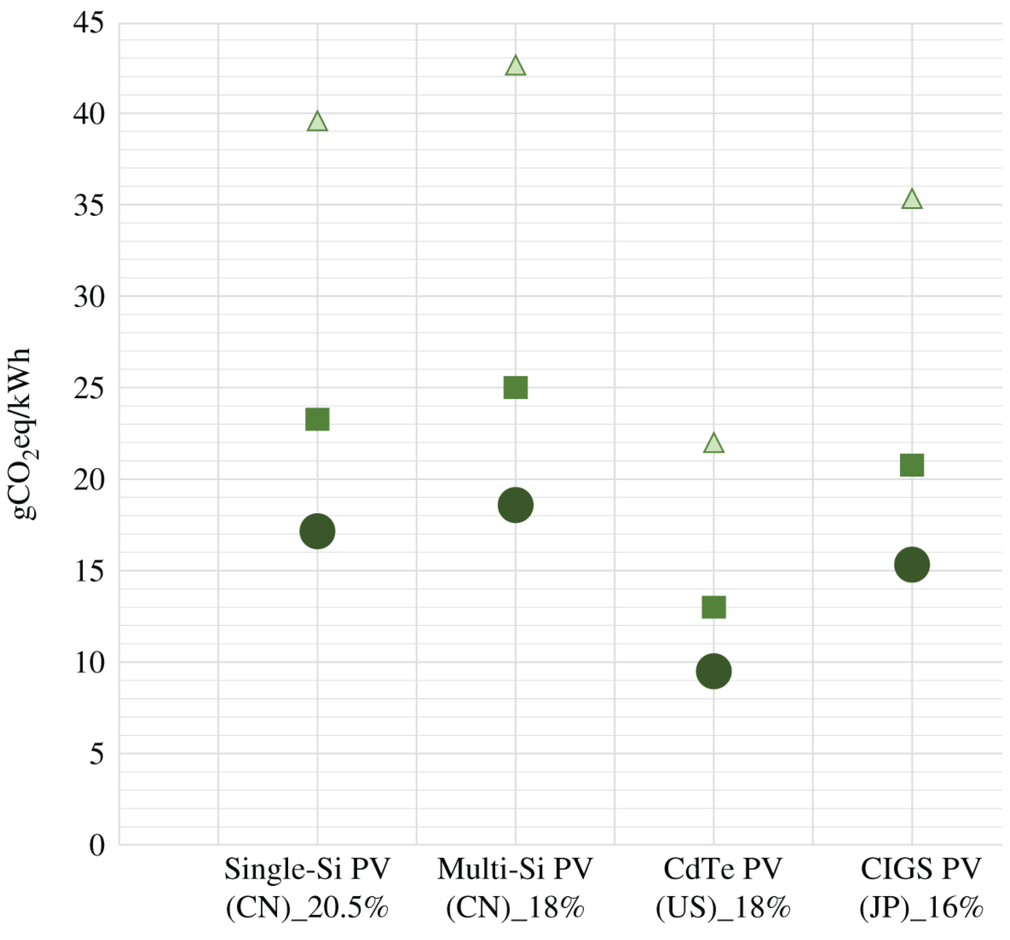
Energy Payback Time



Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

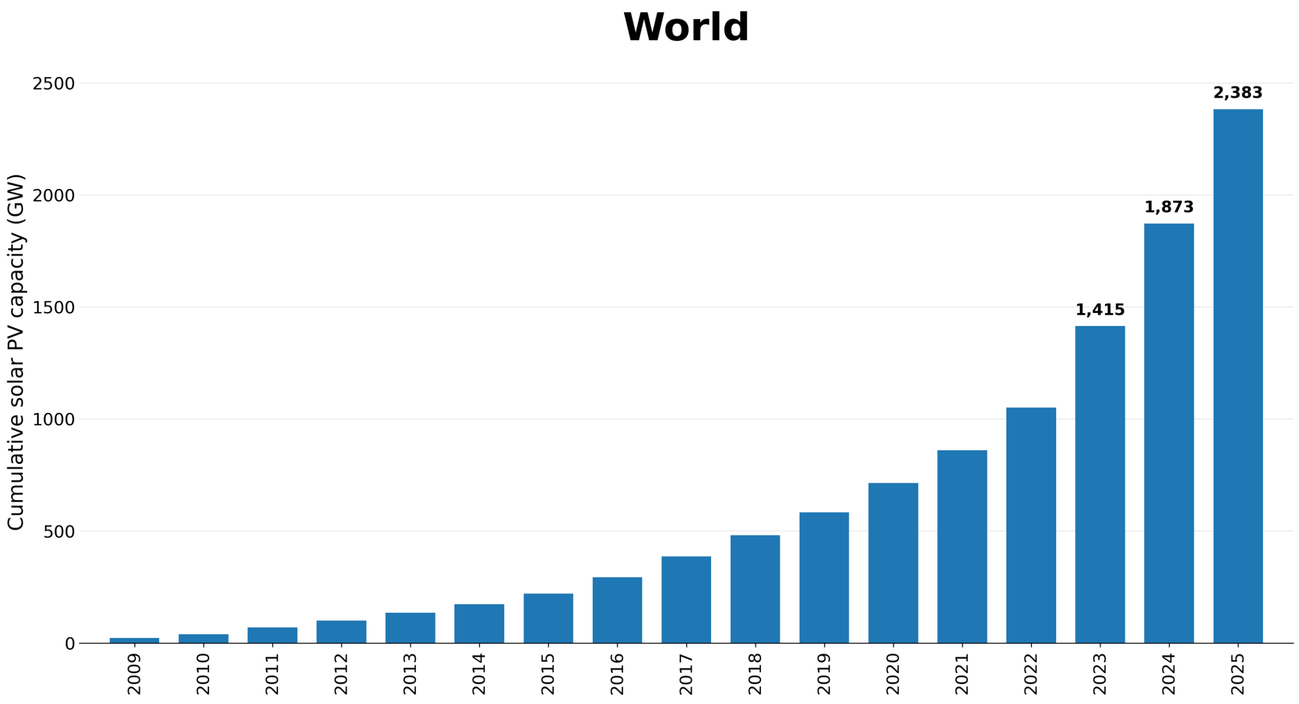
EROI and CO2 emissions



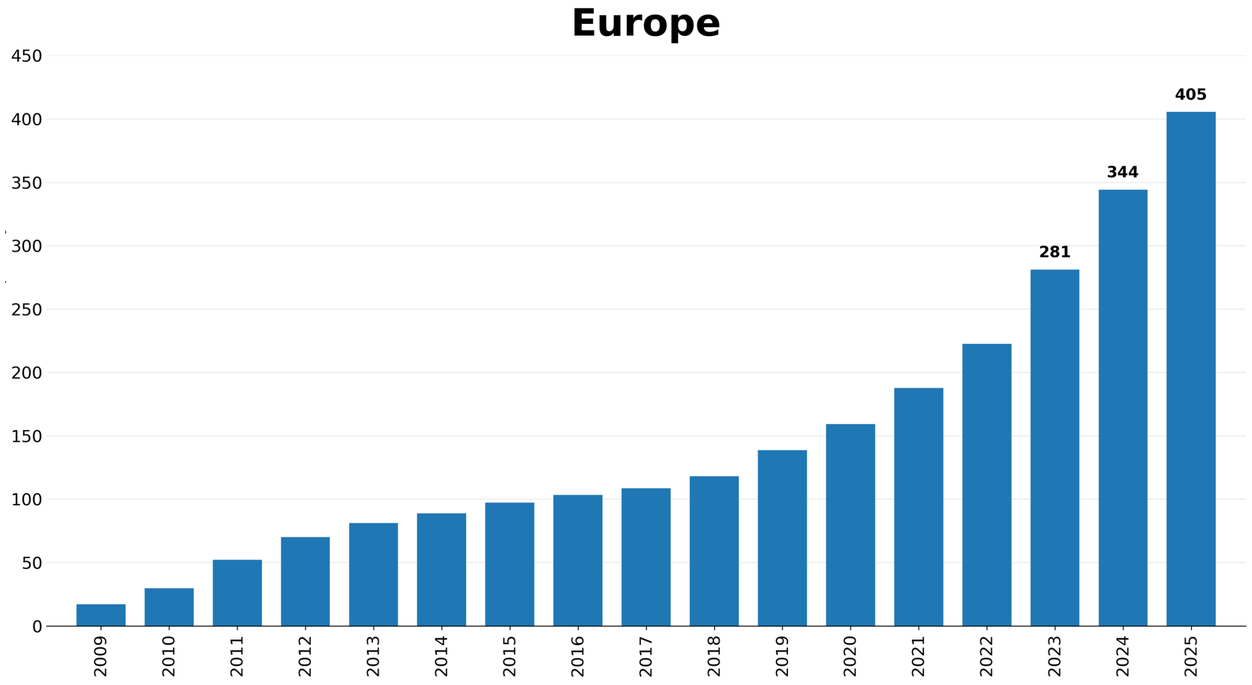


Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

Cumulative installed power (MWp)

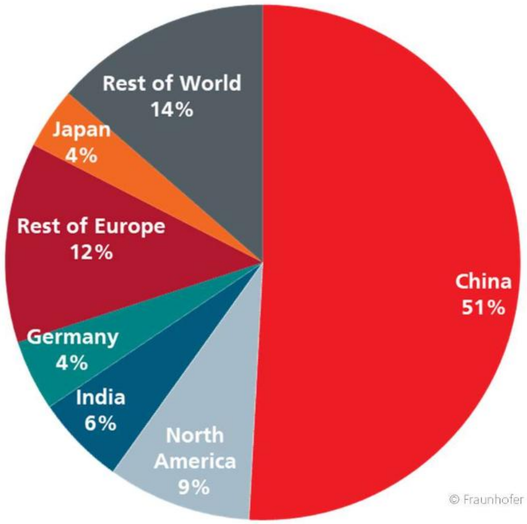


Source: IRENA, Renewable Capacity Statistics (historical series; 2026 edition for 2016–2025).



ırce: IRENA, Renewable Capacity Statistics (historical series; 2026 edition for 2016–2025).

Cumulative installed power (MWp)



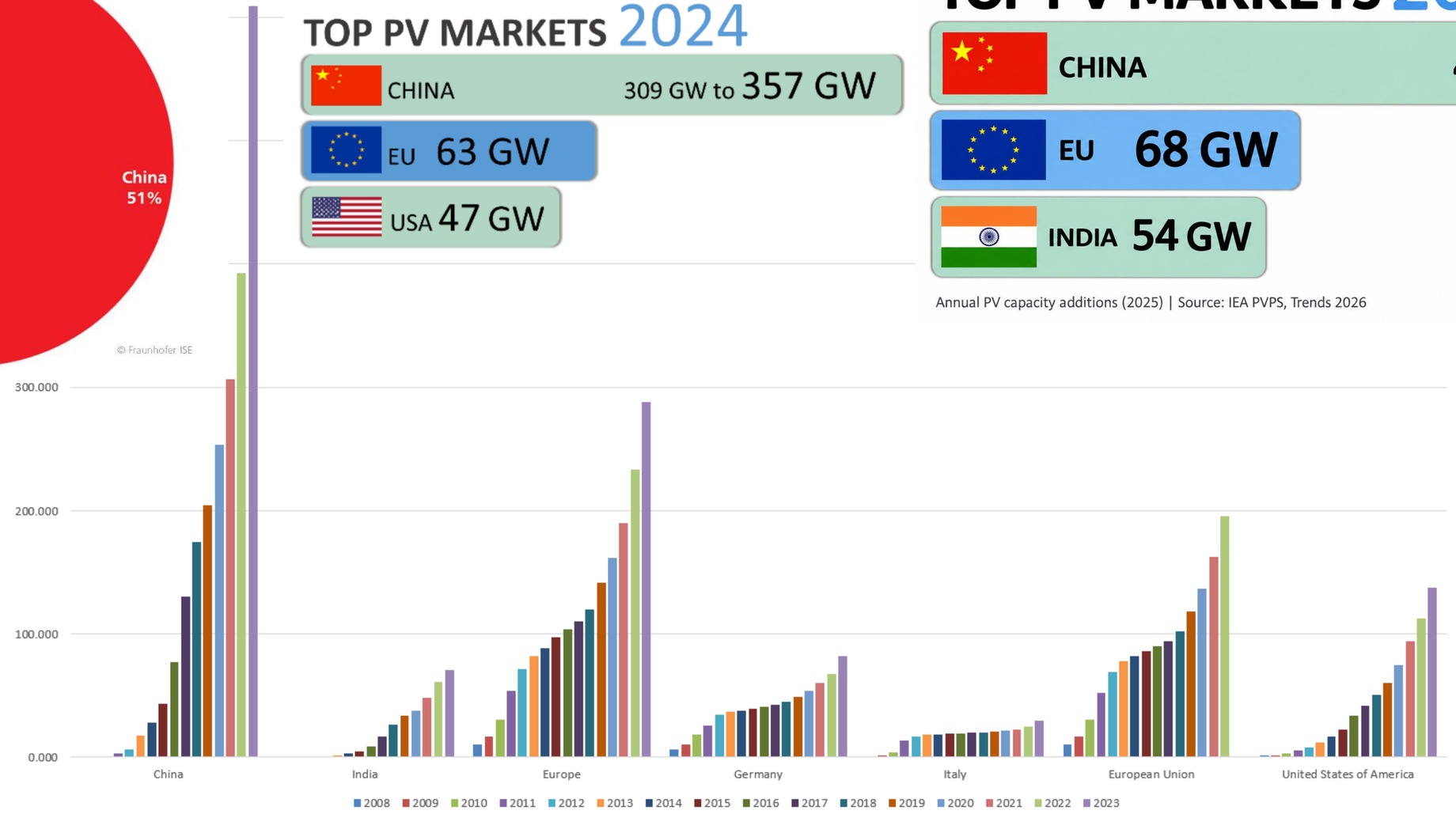
TOP PV MARKETS 2024

- CHINA 309 GW to 357 GW
- EU 63 GW
- USA 47 GW

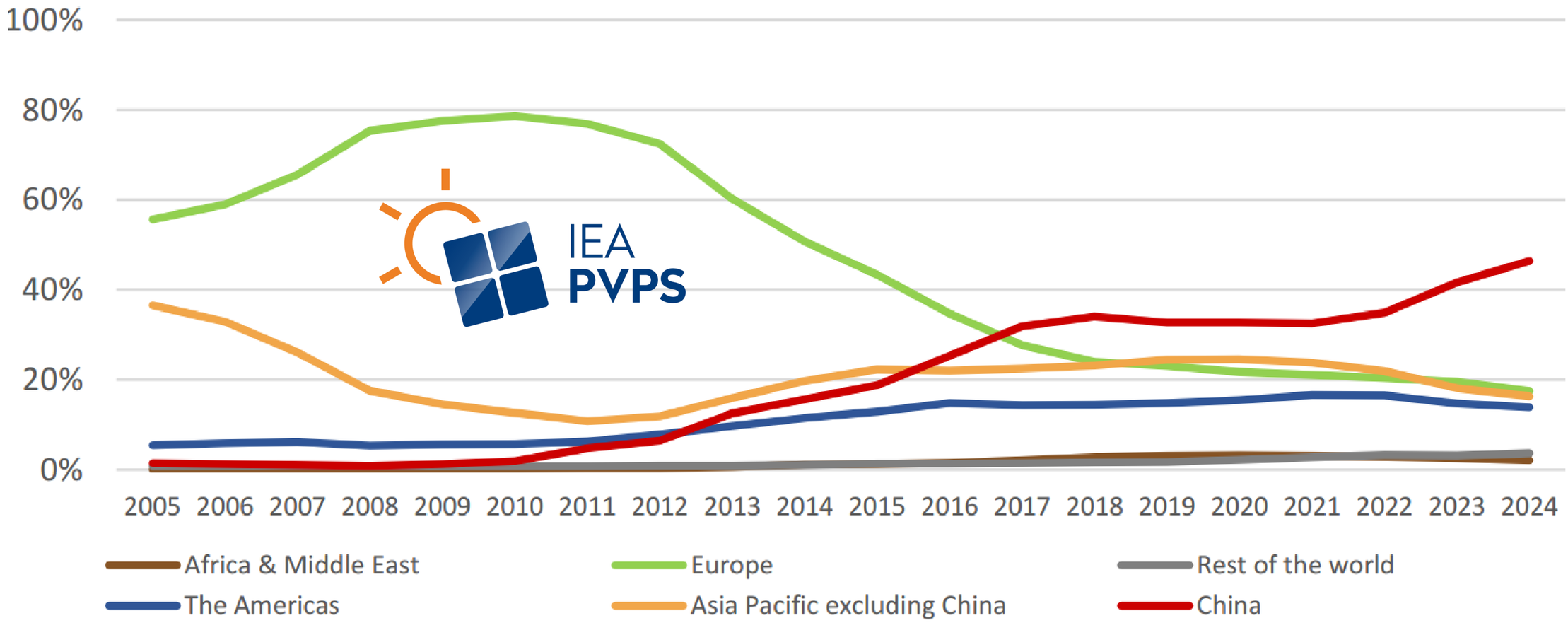
TOP PV MARKETS 2025

- CHINA 415 GW
- EU 68 GW
- INDIA 54 GW

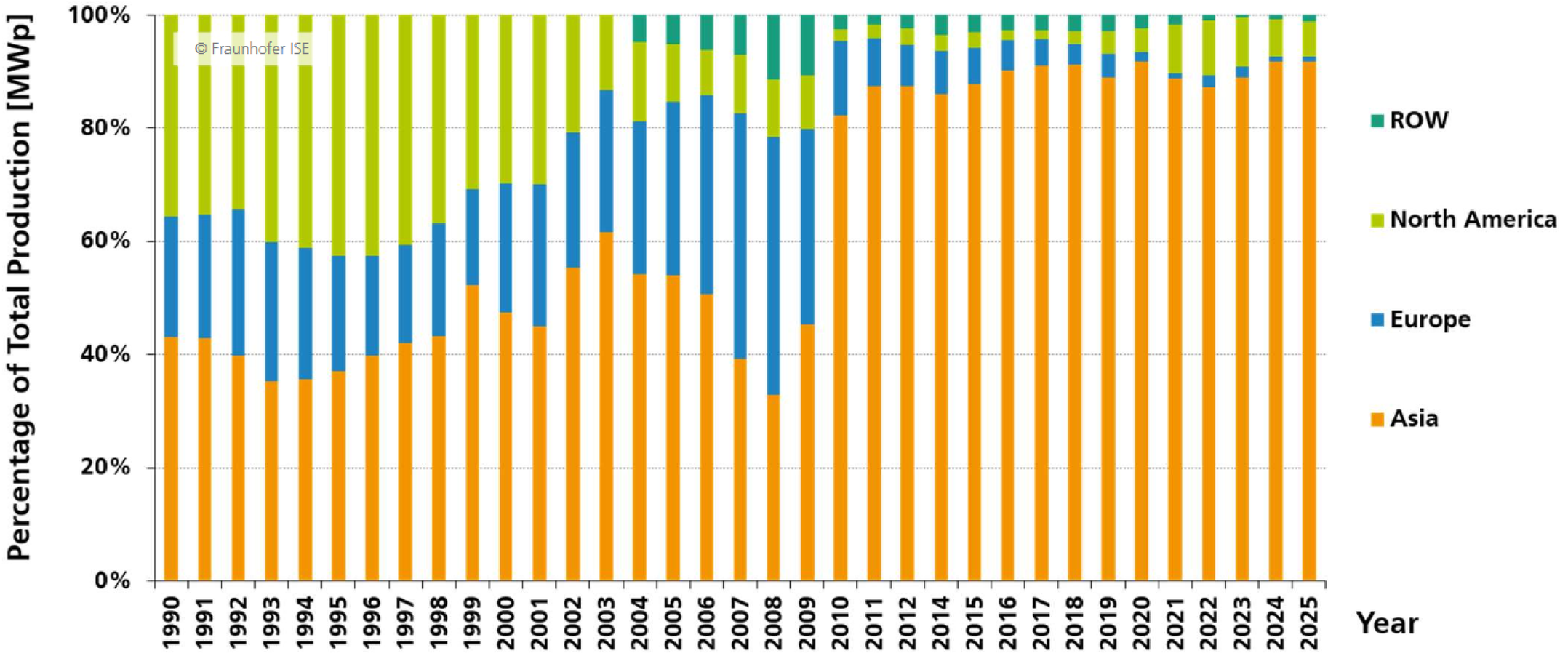
Annual PV capacity additions (2025) | Source: IEA PVPS, Trends 2026



Evolution of global market

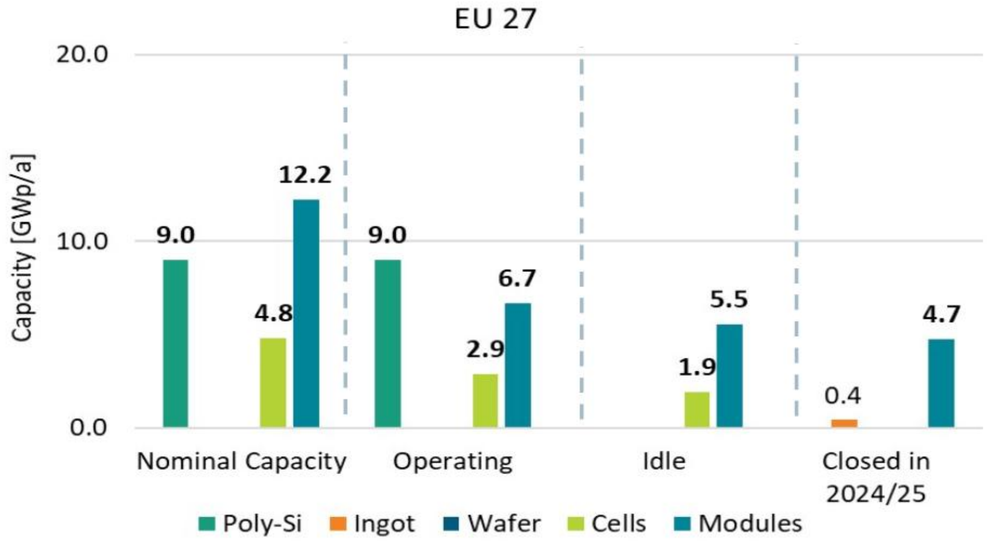


PV module production by region



EU PV Manufacturing Landscape – Status Quo

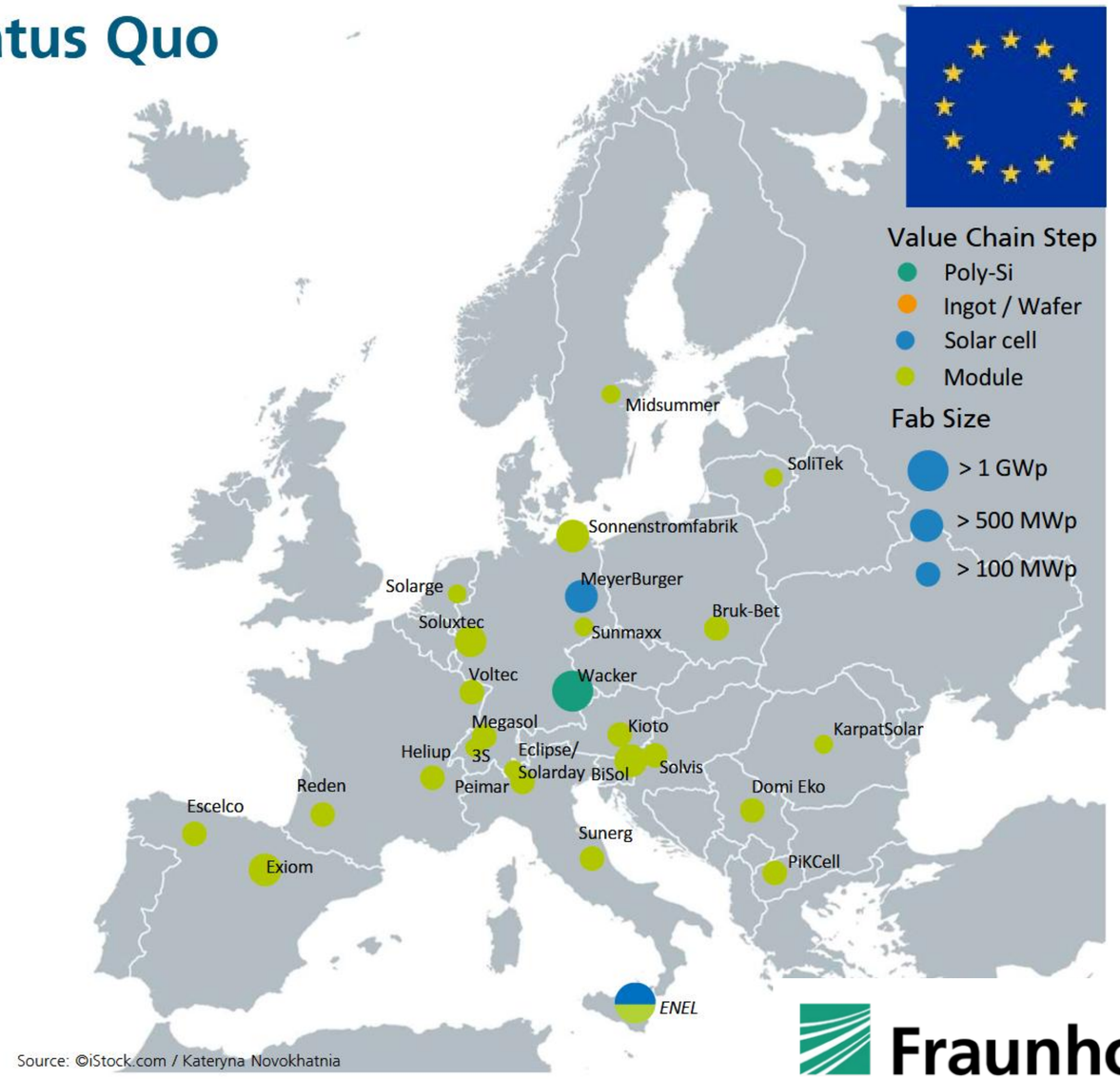
EU 27



Status Quo in the EU

- Many PV Module manufacturers still exist. But almost all of them with a small production capacity (< 1 GWp/a).
- Cell production capacity of <5 GWp/a.
- No active Ingot & Wafer production.
- One Polysilicon manufacturer.

Data and Graph: Dr. Jochen Rentsch, Fraunhofer ISE 2025; last update: 08/2025

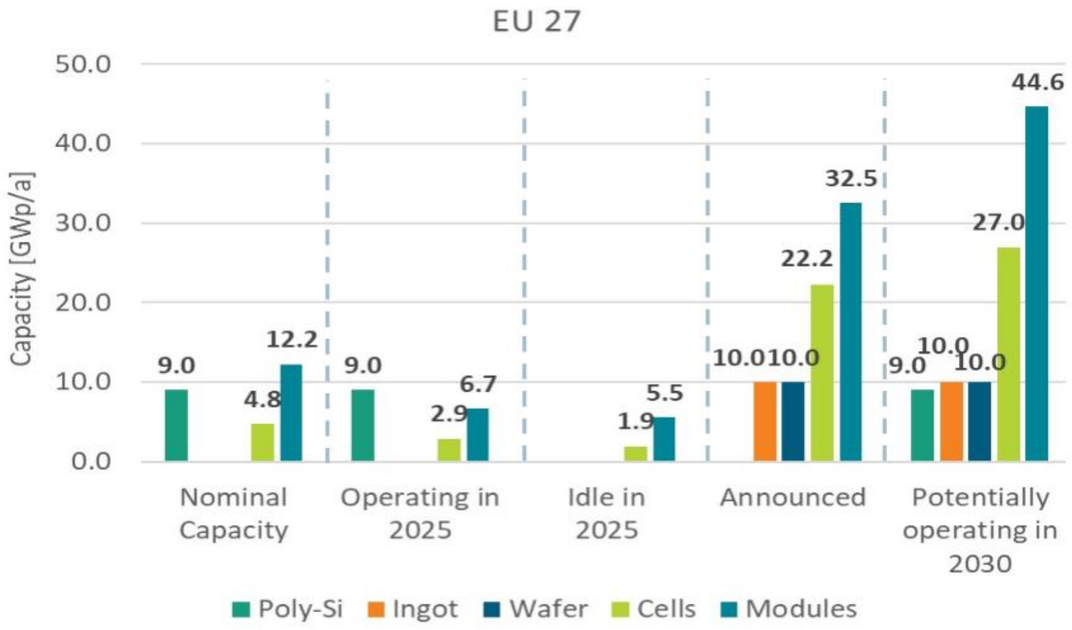


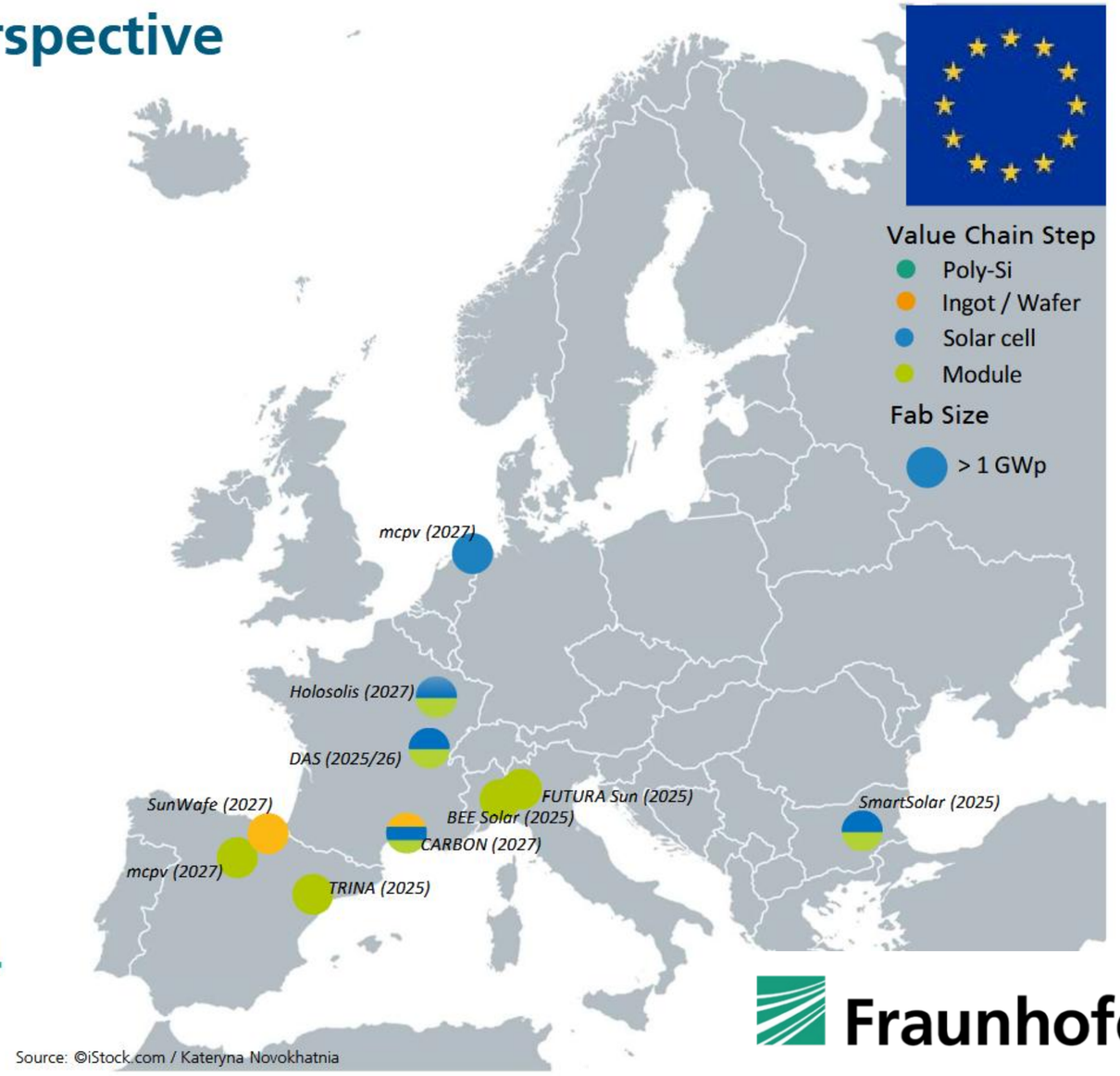
Source: ©iStock.com / Kateryna Novokhatnia

Fraunhofer ISE

EU PV Manufacturing Landscape – Perspective

Announced / Planned GW Fabs





Source: ©iStock.com / Kateryna Novokhatnia

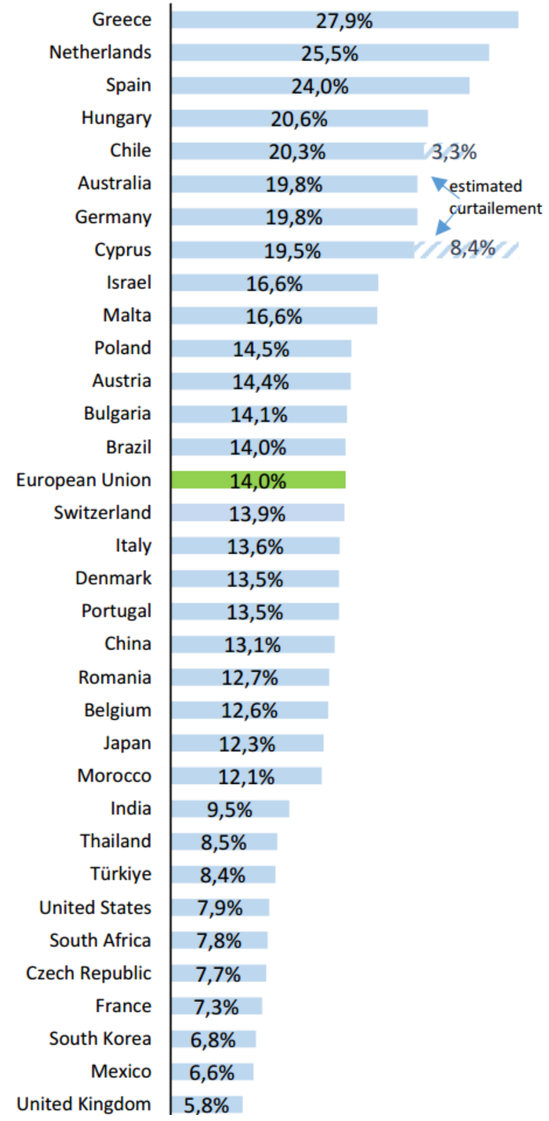
Diversification of European PV supply:

- **GWp PV Manufacturing projects in Europe announced.**
- **What is planned in other global regions?**

Data and Graph: Dr. Jochen Rentsch, Fraunhofer ISE 2025; last update: 08/2025

Fraunhofer ISE

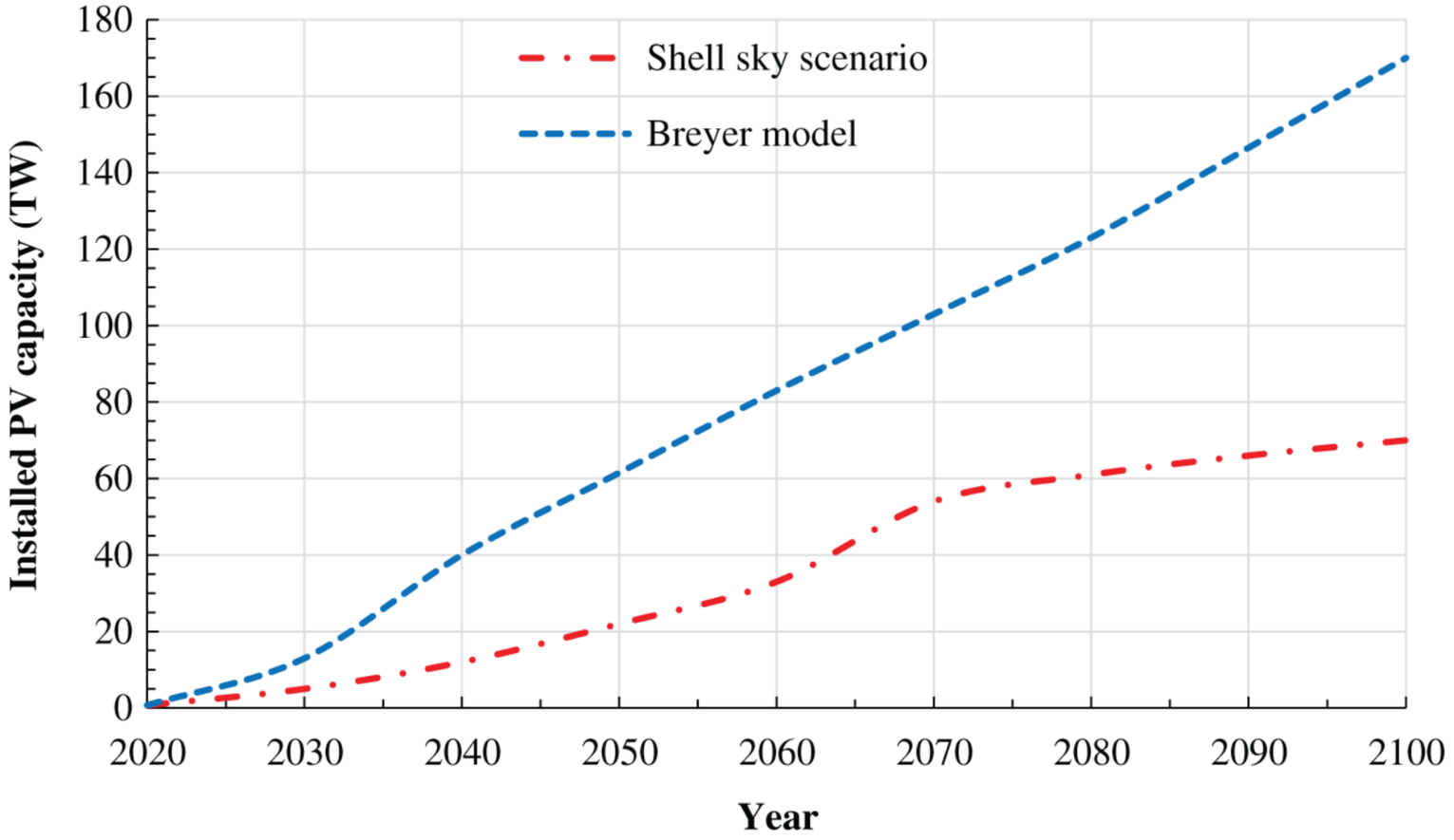
Electricity production in 2023

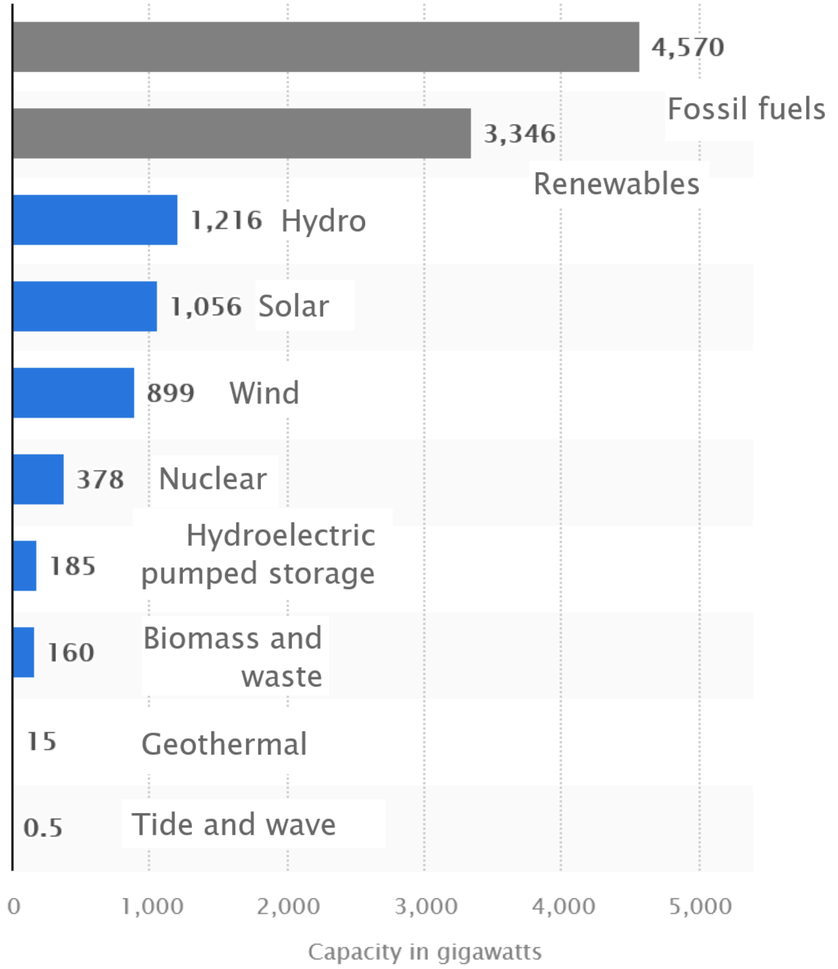


Curtailment is the intentional reduction of electricity generation, preventing it from exporting its maximum potential output to the grid

- oversupply of renewable energy
- grid-related issues like congestion or restrictions to prevent instability and ensure grid balance

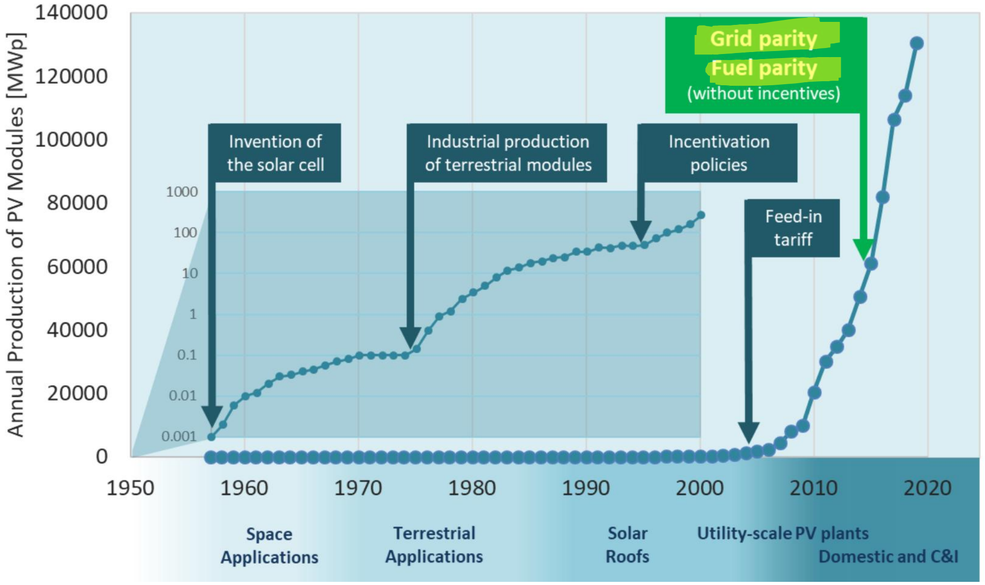
Modeled cumulative installed capacity



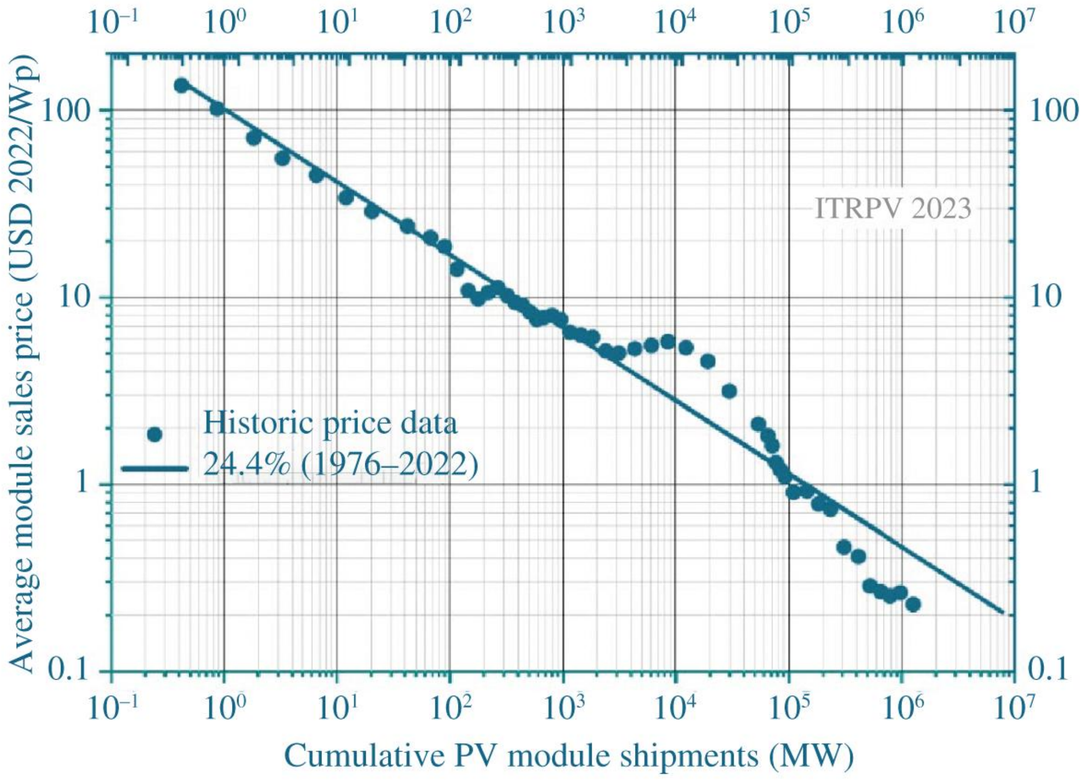


Photovoltaic Solar Energy: From Fundamentals to Applications
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It’s just the beginning: the first clue



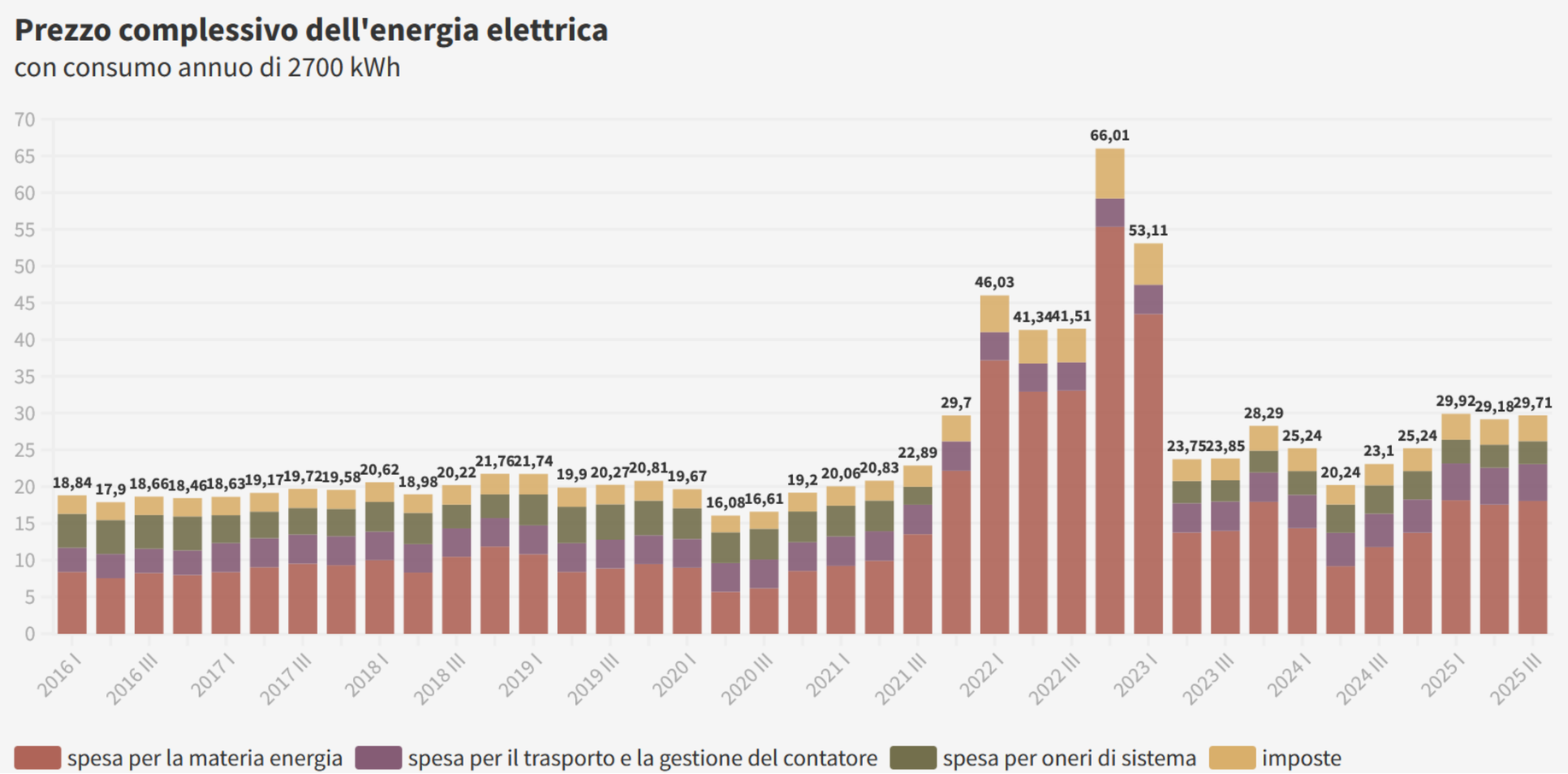
ITRPV (2023)/International Technology Roadmap for Photovoltaics



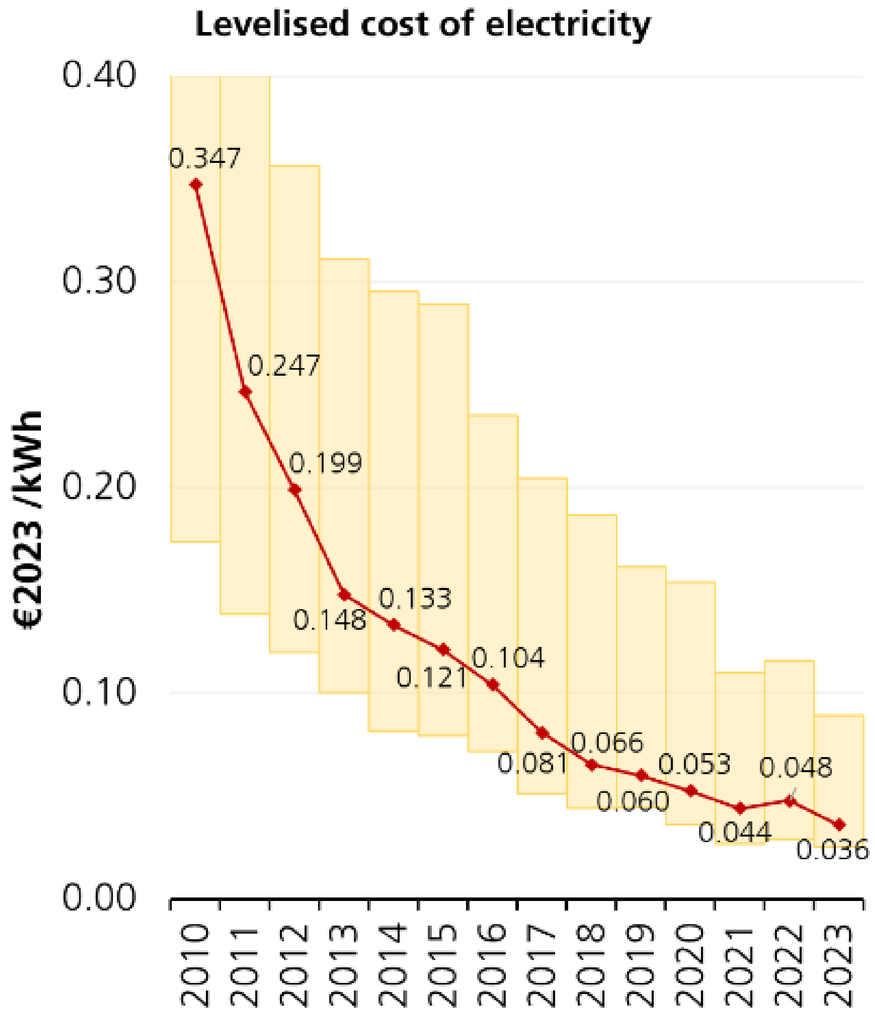
- 1955, 1975, 1995, 2015 …
- **Grid-parity**: electricity price [16 – 60 cent/kWh] > PV LCOE [4 – 14 cent/kWh]
- **Fuel-parity**: LCOE from conventional sources [9 – 58 cent/kWh] > PV LCOE [2.5 – 5 cent/kWh]

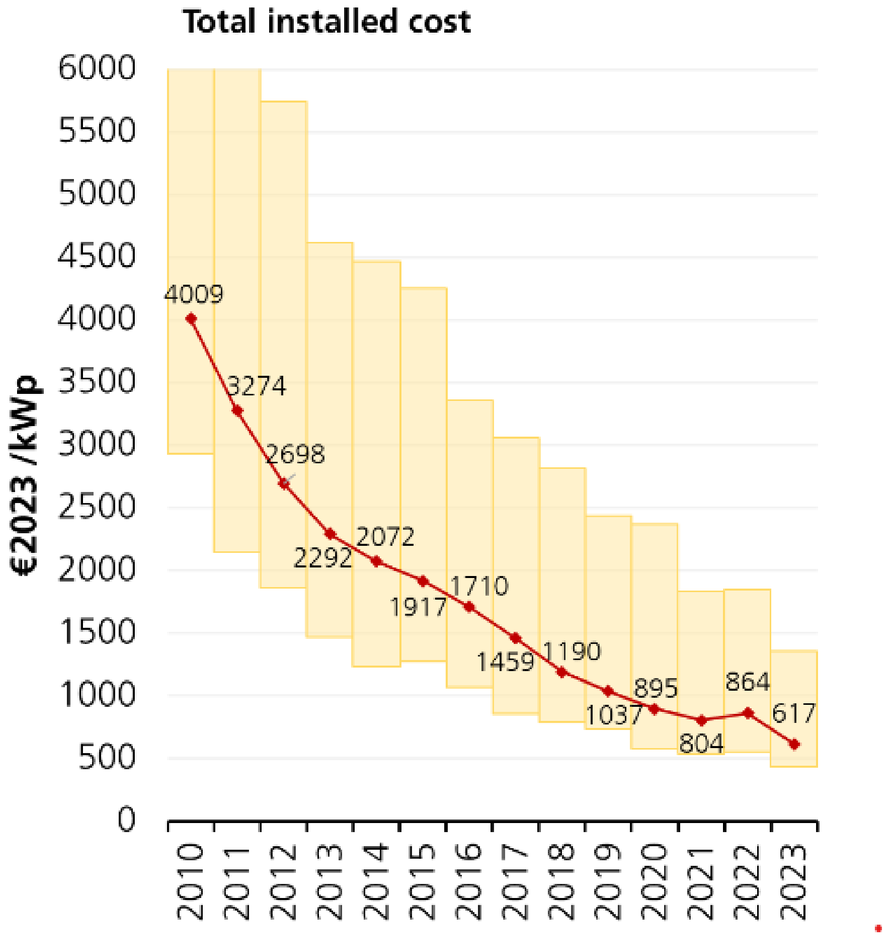
Grid-parity

The **grid-parity** occurs when the price of electricity for the end consumer is lower than the generation cost from PV (4–14 cent/kWh)



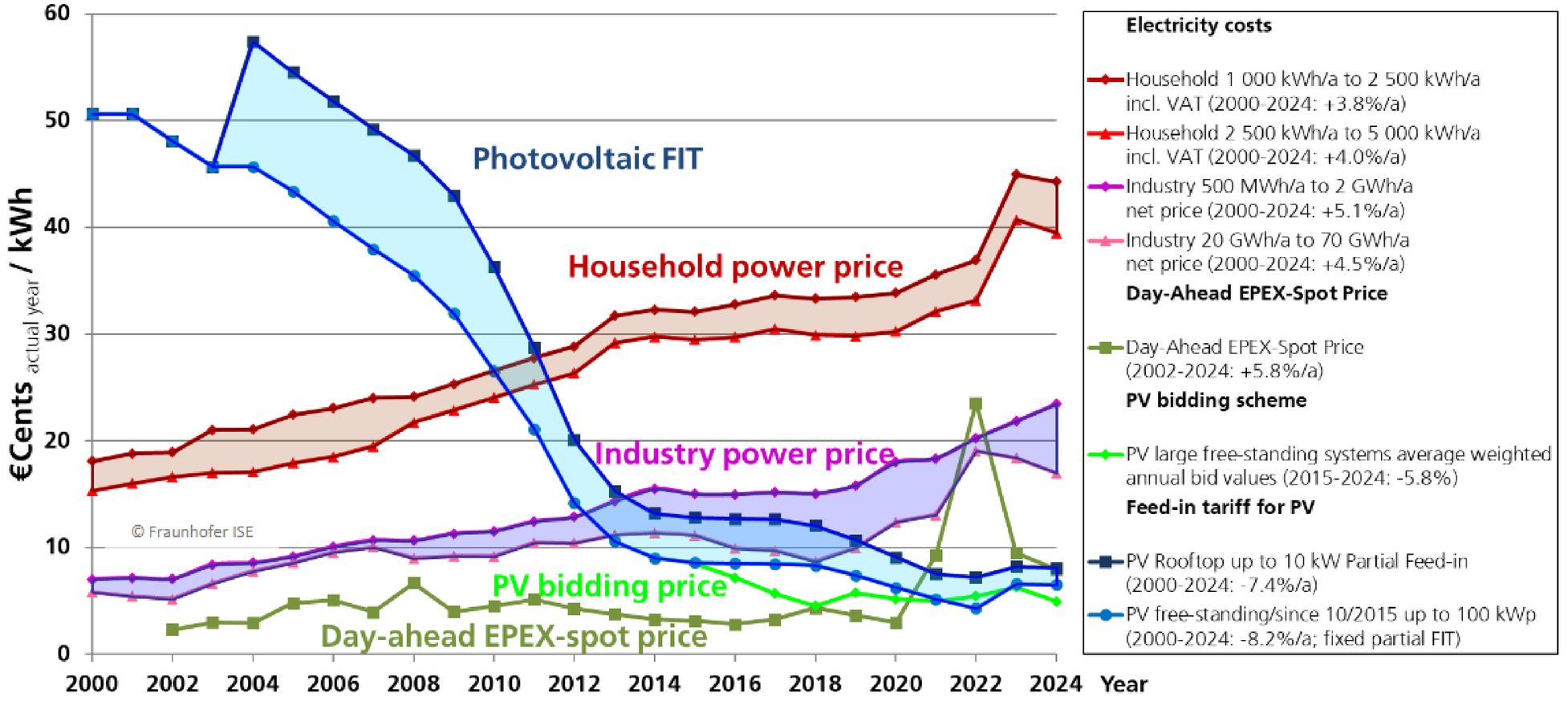
Global LCOE and cost for large PV systems





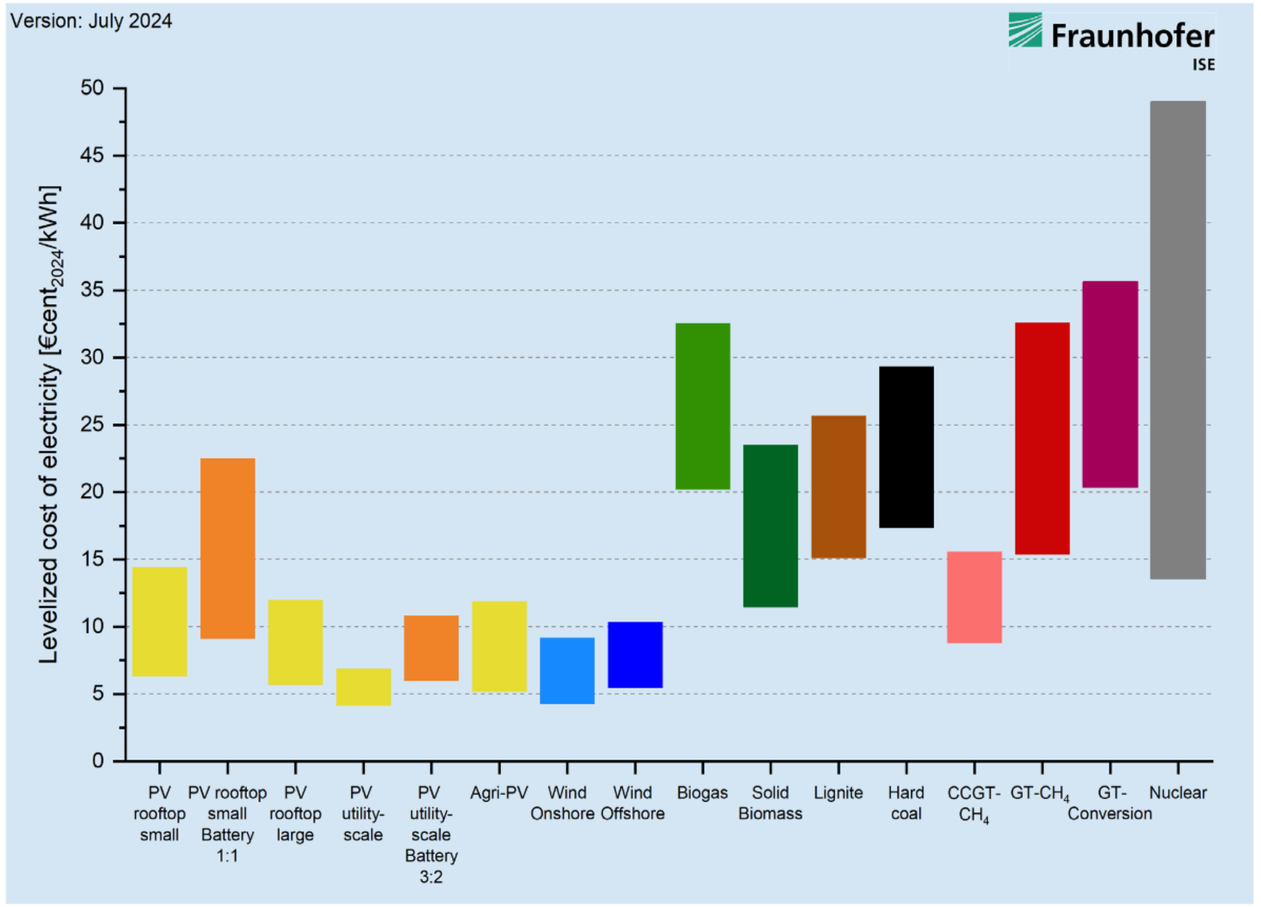
Evolution of LCOE and electricity price

Fraunhofer ISE



Fuel-parity

The **fuel-parity** occurs when the cost of electricity from PV(2.5-5 cent/kWh) is comparable with the one from conventional technologies

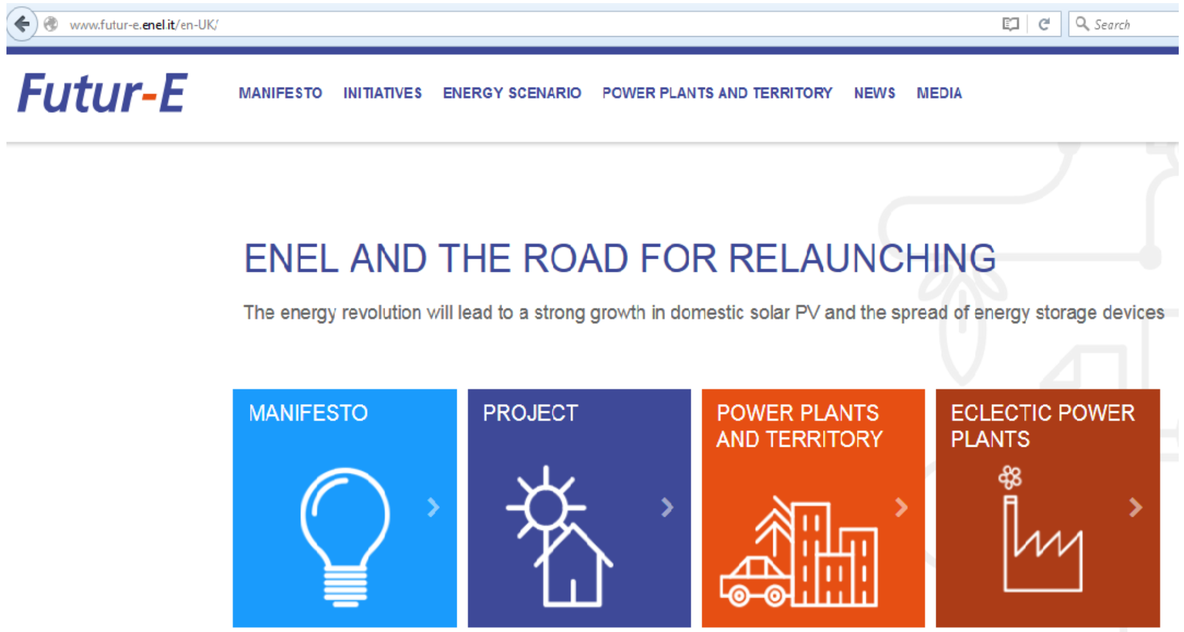


It’s just the beginning: the second clue

COUNTRY	INSTALLED POWER* [GW]	POPULATION* [MILIONI]	POWER PER CAPITA	GROWTH [%]
GERMANY	106	84	1273	16.5 (20.8)
ITALY	41	59	699	16.2 (20.7)
JAPAN	92	123	747	2.9 (2.9)
EU - 27	365	451	809	18.3 (24)
USA	210	342	615	19.3 (27.2)
CHINA	1200	1407	853	35.5 (45.4)
INDIA	135	1464	92	37.7 (35.0)

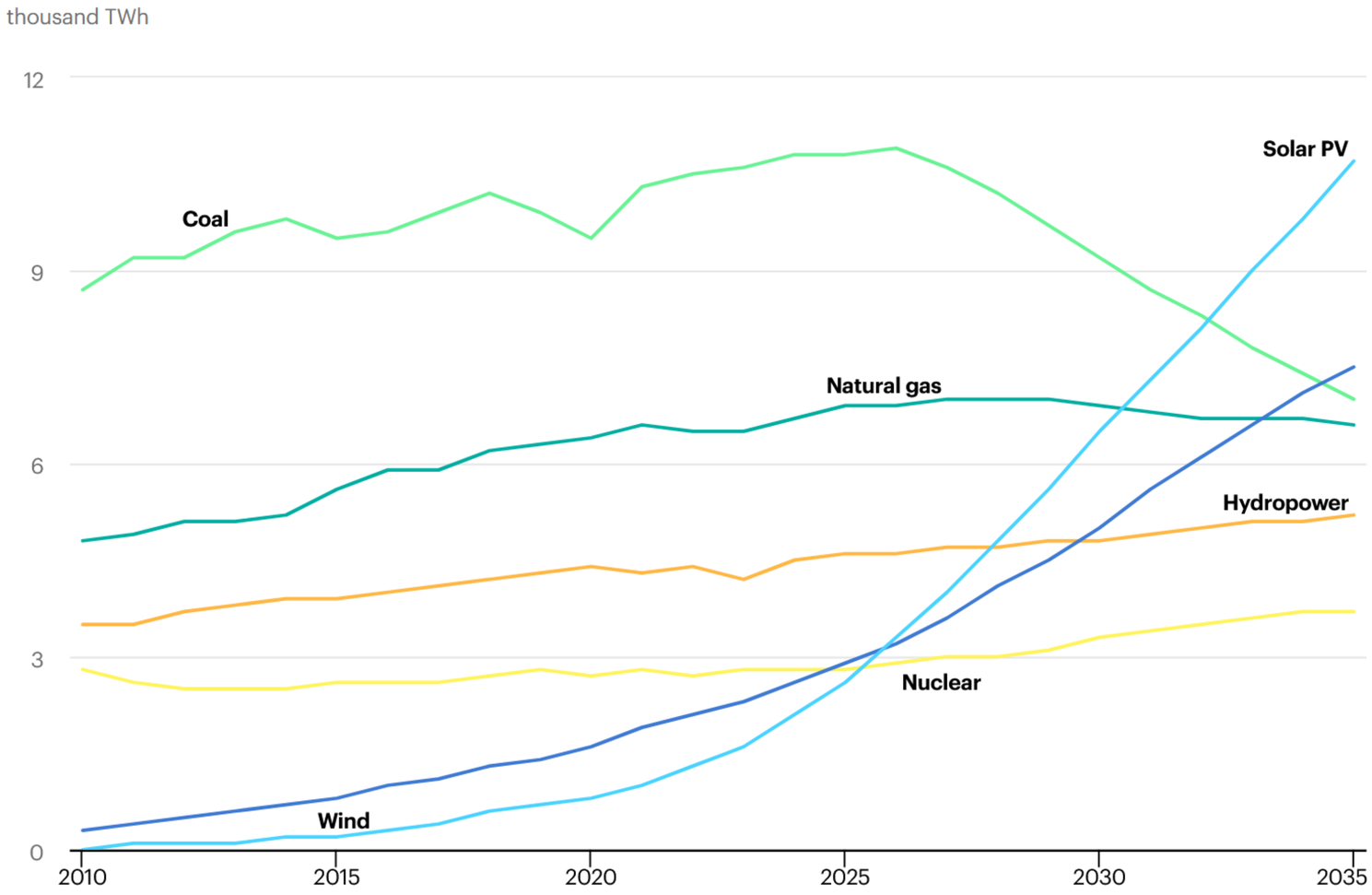
*2025

It’s just the beginning: the third clue





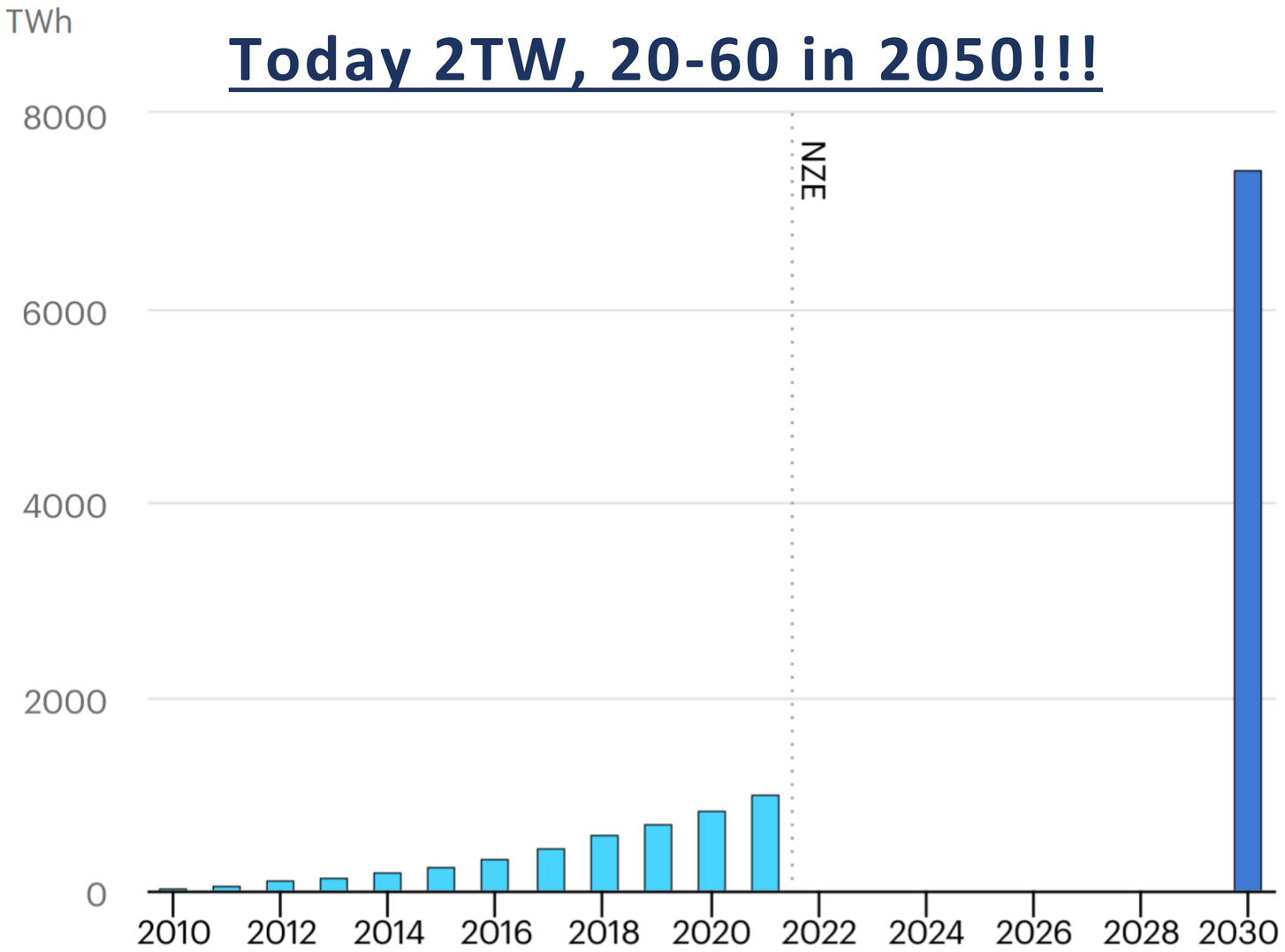
Photovoltaics, the first global power source





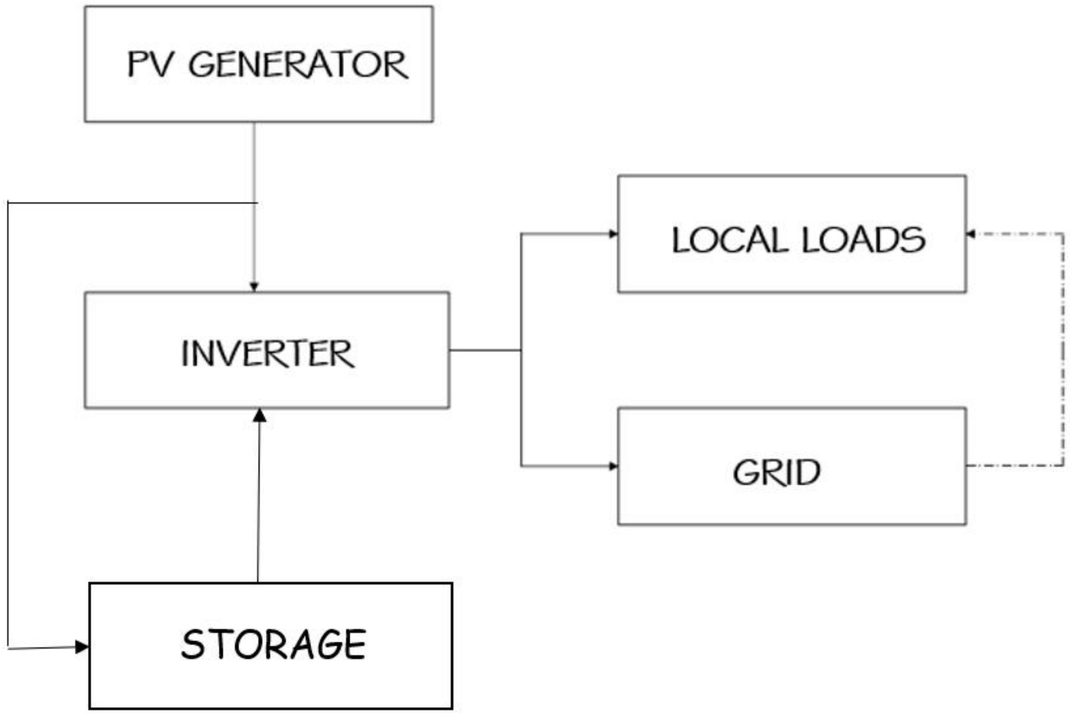


There’s a lot of road to cover



Grid-connected photovoltaic systems

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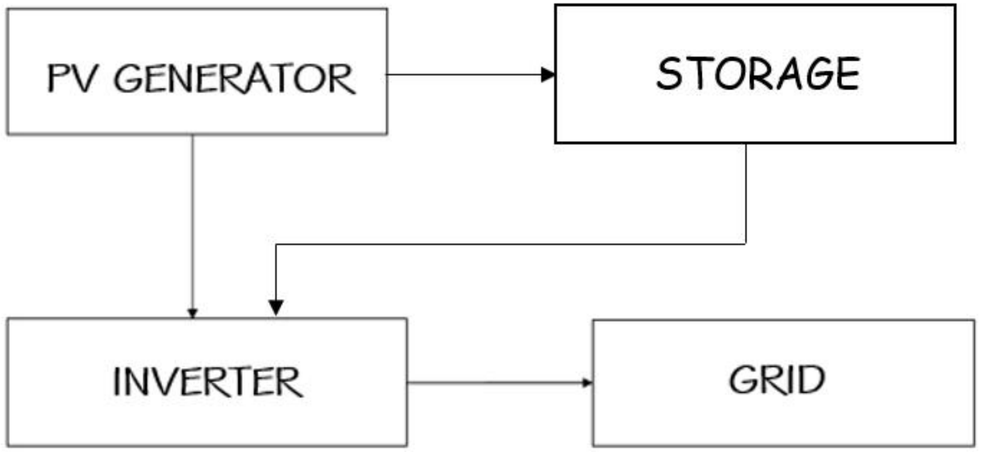




Grid-connected photovoltaic systems

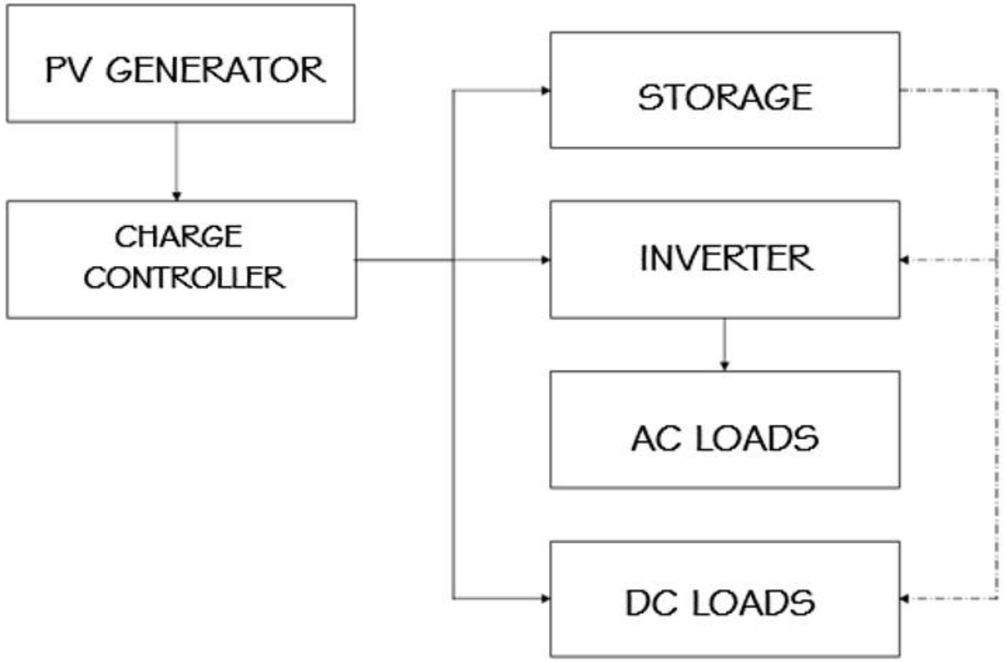
CENTRALIZED





Off-grid photovoltaic systems

RESIDENTIAL

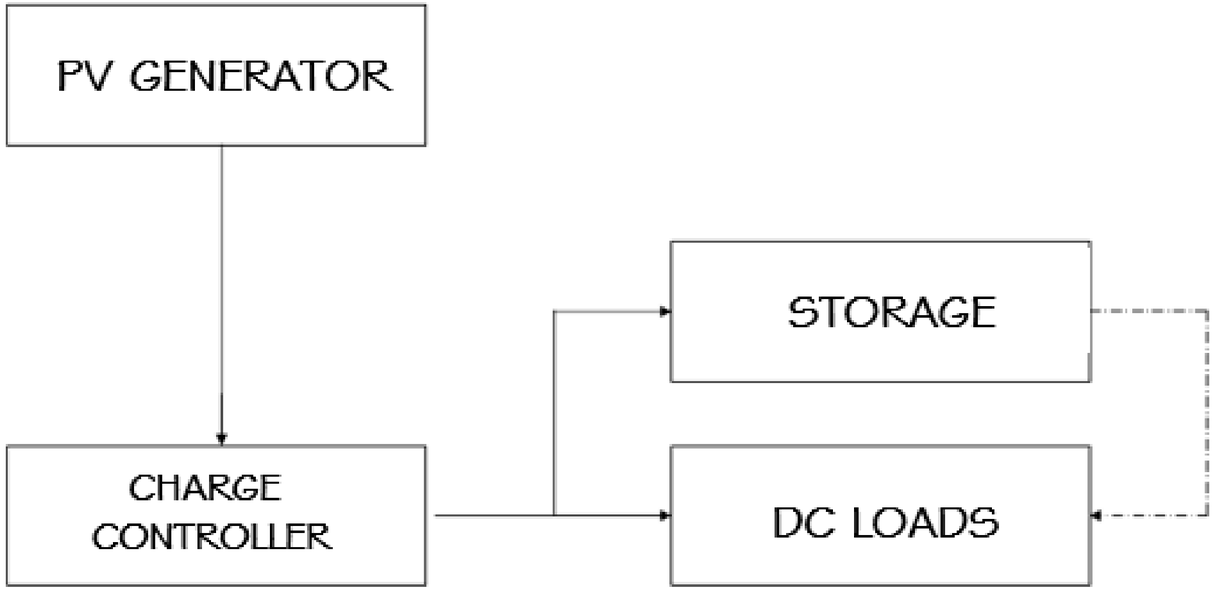




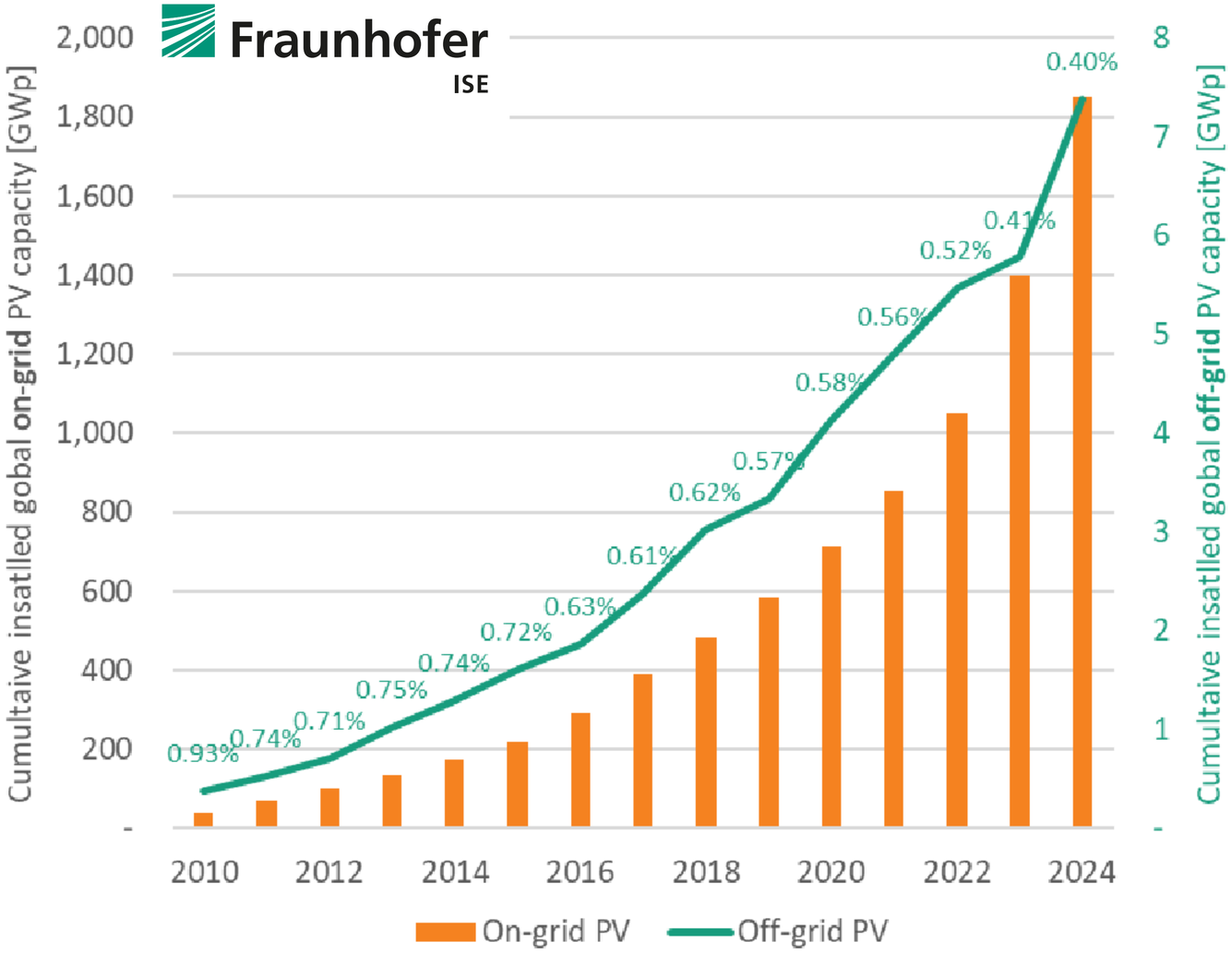
Off-grid photovoltaic systems

INDUSTRIAL





Off-grid photovoltaic systems



Standard photovoltaics

Residential



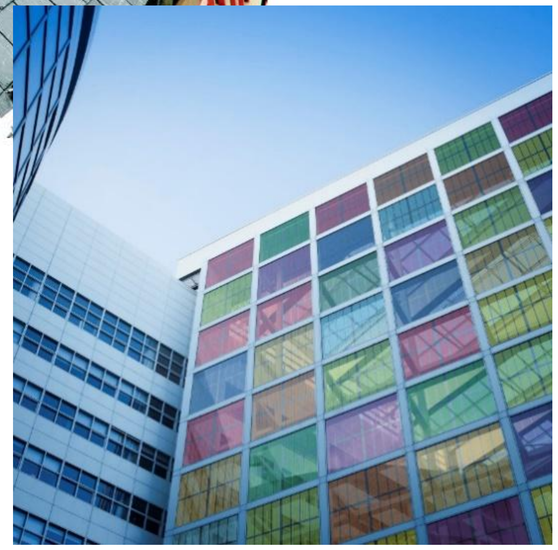
Commercial/industrial

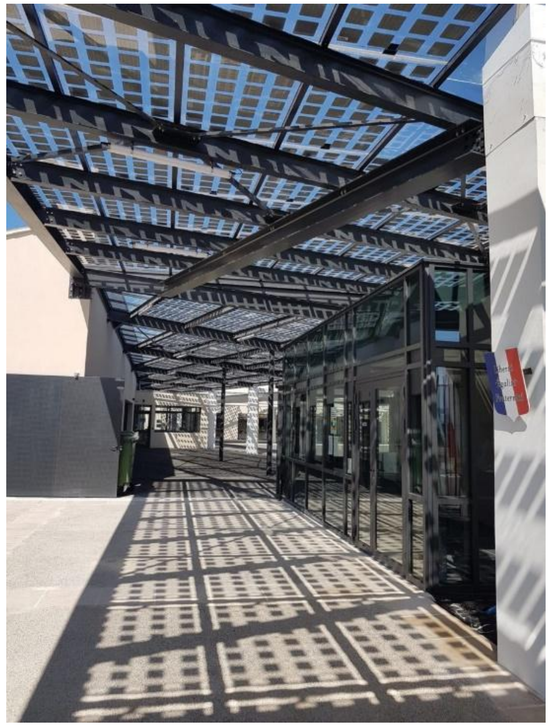


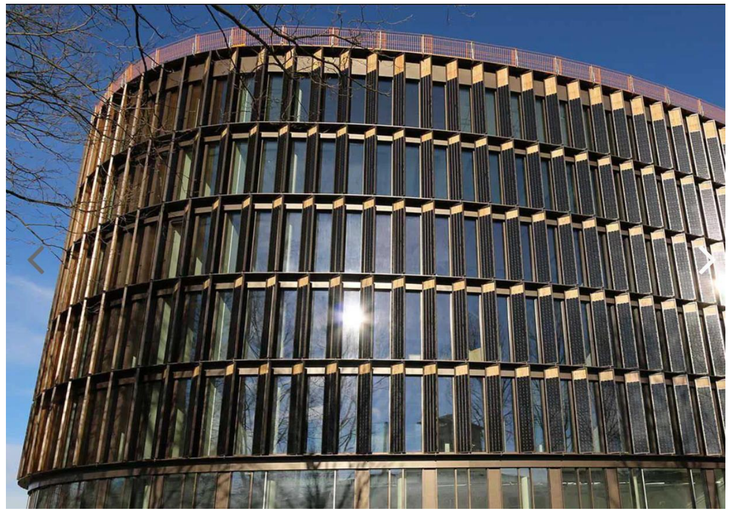


Building Integrated Photovoltaics (BIPV)





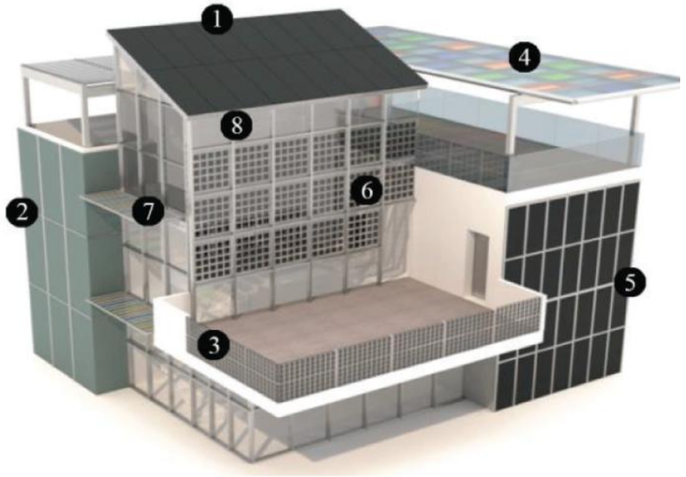




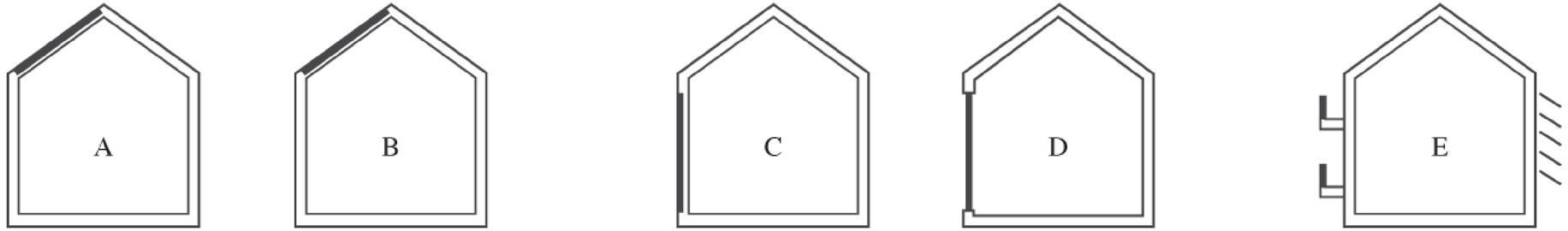


Building Integrated Photovoltaics (BIPV)

BIPV categories		
	Roof	Discontinuous roofing (1)
		Continuous roofing
		Atrim/skylight (4)
	Facade	Rainscreen facace (5)
		Double skin facade
		Curtain walling (2–6)
		Window (8)
		Masonry wall
	External device	Parapet/Balustrade (3)
		Canopy (4)
		Solar shading (7)



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IEC63092 standard

Black Asphalt





Grey Asphalt

Black slate





Brown Asphalt

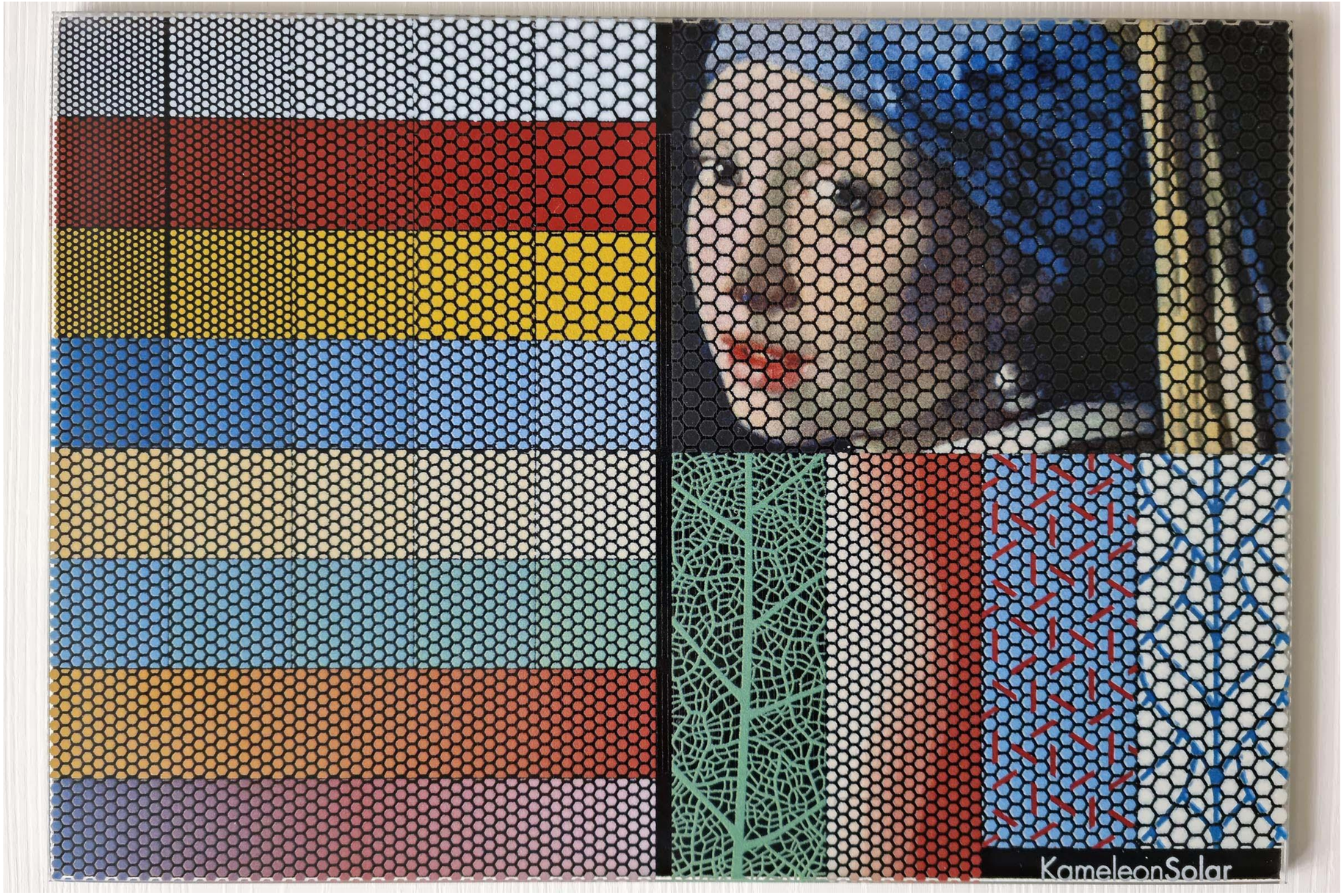
Spanish Clay



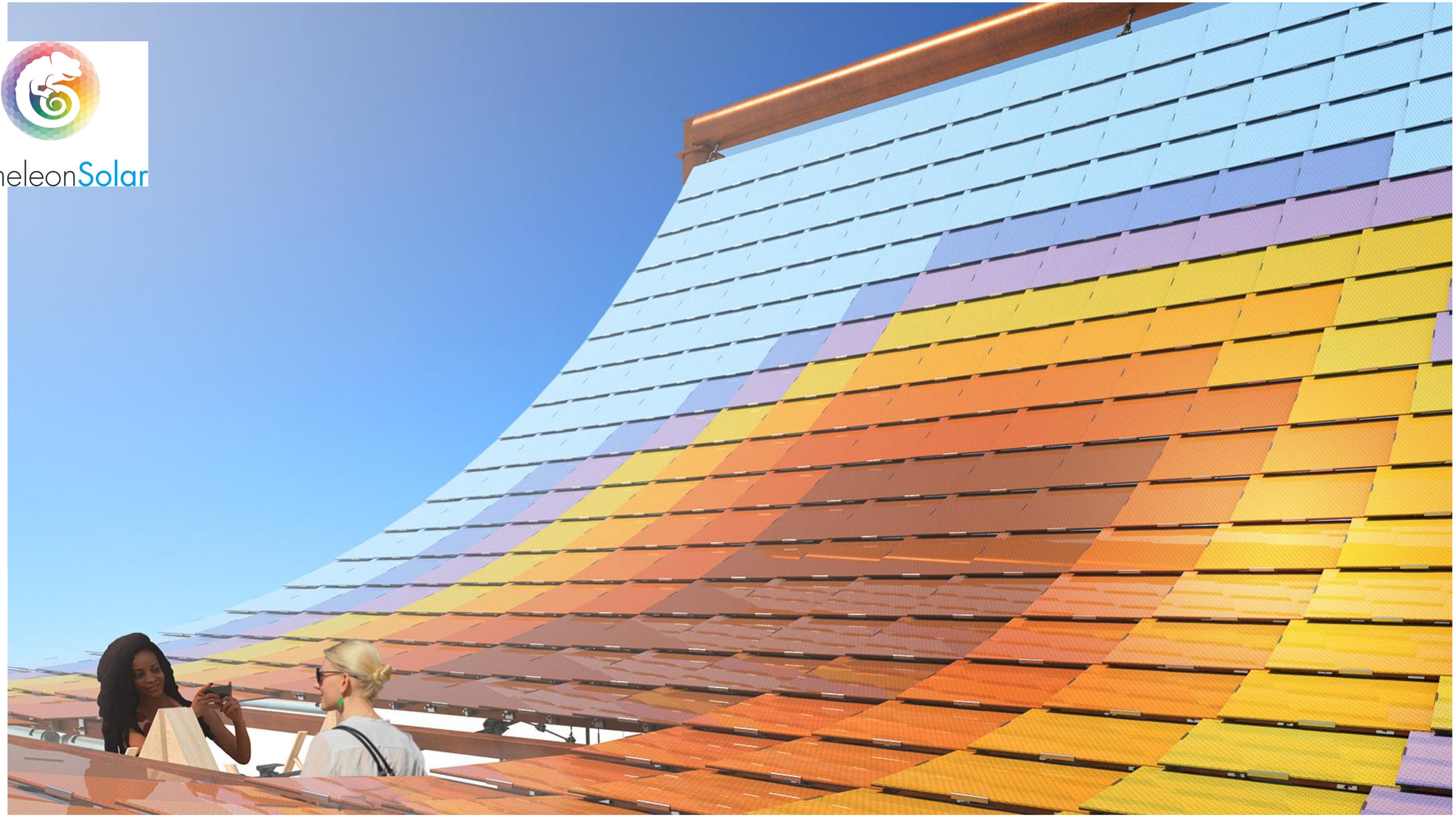
MITREX

MITREX™




KameleonSolar

KameleonSolar




SolaRail™
Electrifying skylines with solar railings


Solar Panel & Roof

Standard photovoltaics

Utility-scale





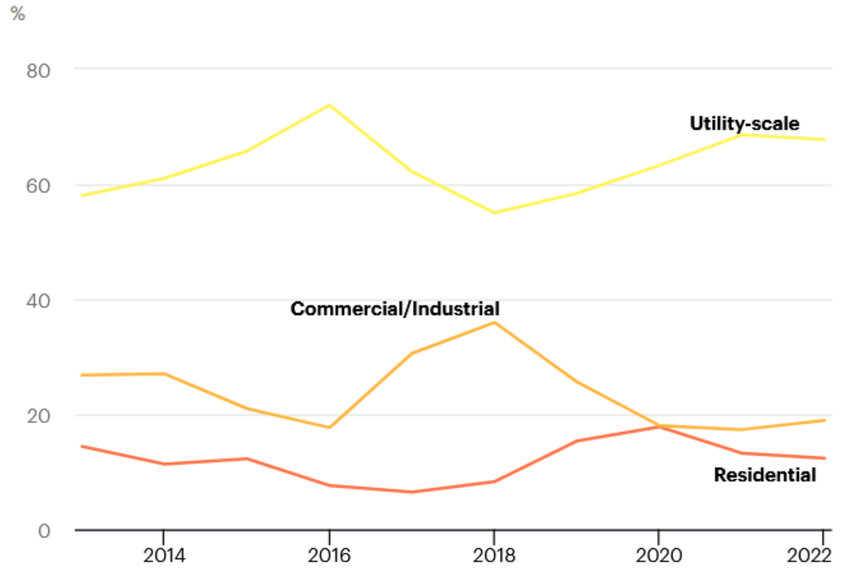
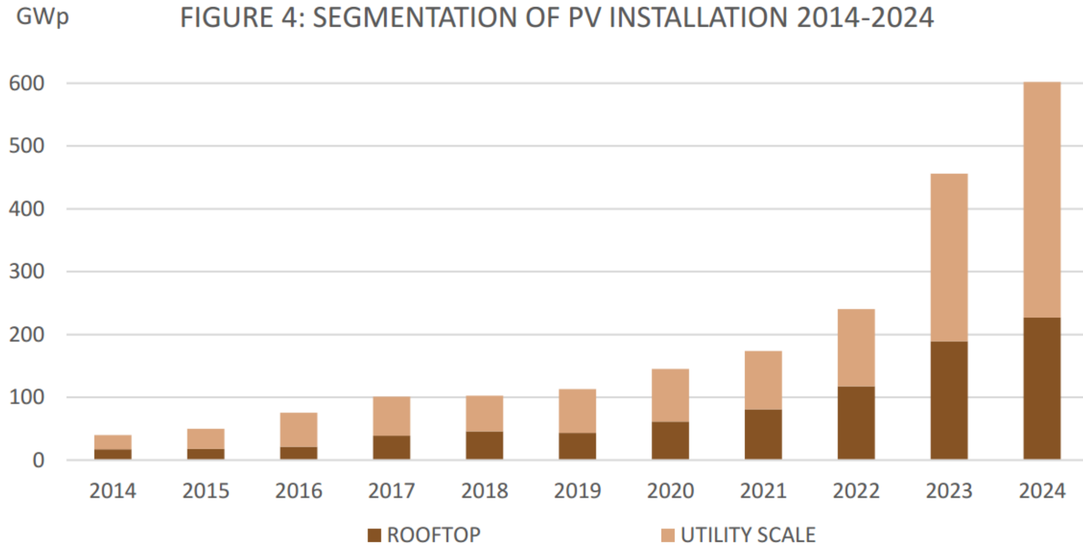


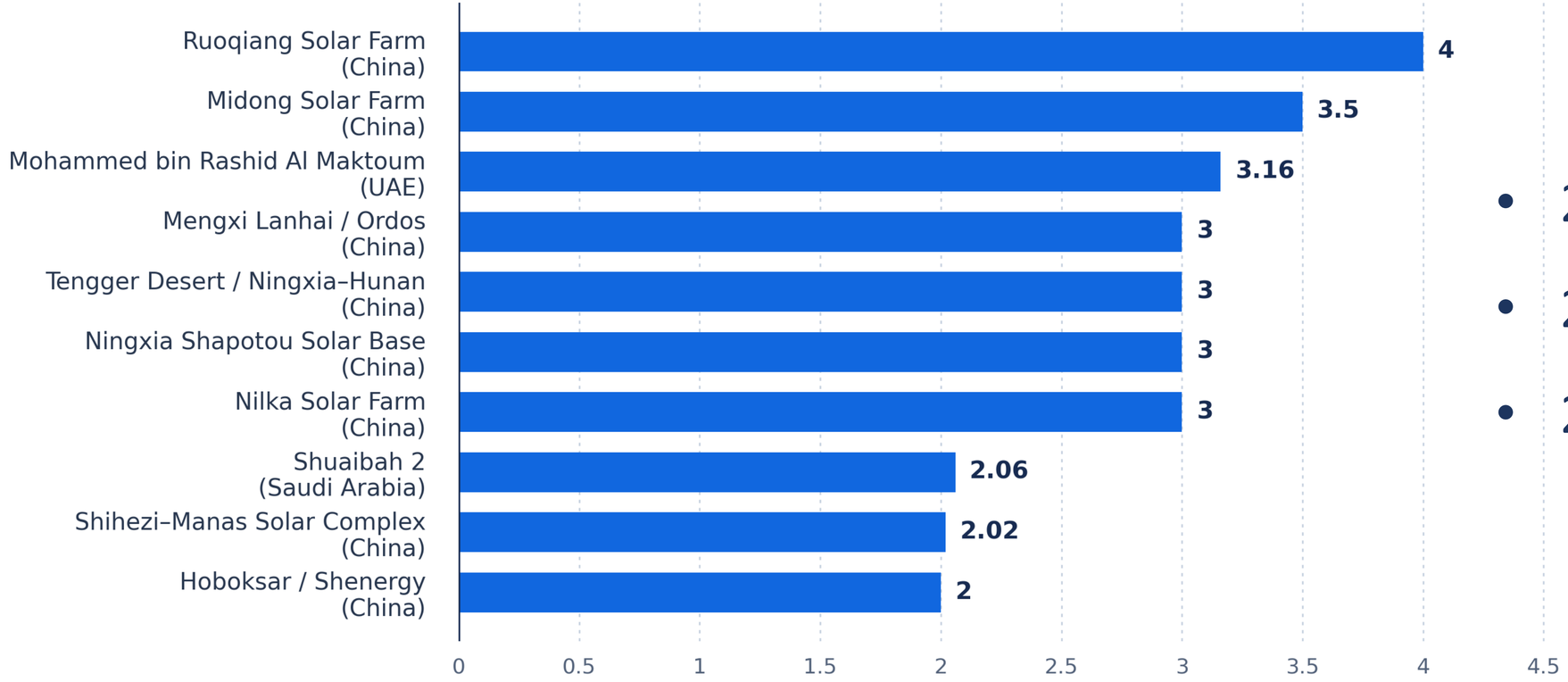
FIGURE 4: SEGMENTATION OF PV INSTALLATION 2014-2024



Ground-mounted pv systems

WORLD'S LARGEST OPERATING SOLAR PV PLANTS

Installed photovoltaic capacity at 31 December 2025 · GW



- 2000 – 0.02MW
- 2008 – 1MW
- 2018 – 1,365MW

Witznitz Energy Park, Germany

The 650MW Witznitz Energy Park in Germany commenced operations in July 2024.



C&I rooftop pv systems

LARGEST SINGLE-ROOF PV INSTALLATIONS

Selected VERIFIED projects | Operational by 31 December 2025

POWER	LOCATION	DESCRIPTION	ON GRID
34.5 MWp	DENMARK · Horsens	DSV · integrated logistics building	2025
25.0 MWp	BELGIUM · Ghent	WDP Big Box · 8 units, one continuous roof	2023
18.0 MWp	NETHERLANDS · Venlo	Heylen Energy · VE-Commerce logistics roof	2020
16.82 MWp	GHANA · Tema	Helios Solar · IWC Mega Warehouse	2024
12.0 MWp	GERMANY · Marl	Goodman / METRO · single 12-MWp roof	2023–24
12.0 MWp	INDIA · Angul	Jindal Steel · plate mill (one tin roof)	2024
10.27 MWp	GERMANY · Magdeburg	VGP Park Sülzetal · Building C	2024

Strict criterion: ONE BUILDING / ONE ROOF per row (multiple sections of the SAME building are allowed).

Excludes multi-building parks (e.g. Jining 120 MWp / 43 roofs, LaiYih 38 MWp, Rotterdam Maasvlakte 25 MWp).

Sources: SolarFuture; WDP (2023 interim report); Heylen/Encon; Helios/3E; Goodman/BayWa; Jindal/Saatvik; VGP.

Selected, source-verified examples — NOT an exhaustive global ranking. Power values are DC nameplate (MWp).

2025

Photovoltaic carports



ZERO POINT ENERGY



Photovoltaic charging stations



Photovoltaic noise barriers



Agrivoltaics





Fraunhofer ISE

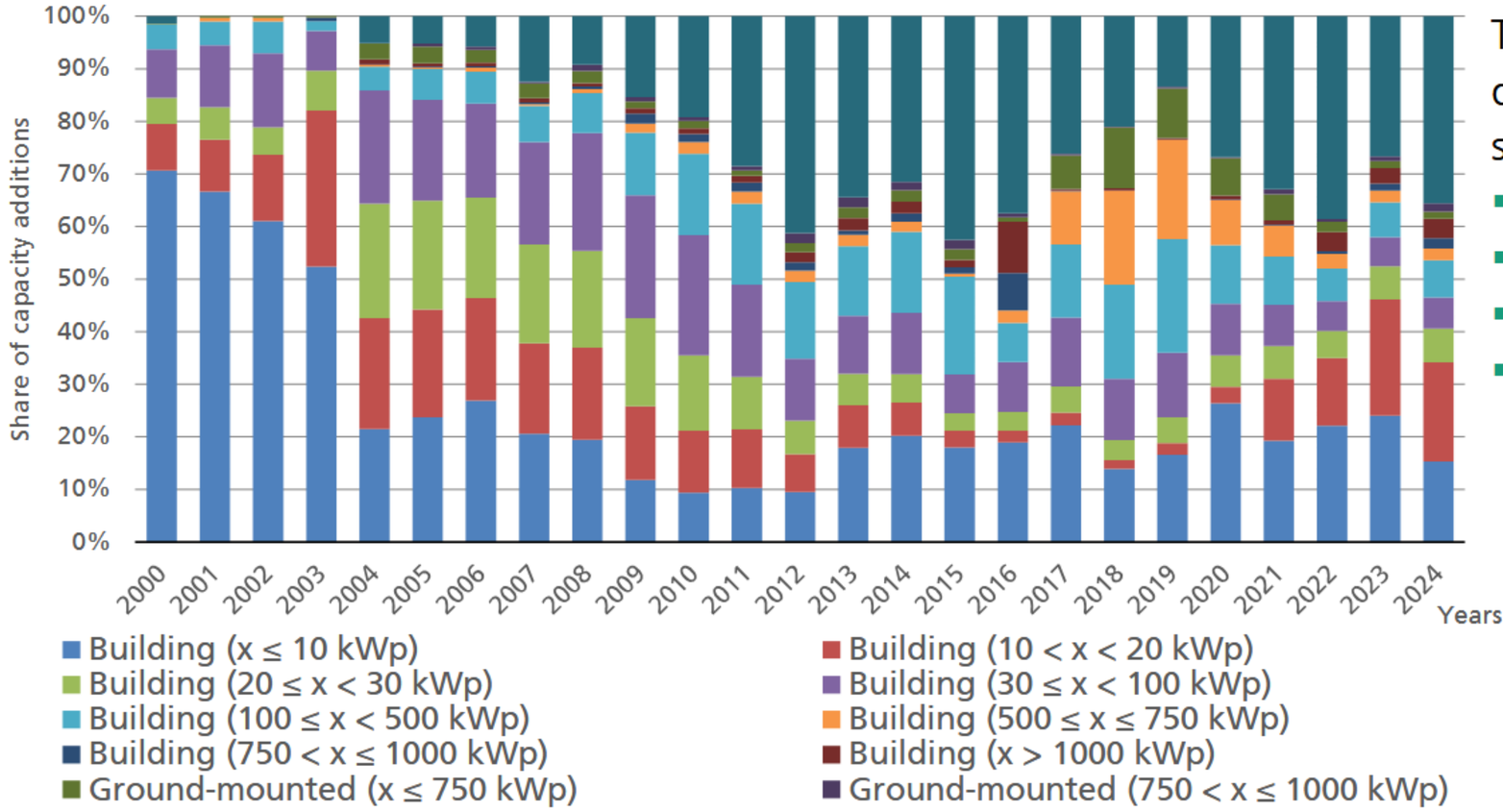
Floating photovoltaics





Shares of PV additions by application in Germany

Fraunhofer ISE



The annual distribution of the different system size categories strongly depends on current:

- regulations
- market incentives (like EEG)
- tender procedures
- bankability (trust of investors)

Note:

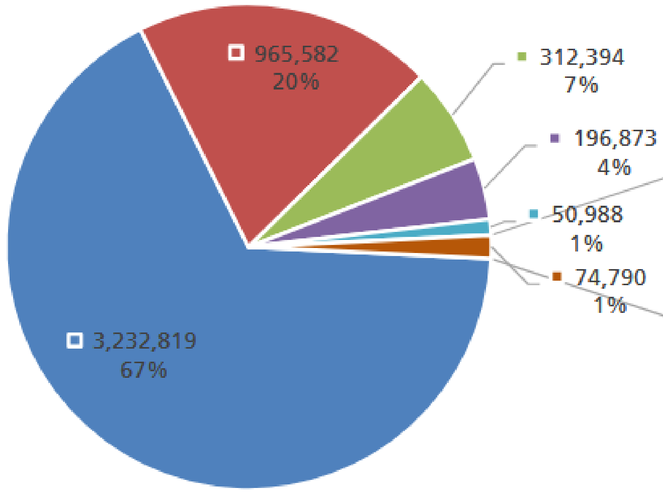
"Building" includes roofs, facades and plug-in systems.

"Ground-mounted" includes bodies of water, parking lots and other structures.

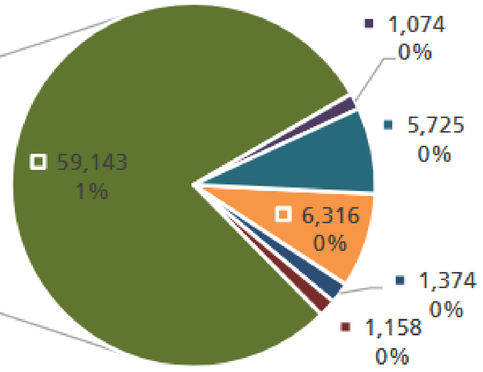
Shares of PV additions by application in Germany

Fraunhofer ISE

Total Installations and Share of Grid-Connected PV Systems



Total Installations and Share of PV Systems > 500 kWp



- Building (x ≤ 10 kWp)
- Building (10 < x < 20 kWp)
- Building (20 ≤ x < 30 kWp)
- Building (30 ≤ x < 100 kWp)
- Building (100 ≤ x < 500 kWp)
- Building (500 ≤ x ≤ 750 kWp)
- Building (750 < x ≤ 1000 kWp)
- Building (x > 1000 kWp)
- Ground-mounted (x ≤ 750 kWp)
- Ground-mounted (750 < x ≤ 1000 kWp)
- Ground-mounted (x > 1000 kWp)

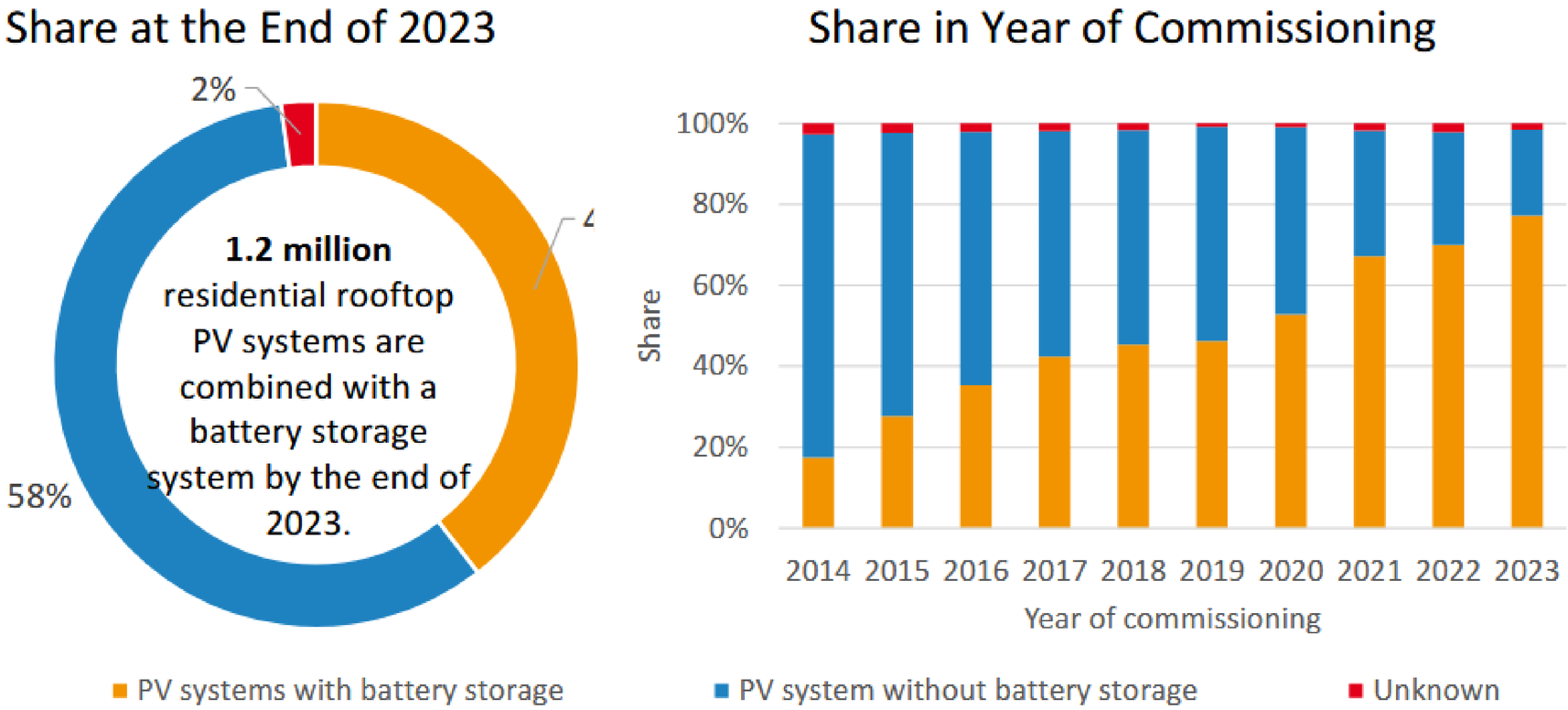
At the end of 2024, about 4.8 million grid-connected PV systems were installed in Germany.

Note:
In 2024, around 800,000 plug-in systems (up to 800 W feed-in power from so-called balcony PV systems), were registered in Germany.
Due to underreporting, the actual number is estimated to be around 3 million installed systems. [1]

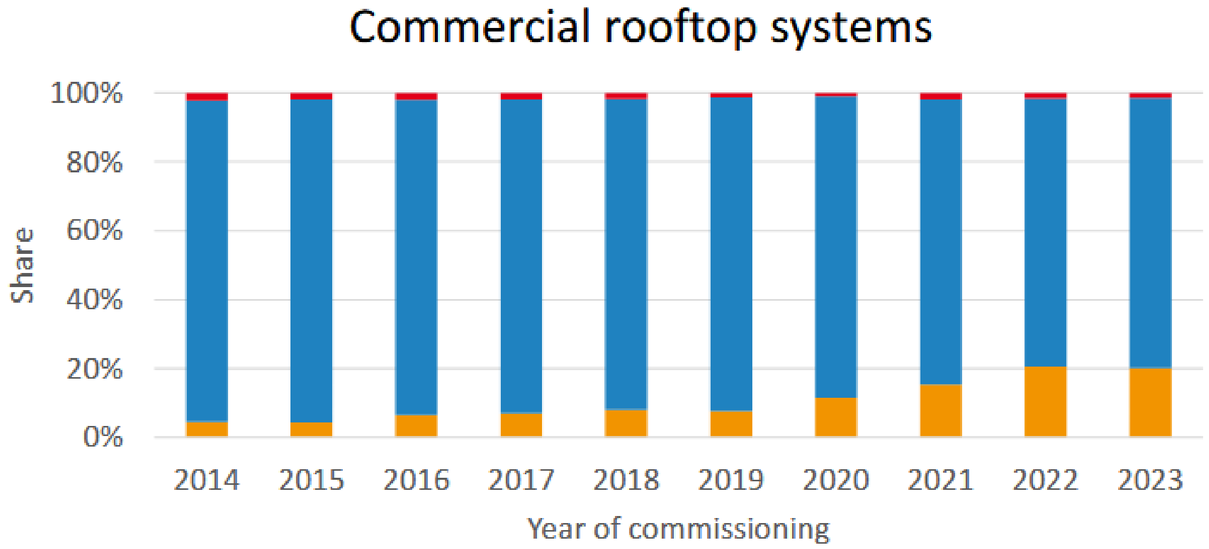
© Fraunhofer ISE

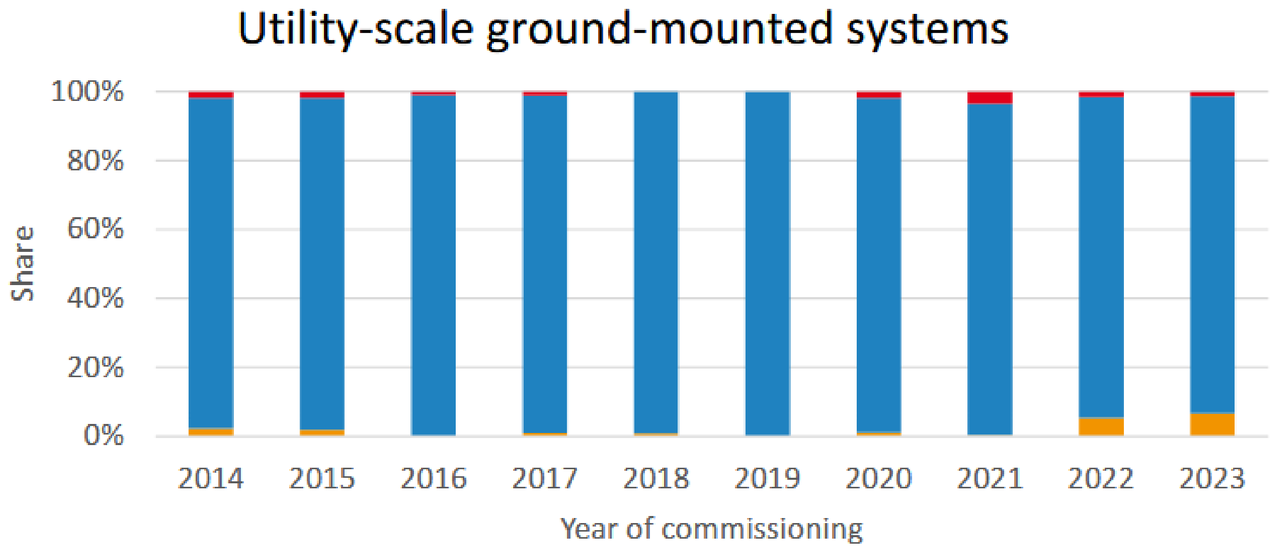
Shares of residential PV with and without storage in Germany

Fraunhofer ISE



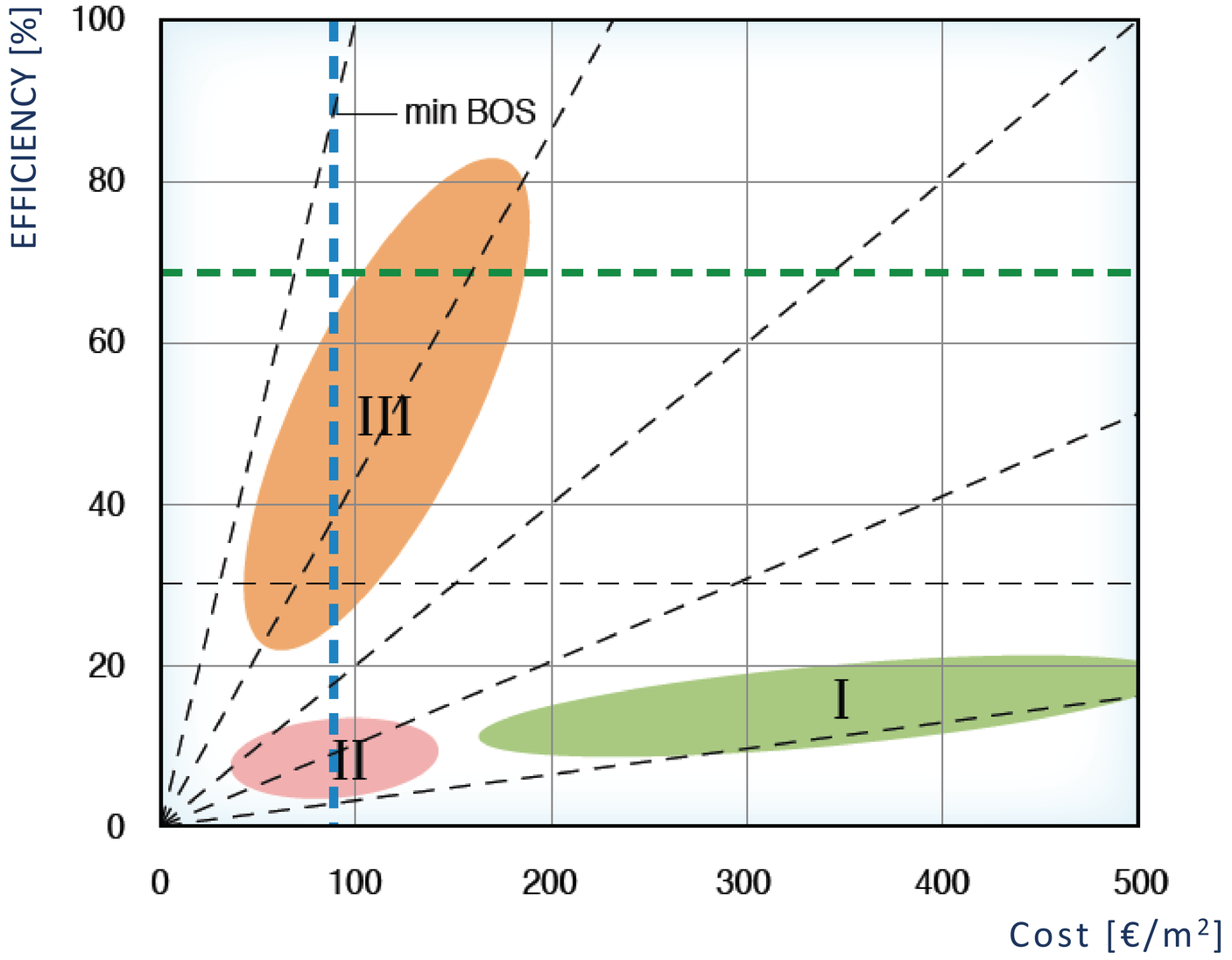
Shares of C&I and Utility-scale PV with storage in Germany





Fraunhofer ISE

Generations of photovoltaic modules



Efficiencies and power of commercial PV modules

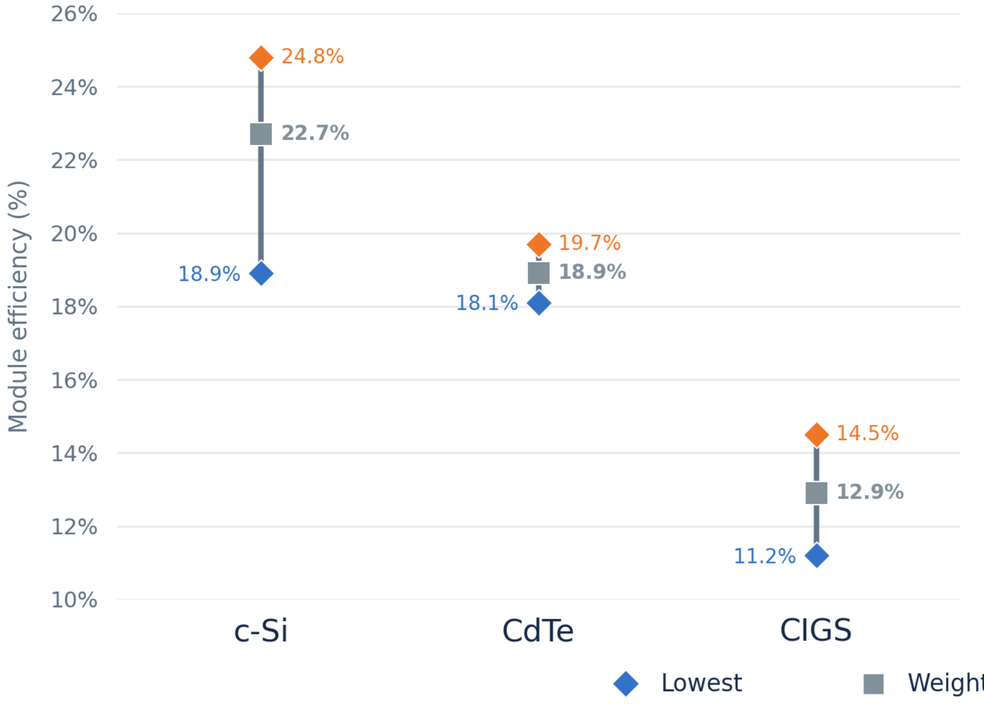
COMMERCIAL PV MODULES

Efficiency and nominal power by technology

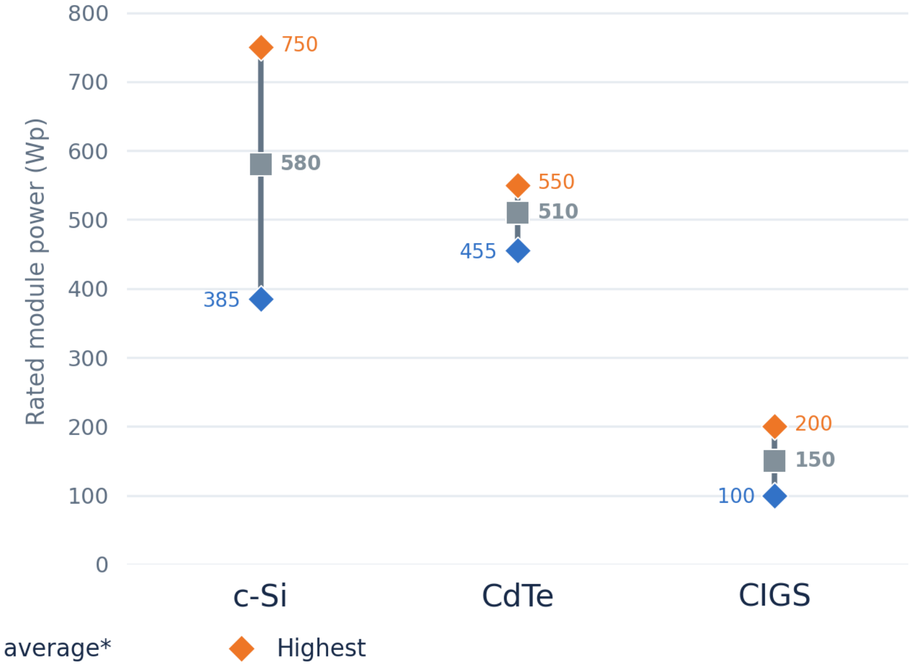
DATA: SEPTEMBER 2025

Fraunhofer ISE report · July 2026

EFFICIENCY



NOMINAL POWER



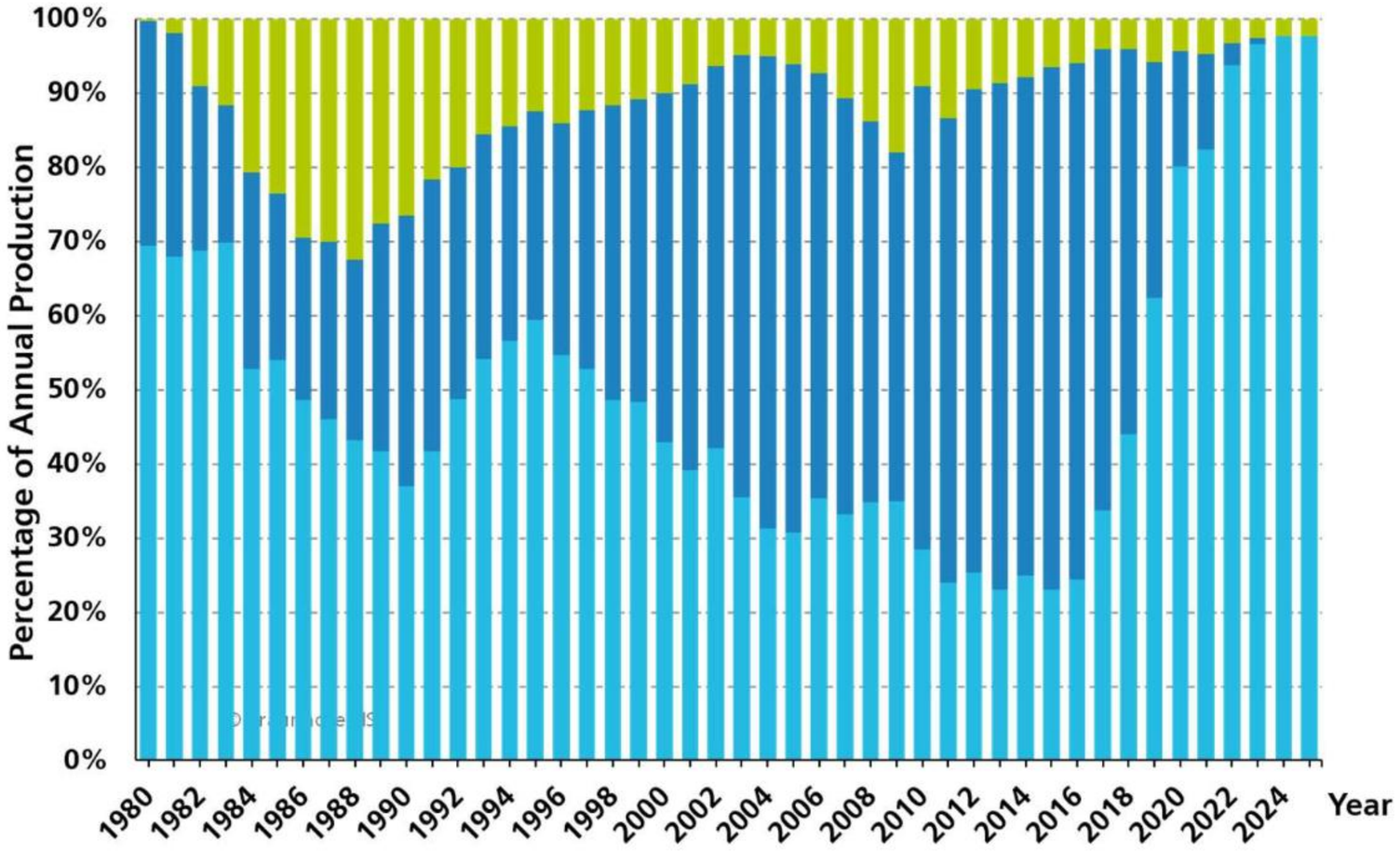
Lowest · Weighted average* · Highest

Source: Fraunhofer ISE, Photovoltaics Report (14 July 2026), p. 33; manufacturer datasheets (09/2025).

*Approximate points read from Fraunhofer chart; c-Si average 22.7% stated in report (weighted by 2024 shipments).

Selection: top-10 c-Si manufacturers; CdTe: First Solar; CIGS: Avancis. Module wattage also depends on module area.

Global PV production by technology



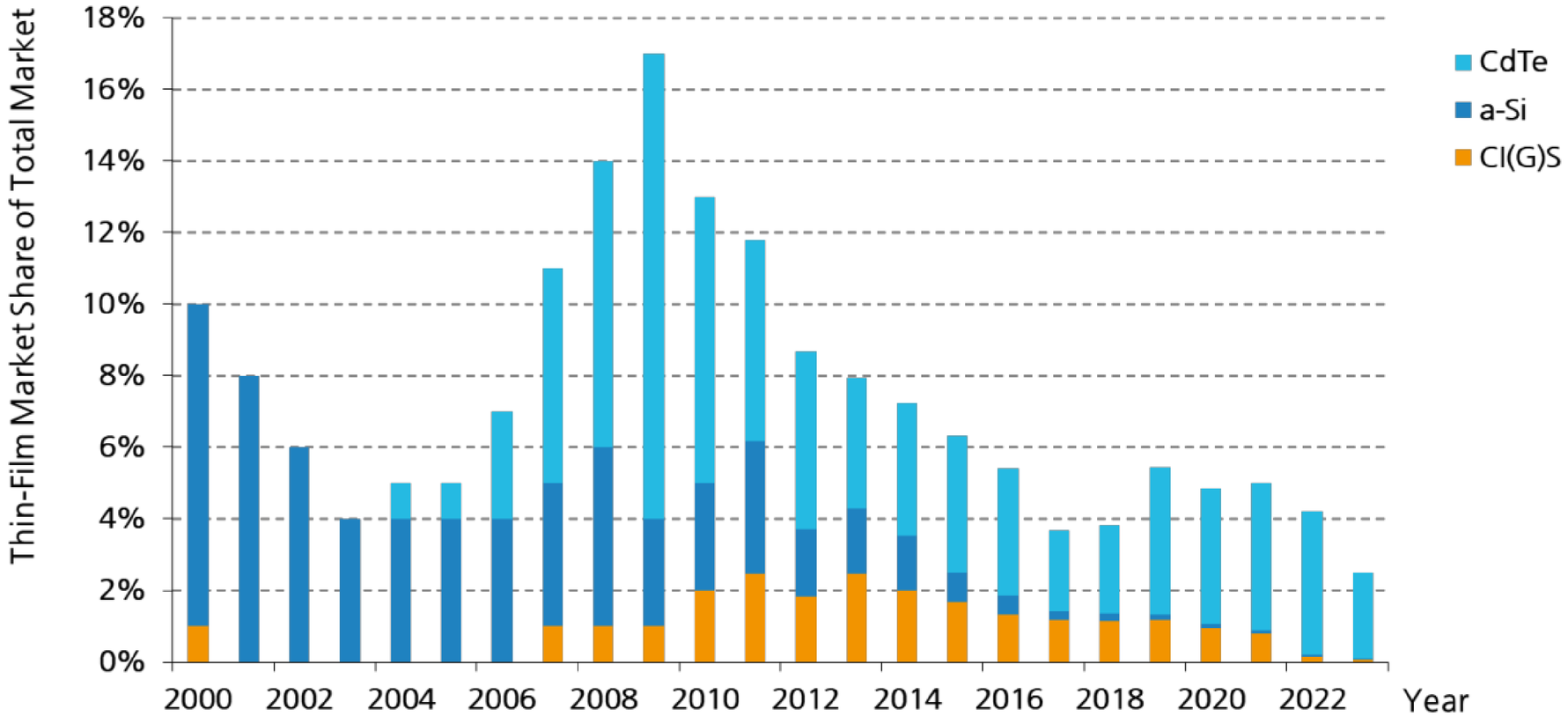
Production 2025 (GWp)

Thin film*	16	
Multi-Si	0	
Mono-Si	690	
Total	706	(ITRPV)

*only First Solar is considered when calculating the thin film technology.

Fraunhofer ISE

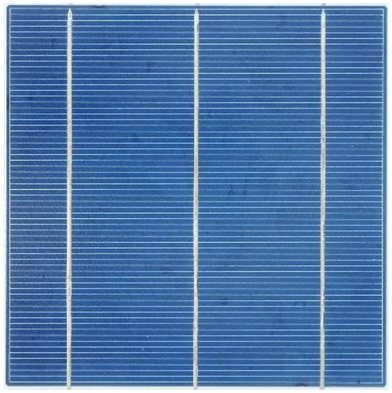
Thin film photovoltaic modules

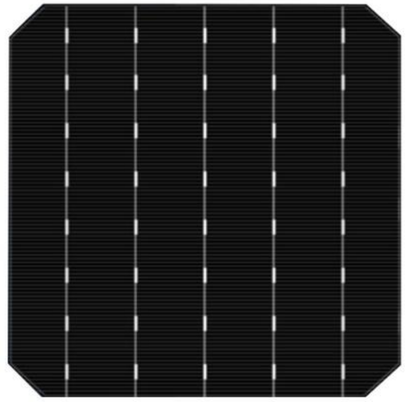


Thin-Film technology contributed in year 2023 with about 2.5% to the total PV-market.

First generation

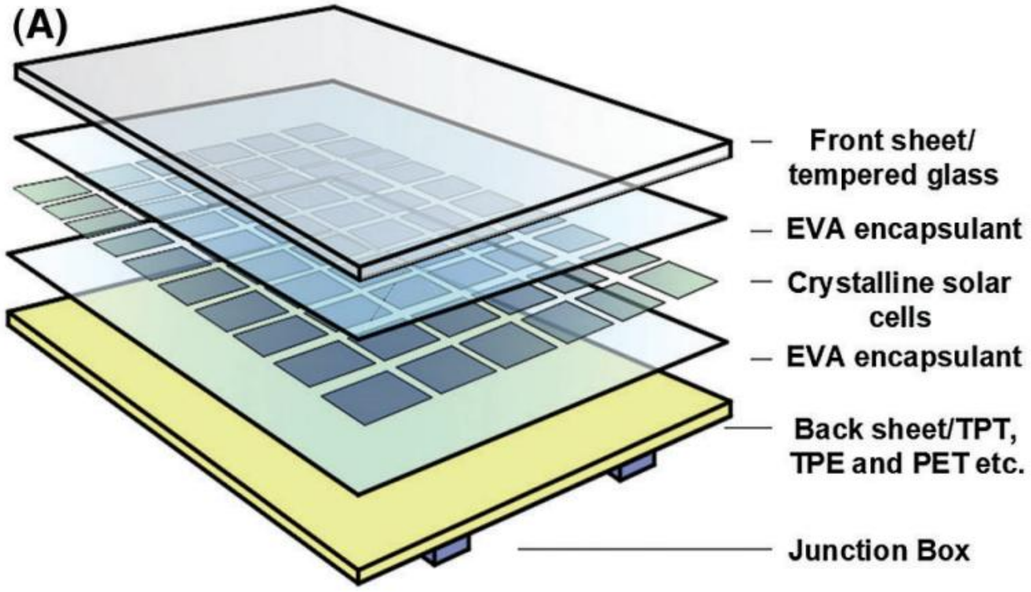
Poly - Si



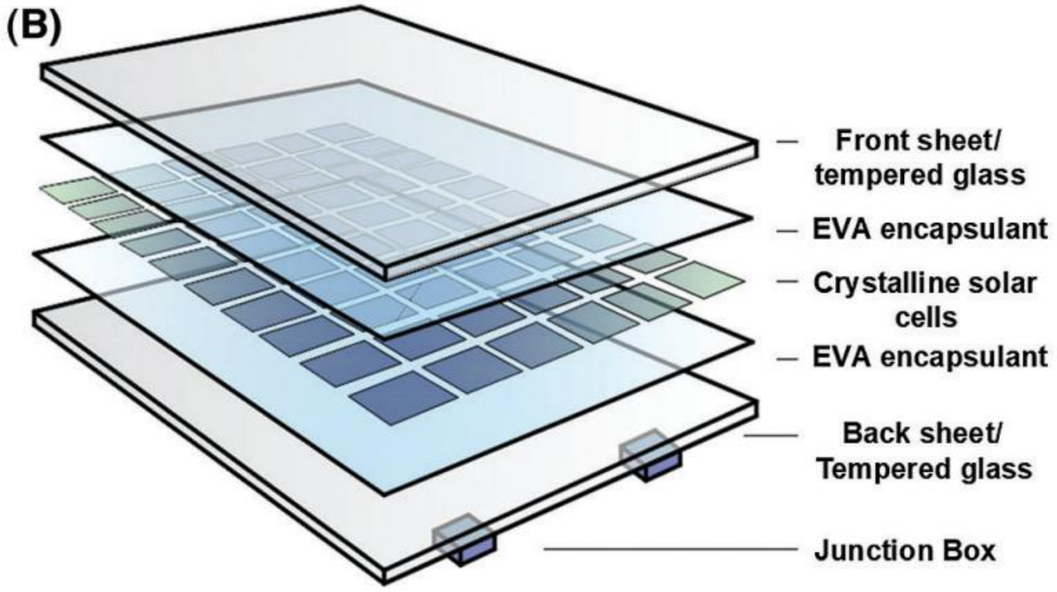


Mono - Si

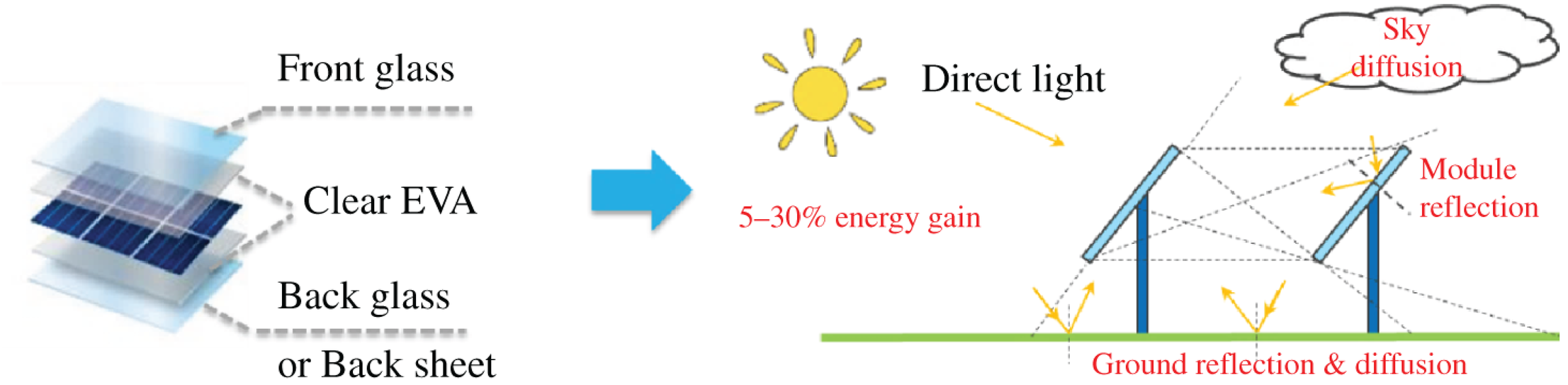
Single-glass photovoltaic modules



Double-glazed photovoltaic modules

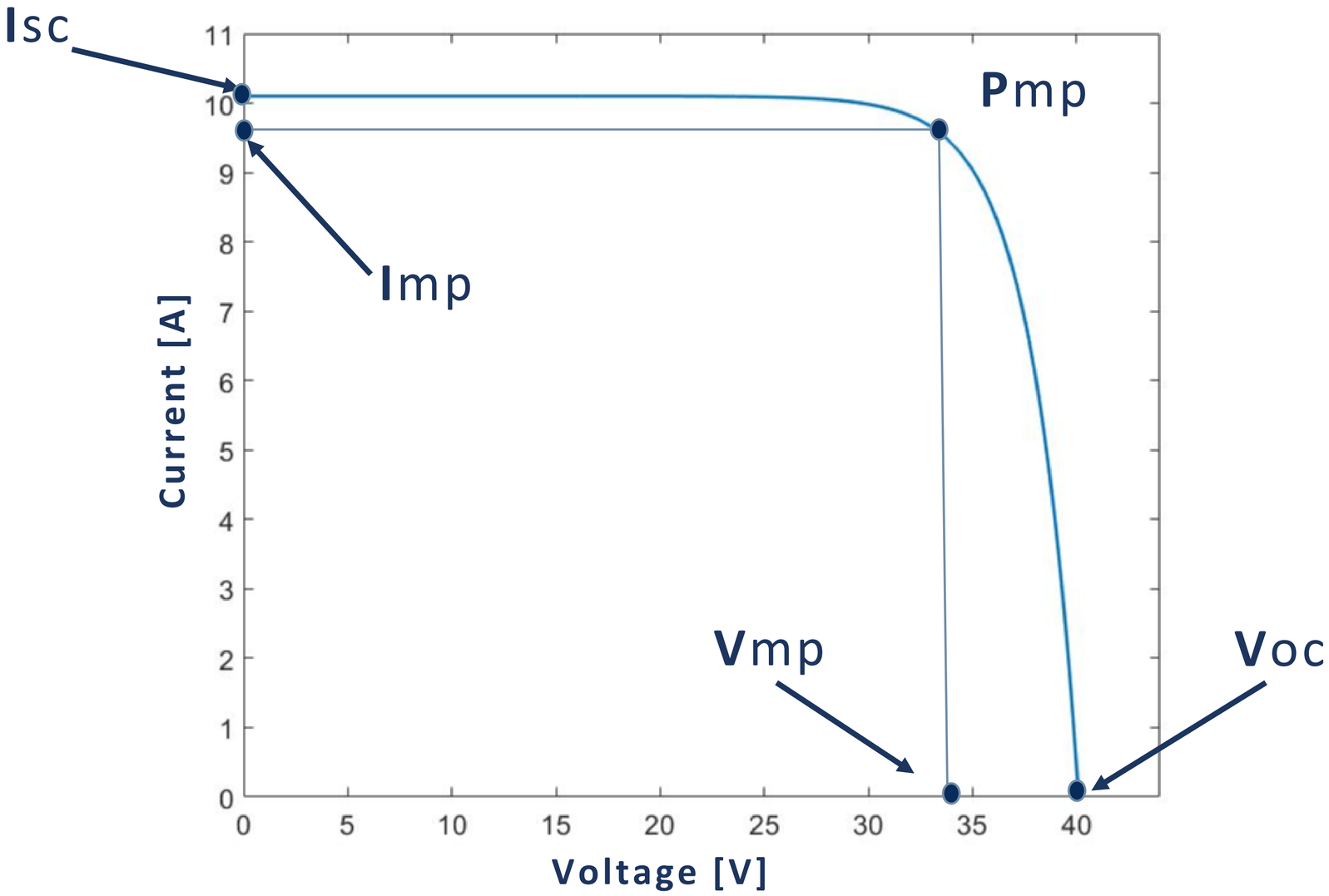


Bifacial modules



Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

Electrical parameters – Current/voltage curve



Electrical parameters

STANDARD TEST CONDITIONS (STC)

Irradiance 1.000 W/m^2 - Cell Temperature 25 °C - Air Mass 1.5

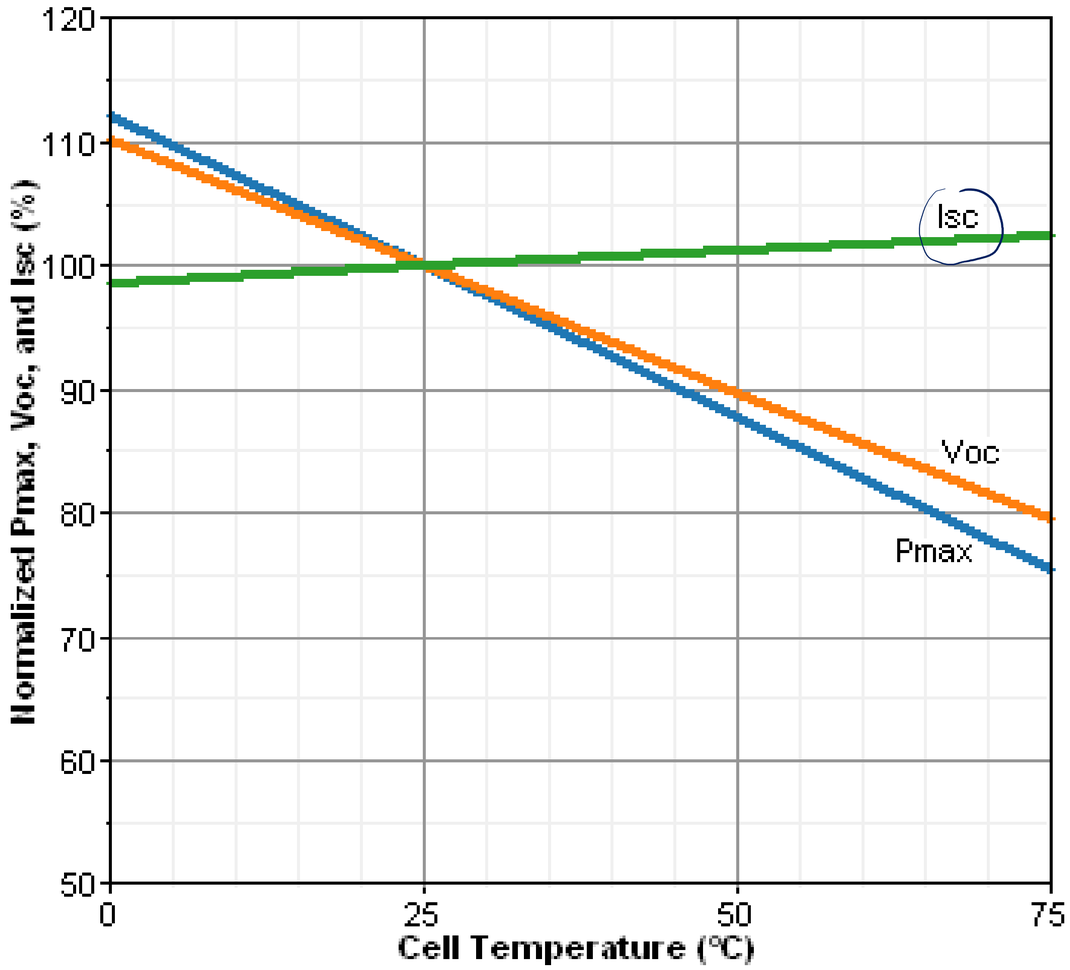
PV MODULE Q.CELLS – Q.PEAK DUO-G5 320	
Nominal Power - P_{mp} [Wp]	320 + [0-5]
Short circuit current - I_{sc} [A]	10,1
Open circuit voltage – V_{oc} [V]	40,1
Current at MPP – I_{mp} [A]	9,6
Voltage at MPP – V_{mp} [V]	33,3
Temperature coefficient of I_{sc} – Z [%/K]	+0.04%/K
Temperature coefficient of V_{oc} – W [%/K]	-0.28%/K
Temperature coefficient of P_{mp} – P [%/K]	-0.37%/K
Cells	m-Si
Size [mm*mm]	1685*1000
Degradation rate [%/year]	0.54
Nominal Operating Cell Temperature – T_{NOCT} [°C]	43±3

$$\eta_{STC} = \frac{P_{MP}}{1000 \times A}$$

$$A_{1kWp} = \frac{1}{\eta_{STC}}$$

$$FF_{STC} = \frac{P_{MP}}{I_{SC} \times V_{OC}}$$

Temperature dependence



Electrical parameters

STANDARD TEST CONDITIONS (STC)

Irradiance 1.000 W/m^2 - Cell Temperature 25 °C - Air Mass 1.5

$$\eta_{STC} = \frac{P_{MP}}{1000 \times A}$$

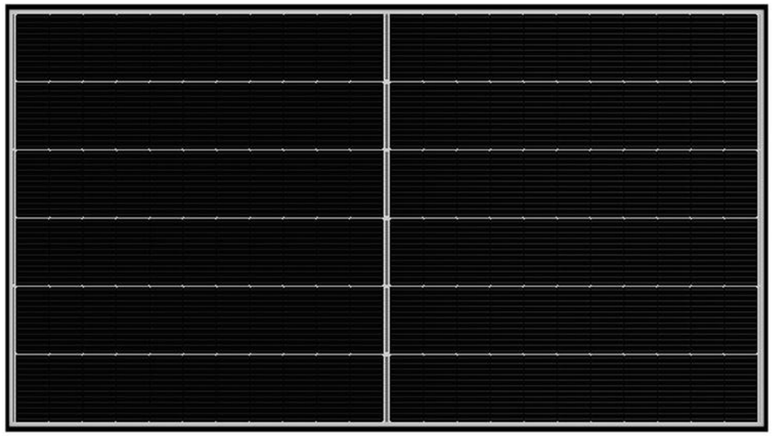
$$A_{1kWp} = \frac{1}{\eta_{STC}}$$

$$FF_{STC} = \frac{P_{MP}}{I_{SC} \times V_{OC}}$$

A first generation photovoltaic module

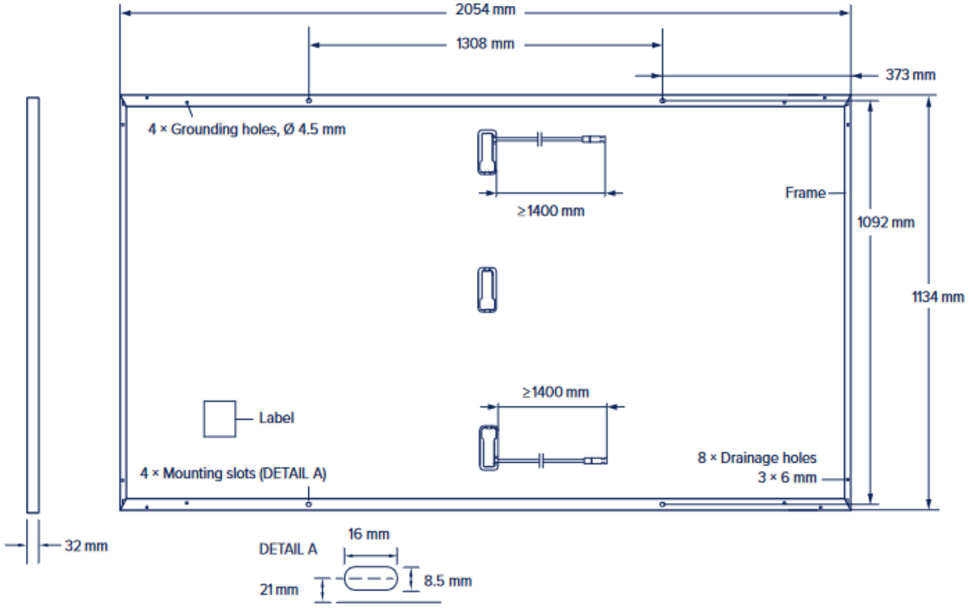
Q.PEAK DUO ML-G11

qcells



Mechanical Specification

Format	2054 mm × 1134 mm × 32 mm (including frame)
Weight	26.0 kg
Front Cover	3.2 mm thermally pre-stressed glass with anti-reflection technology
Back Cover	Composite film
Frame	Silver anodised aluminium
Cell	6 × 22 monocrystalline Q.ANTUM solar half cells
Junction box	53-101 mm × 32-60 mm × 15-18 mm Protection class IP67, with bypass diodes
Cable	4 mm^2 Solar cable; (+) ≥1400 mm, (−) ≥1400 mm
Connector	Stäubli MC4-Evo2, Hanwha Q CELLS HQC4; IP68



A first-generation photovoltaic module

■ Electrical Characteristics

POWER CLASS				480	485	490	495	500
MINIMUM PERFORMANCE AT STANDARD TEST CONDITIONS, STC[1] (POWER TOLERANCE +5 W / −0 W)								
Minimum	Power at MPP[1]	P_{MPP}	[W]	480	485	490	495	500
	Short Circuit Current[1]	I_{SC}	[A]	13.51	13.54	13.57	13.60	13.63
	Open Circuit Voltage[1]	V_{OC}	[V]	45.59	45.62	45.65	45.67	45.70
	Current at MPP	I_{MPP}	[A]	12.78	12.83	12.89	12.95	13.00
	Voltage at MPP	V_{MPP}	[V]	37.57	37.79	38.02	38.24	38.45
	Efficiency[1]	η	[%]	≥20.6	≥20.8	≥21.0	≥21.3	≥21.5

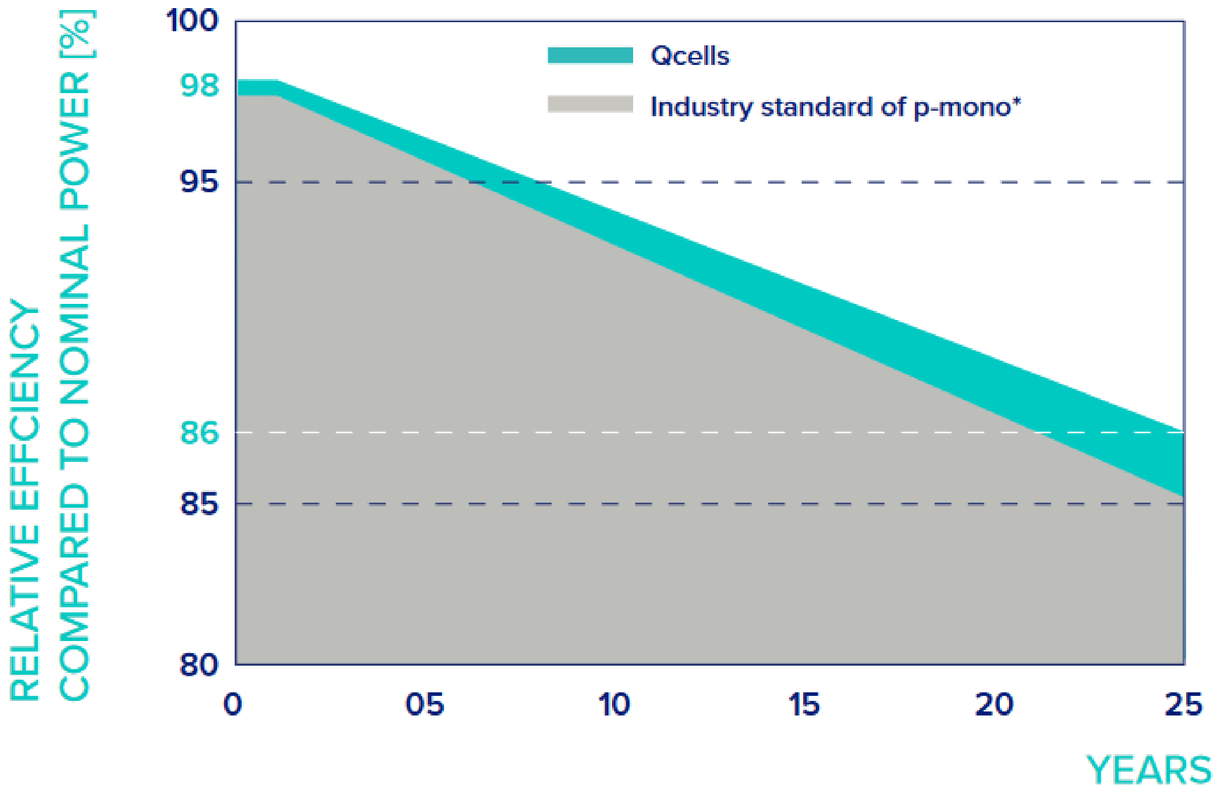
TEMPERATURE COEFFICIENTS							
Temperature Coefficient of I_{SC}	α	[%/K]	+0.04	Temperature Coefficient of V_{OC}	β	[%/K]	−0.27
Temperature Coefficient of P_{MPP}	γ	[%/K]	−0.34	Nominal Module Operating Temperature	NMOT	[°C]	43±3

■ Properties for System Design

Maximum System Voltage	V_{SYS}	[V]	1500	PV module classification			Class II
Maximum Reverse Current	I_R	[A]	25	Fire Rating based on ANSI / UL 61730			C / TYPE 1
Max. Design Load, Push / Pull		[Pa]	3600 / 1600	Permitted Module Temperature on Continuous Duty			−40 °C - +85 °C
Max. Test Load, Push / Pull		[Pa]	5400 / 2400				

A first-generation photovoltaic module

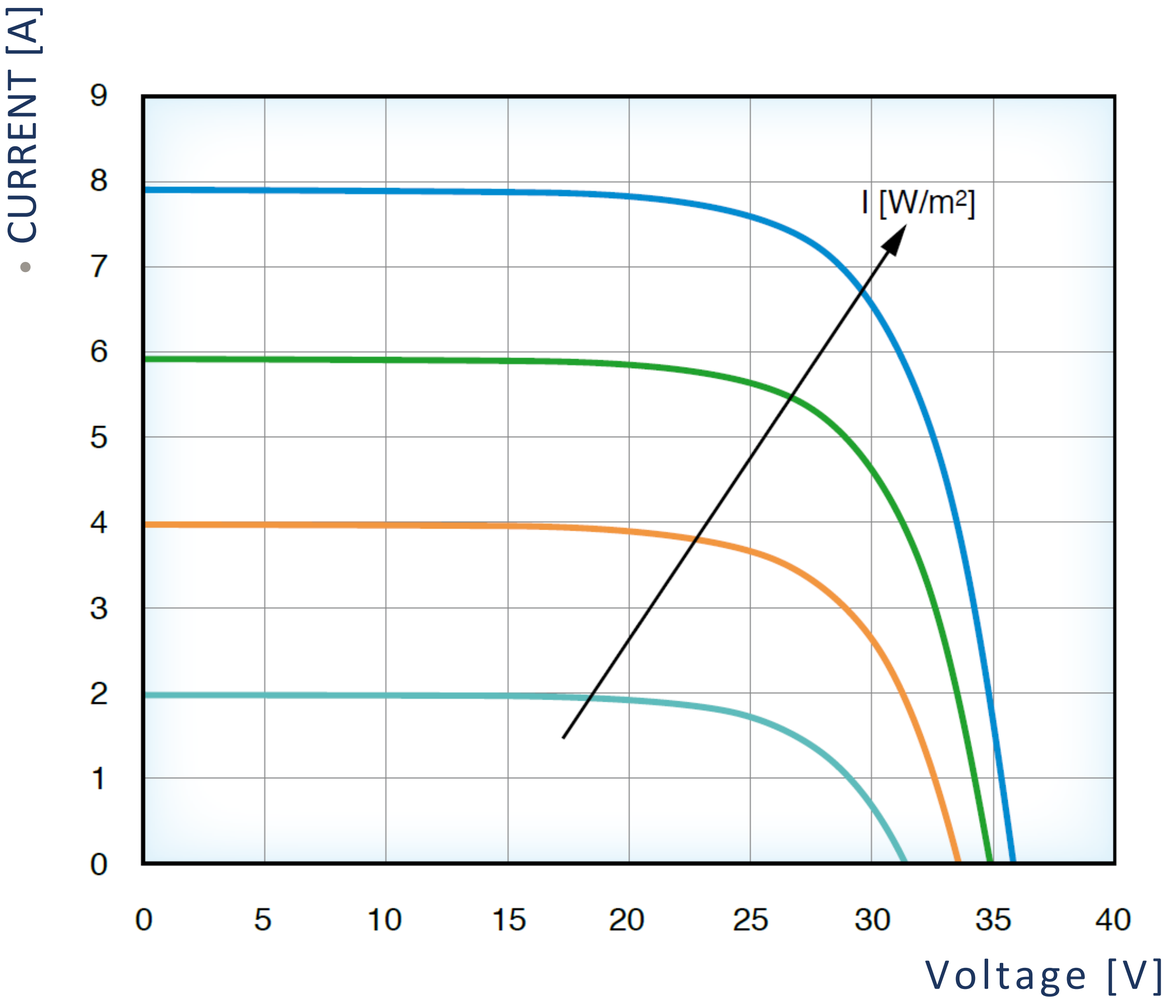
Qcells PERFORMANCE WARRANTY

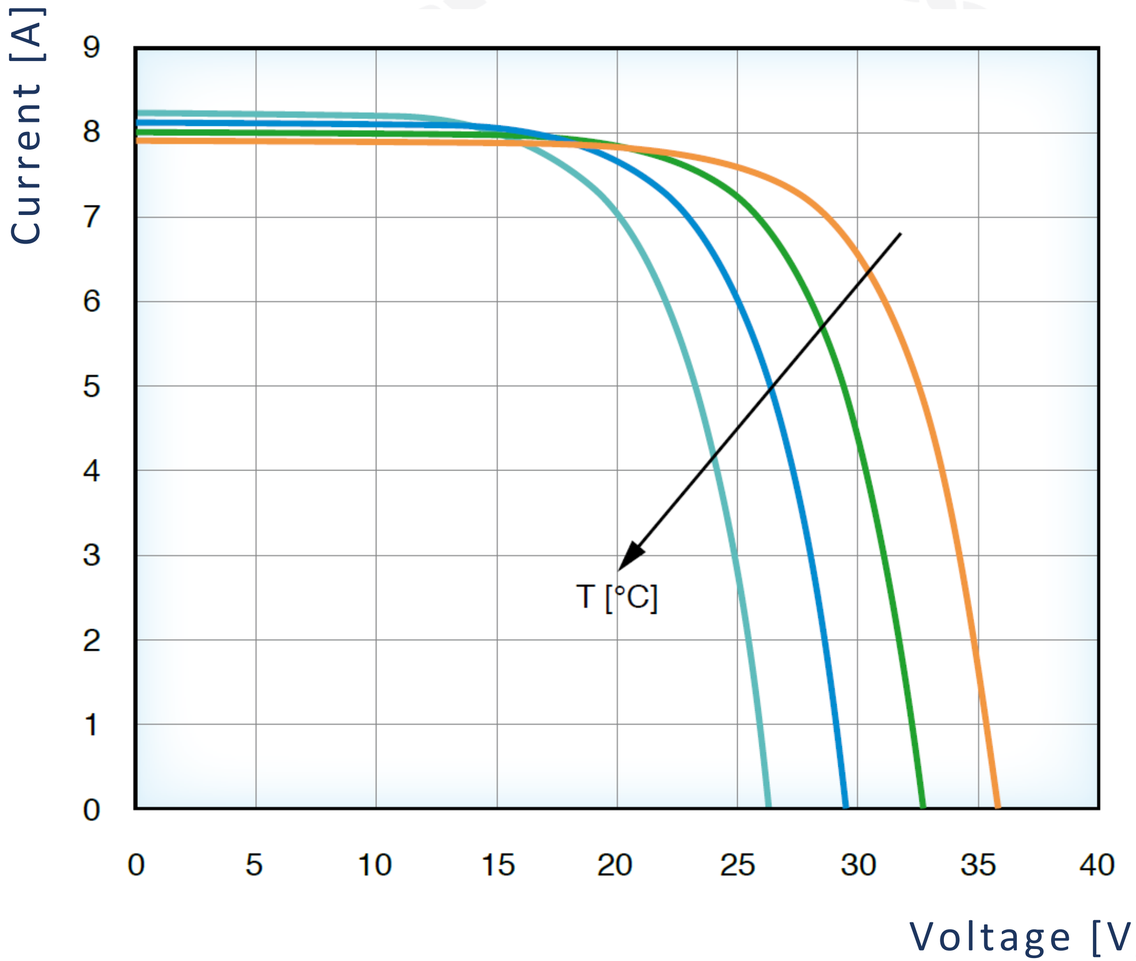


At least 98 % of nominal power during first year. Thereafter max. 0.5 % degradation per year. At least 93.5 % of nominal power up to 10 years. At least 86 % of nominal power up to 25 years.

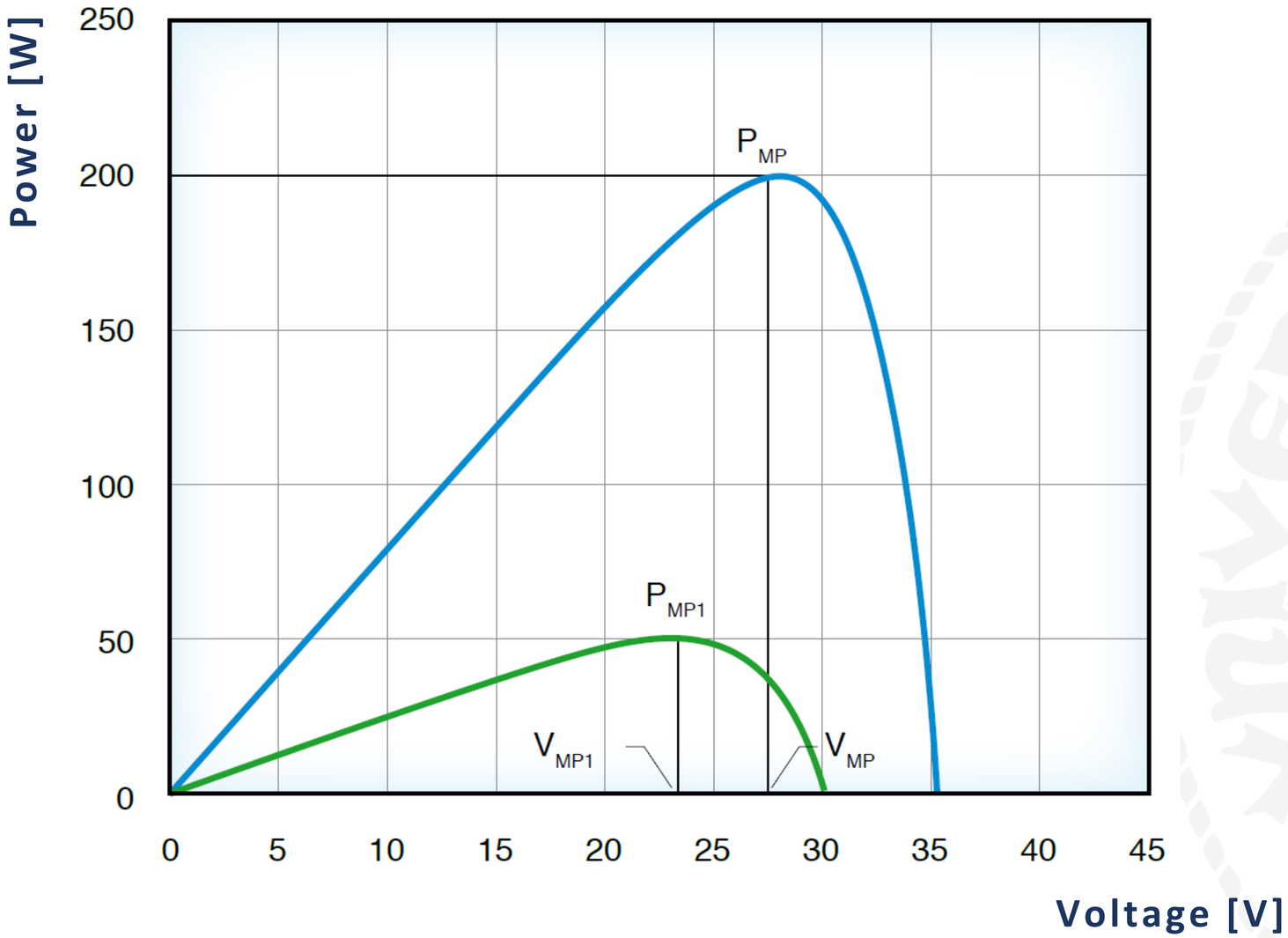
All data within measurement tolerances. Full warranties in accordance with the warranty terms of the Qcells sales organisation of your respective country.

Solar irradiance and cell temperatures dependences





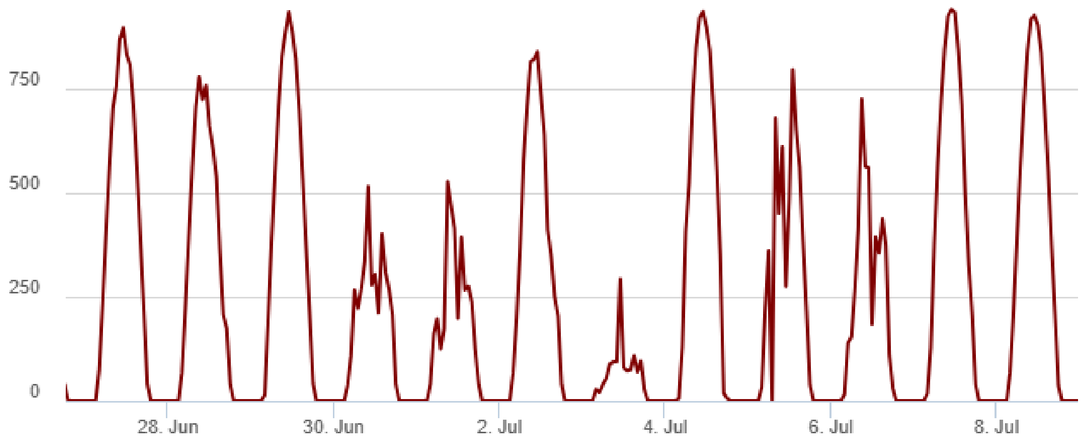
Power/voltage characteristic



Photovoltaic devices modelling: simple model 1

$$P_{AC} = A \cdot G_{POA} \cdot \eta_{STC} \cdot PR$$

$$P_{AC} = P_n \cdot \frac{G_{POA}}{1000} \cdot PR$$



- G_{poa} [W/m^2] – Solar Irradiance (Plane Of Array)
- A [m^2] – Area of the module
- P_{AC} [W] – Power produced by the PV system
- P_n [W] – Nominal power of the PV system
- PR [-] – Performance ratio

Photovoltaic devices modelling: simple model 2

$$I_x(G) = \frac{G}{1000} \times I_{x,STC}$$ x = SC, MP

$$V_x(T) = V_{x,STC} + W \times (T_c - 25)$$ x = OC, MP

$$T_c(G, Ta) = T_a + \frac{T_{NOCT} - 20}{800} \times G$$

- G [W/m^2] – Solar Irradiance (POA)
- I [A] – Current
- V [V] – Voltage
- T_c [°C] – cell temperature
- T_a [°C] – ambient temperature
- $W\left[\frac{V}{°C}\right] = \frac{W\,[\%/°C]}{100} \cdot V_{oc}$

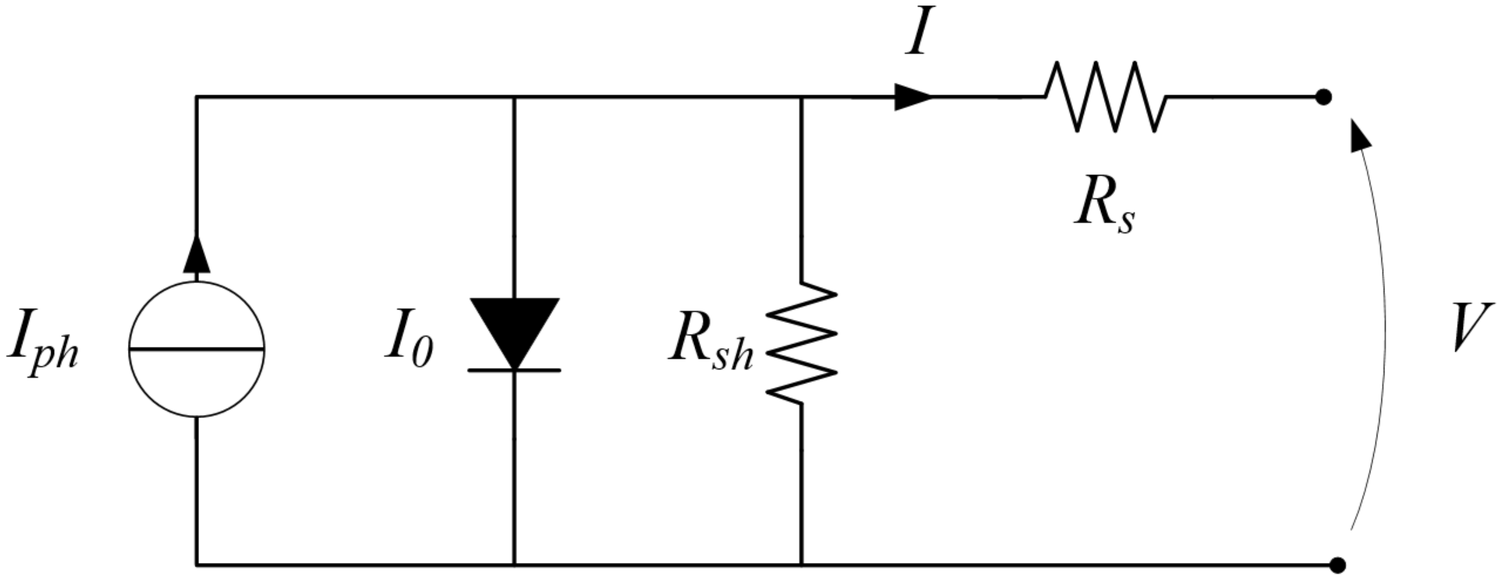
Photovoltaic devices modelling: simple models 2

$$I(G) = \frac{G}{1000} \times I_{STC}$$

$$V(T) = V_{STC} + W \times (T_c - 25)$$

$$T_c(G, Ta) = T_a + \frac{T_{NOCT} - 20}{800} \times G$$

Photovoltaic devices modelling: less simple

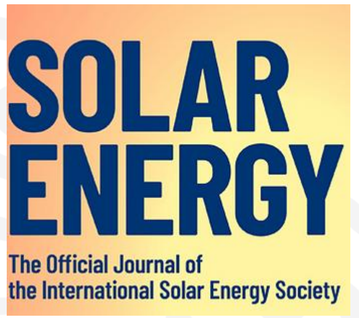


$$I = I_{ph} - I_0 \times \left[e^{(V+I\times R_s)/n\times V_t} - 1\right] - \frac{V + I \times R_s}{R_{sh}}$$

- I_{ph} [A] – photo generated current
- I_0 [A] – dark saturation current
- V_t [V] – thermal voltage
- R_s [Ω] – series resistance
- R_{sh} [Ω] – shunt resistance
- n [ ] – ideality factor

Modelling photovoltaic devices: the empirical model

- A simple and explicit model based on the parameters that **can be always found in the datasheet**
- **Any PV technology** (c-Si, a-Si, CdTe, CIGS, …)
- **Any operating condition**



$$I = I_L + z \times (T_c - 25) - \frac{e^{m \cdot [V + w(25 - T_c)]} - 1}{e^m - 1}$$

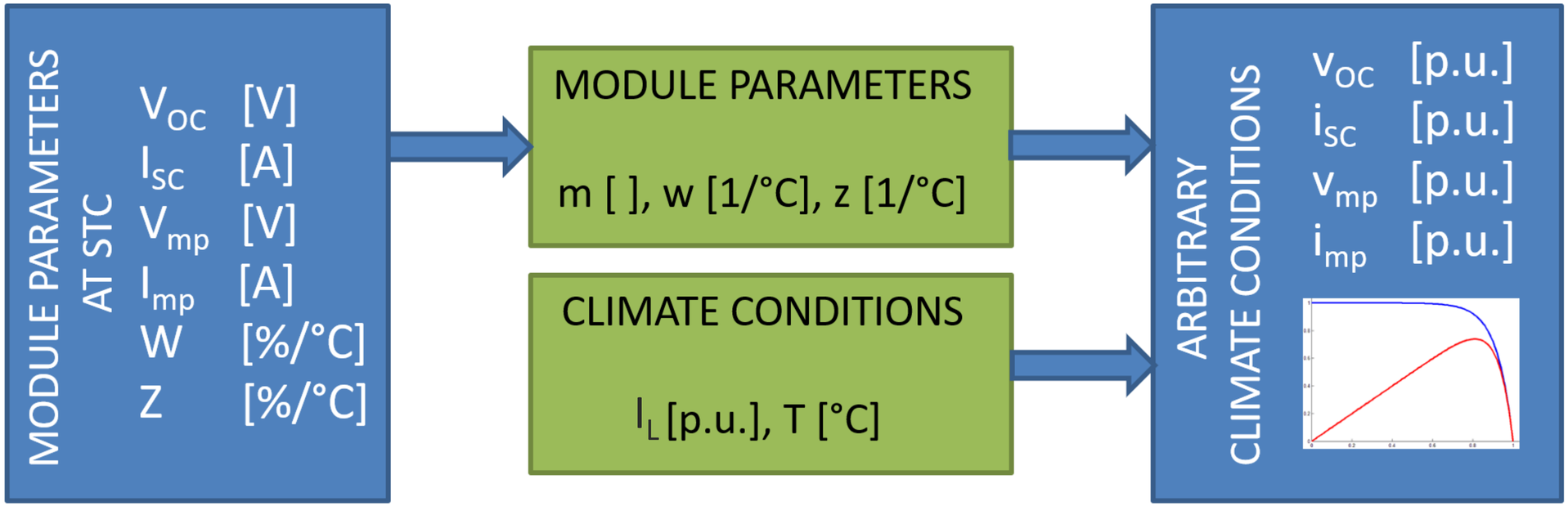
Explicit empirical model for general photovoltaic devices: Experimental validation at maximum power point

A. Massi Pavan [a], A. Mellit [b,c,*], V. Lughi [a]

- I [p.u.] – per unit current referred to Isc
- I_L [p.u.] – per unit irradiance referred to STC
- m [ ] – exponential factor
- V [p.u.] – per unit voltage referred to Voc
- w [1/°C] – voltage/temperature coefficient
- z [1/°C] – current/temperature coefficient
- Tc [°C] – cell temperature

Modelling photovoltaic devices: the empirical model

$$I = I_L + z \times (T_c - 25) - \frac{e^{m \cdot [V + w(25 - T_c)]} - 1}{e^m - 1}$$



The information provided by the manufacturer in the data sheet of the PV device are enough to characterize it at arbitrary climate conditions

The exponential factor

Calculate the exponential factor m of a PV module (Pn = 250Wp, Voc = 37.78V, Isc=8.94A) working at STC (I_L = 1p.u., T_c = 25°C)

$$I = I_L + z \times (T_c - 25) - \frac{e^{m\cdot[V+w(25-T_c)]} - 1}{e^m - 1} \Rightarrow I = 1 - \frac{e^{m\cdot V} - 1}{e^m - 1}$$

$$FF = \frac{250}{8.94 \times 37.78} = 0.7402$$

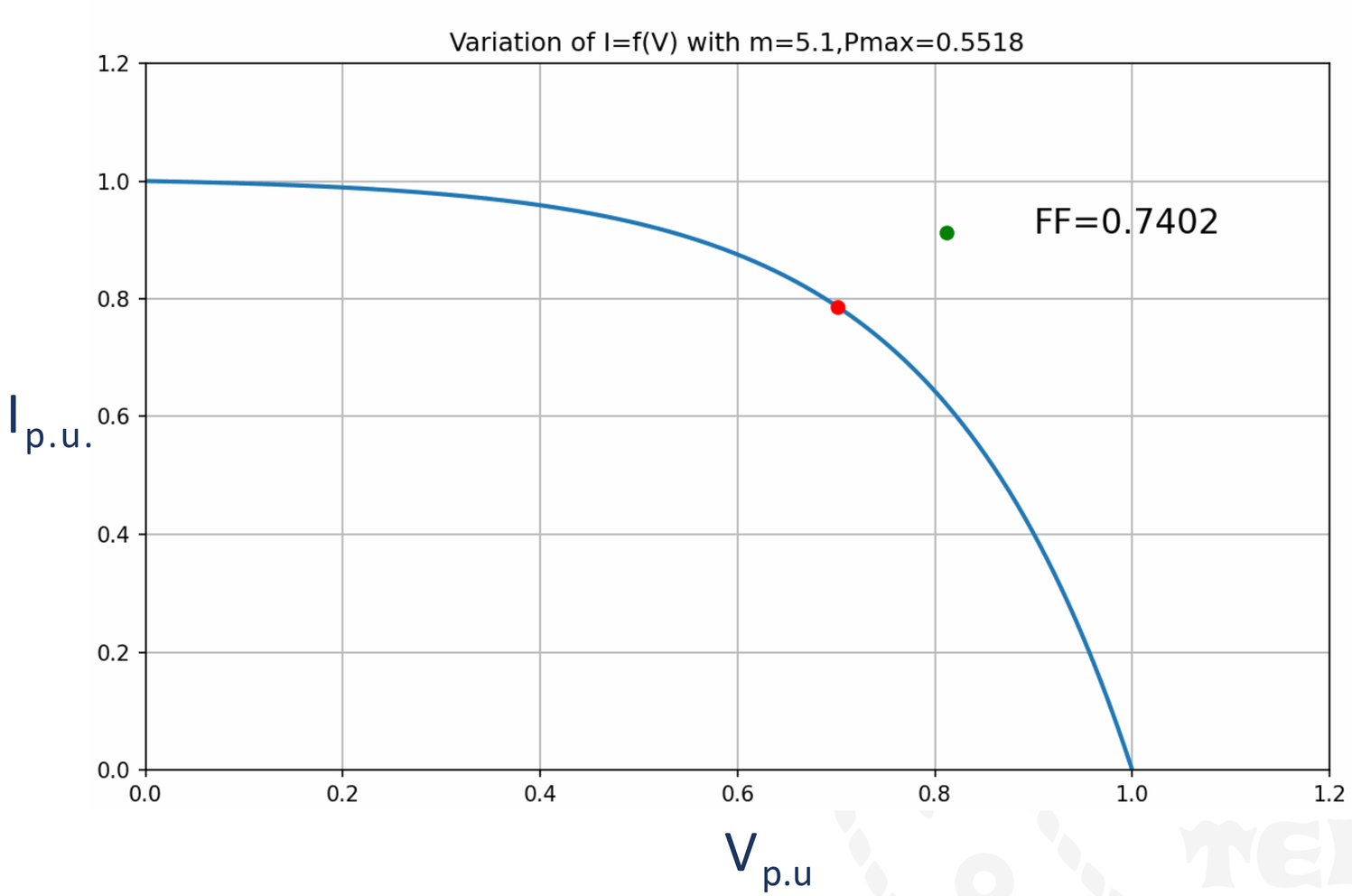
m = 12.0 $\Rightarrow$ $I = 1 - \frac{e^{12V} - 1}{e^{12} - 1}$ $\Rightarrow$ P_{max} =0.7274

m = 12.3 $\Rightarrow$ $I = 1 - \frac{e^{12.3V} - 1}{e^{12.3} - 1}$ $\Rightarrow$ P_{max} =0.7317

m = 12.7 $\Rightarrow$ $I = 1 - \frac{e^{12.7V} - 1}{e^{12.7} - 1}$ $\Rightarrow$ P_{max} =0.7375

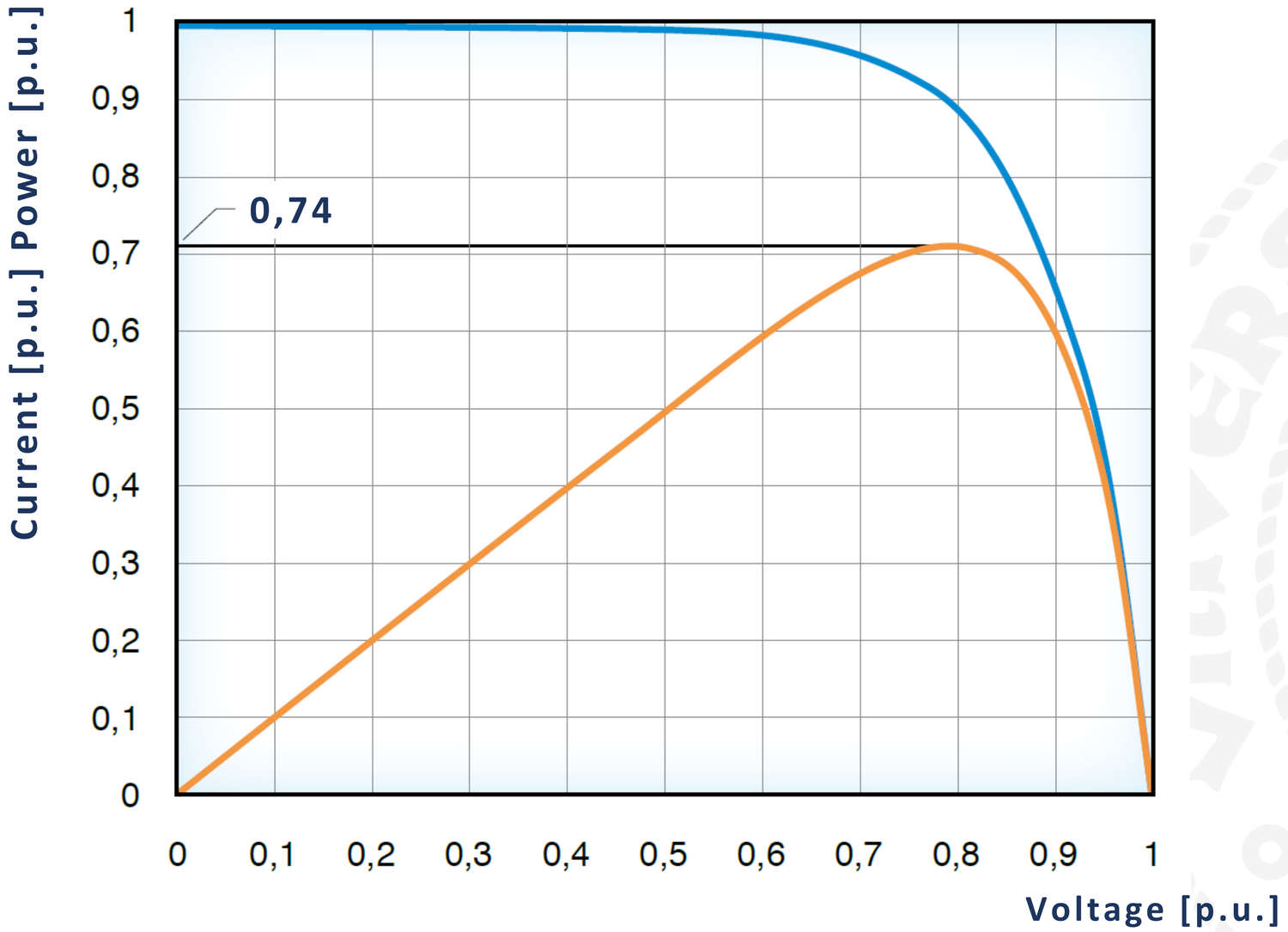
m = 12.9 $\Rightarrow$ $I = 1 - \frac{e^{12.9V} - 1}{e^{12.9} - 1}$ $\Rightarrow$ P_{max} =0.7402

What are we doing?



How can I calculate P?

I/V and P/V curves in p.u.



Parallel and series connections

A study on the mismatch effect due to the use of different photovoltaic modules classes in large-scale solar parks

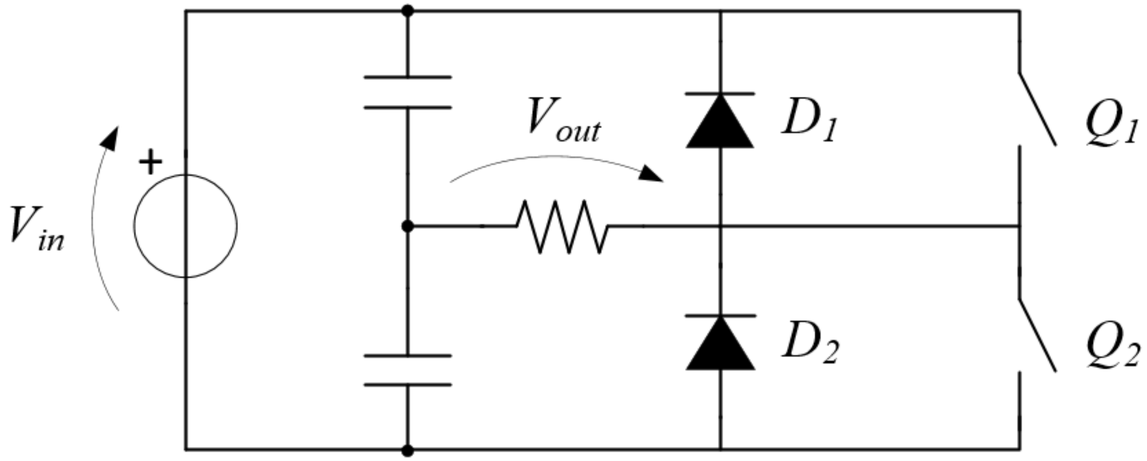
Alessandro Massi Pavan[1,2], Adel Mellit[3,4]*, Davide De Pieri[5] and Vanni Lughi[1]

Progress in PHOTOVOLTAICS

$$\begin{cases} V_n = log\prod_{i=1}^{k} \sqrt[mi]{[I_{Li} - I + z_i \cdot (25\text{-}T_{ci})] \cdot (e^{m_i} - 1) + 1} - \sum_{i=1}^{k} w_i \cdot (25\text{-}T_{ci}) \\ 0 \le I \le k \end{cases}$$

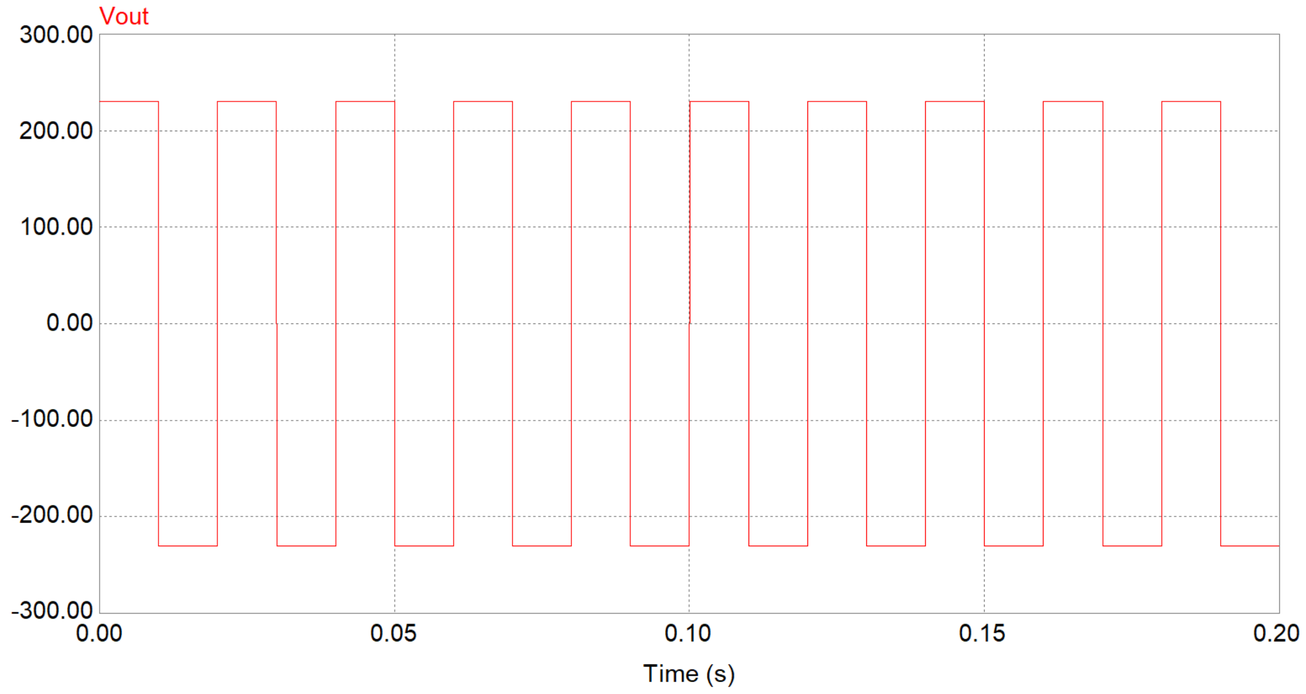
$$\begin{cases} I_n = \sum_{j=1}^{n} I_{Lj} + \sum_{j=1}^{n} z_j \cdot (25\text{-}T_{cj}) - \sum_{j=1}^{n} \frac{e^{m_j \cdot [(V + w_j \cdot (25 - T_{cj})]} - 1}{e^{m_j} - 1} \\ 0 \le V \le n \end{cases}$$

Square-wave half bridge inverter

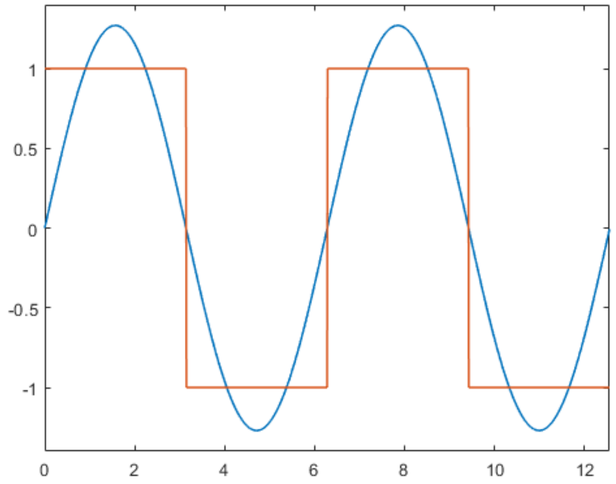


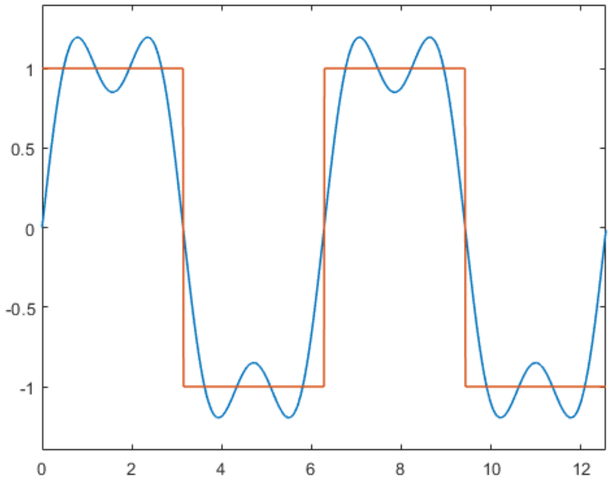
$$V_{out,eff} = \frac{V_{in}}{2}$$

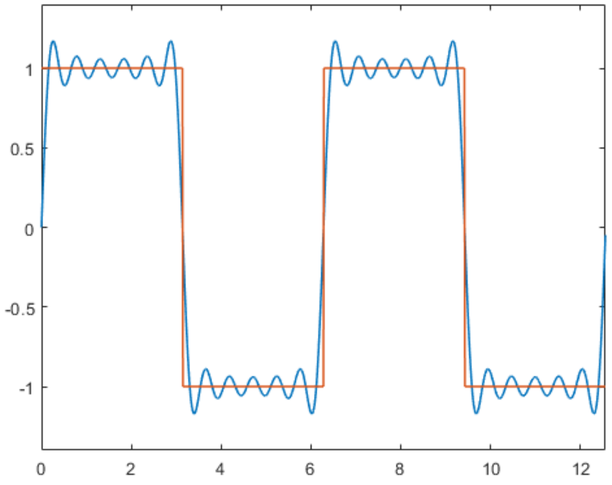
$$V_{out}(t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$$

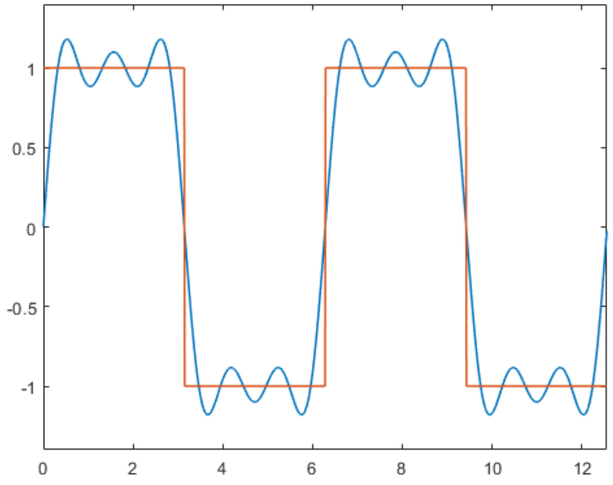


Harmonic analysis using Fourier series

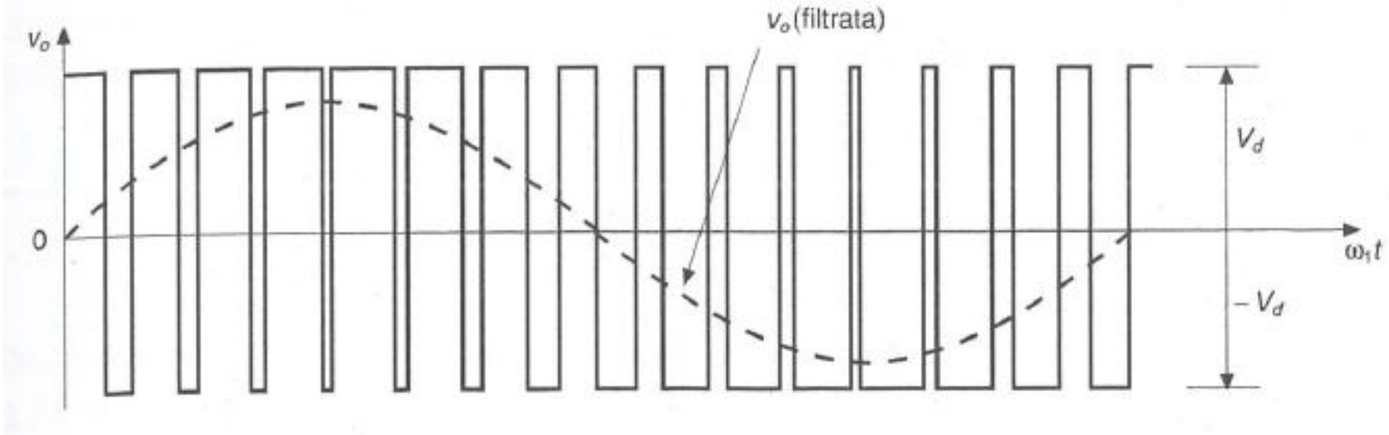


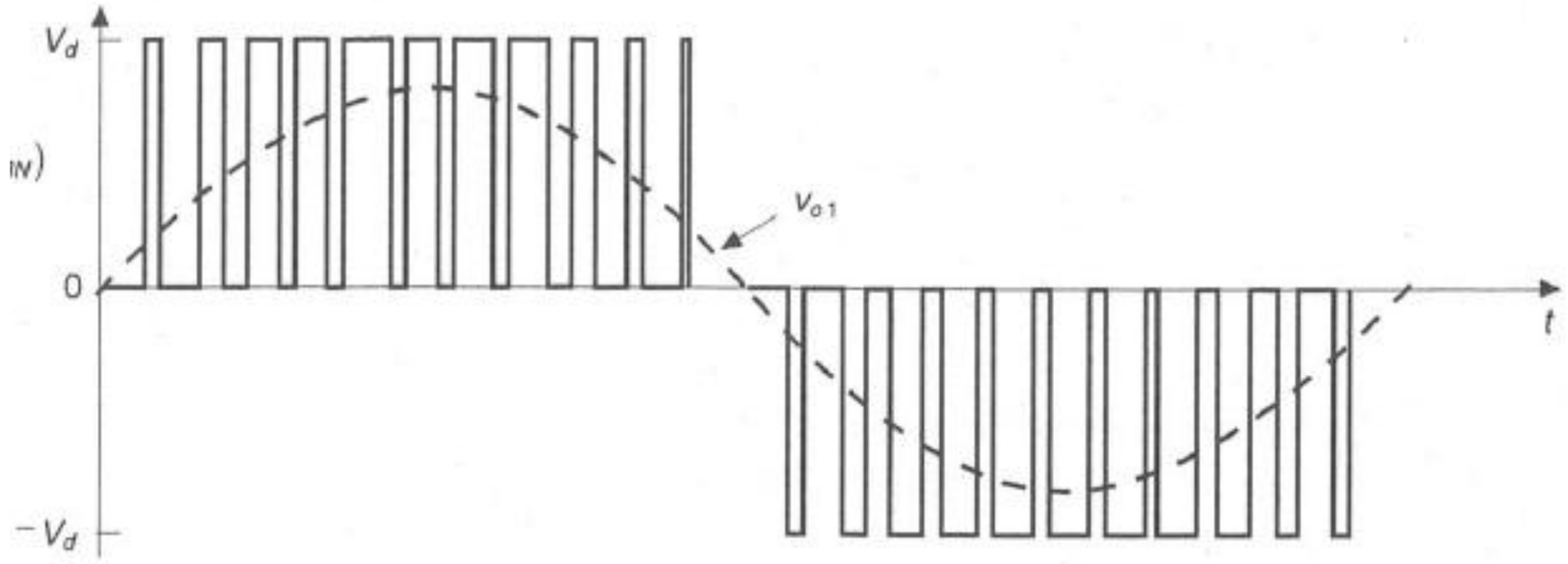






PWM (Pulse With Modulation) Inverter





Inverter for grid-connected applications





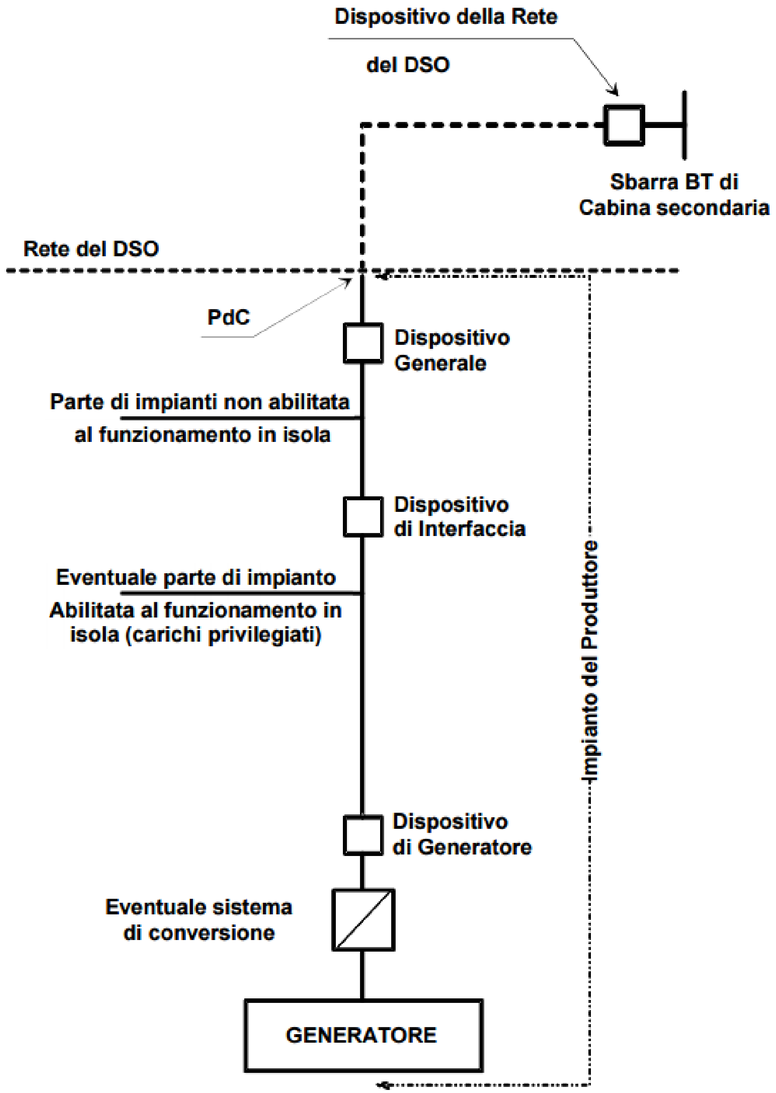


String inverter
3 kVA
30 × 30 × 12 cm
5.5 kg

Centralized inverter
100 kVA
80 × 80 × 160 cm
420 kg

Utility-scale inverter
2200 kVA
2.7 × 2.3 × 1.6 m
3,400 kg

CEI 0-21: Producers connected to the DSO's grid

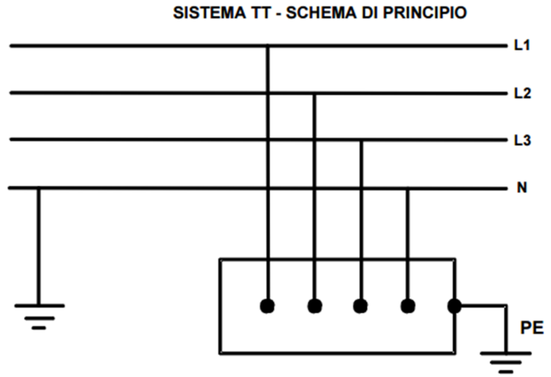


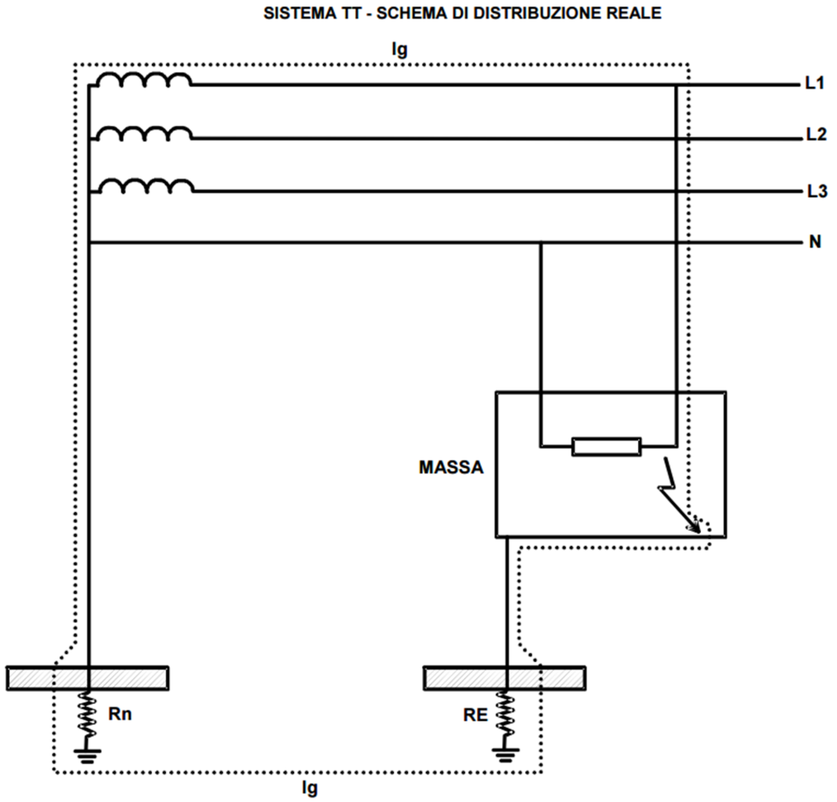
- "Dispositivo della rete": grid switch
- "Cabina secondaria": secondary power station
- "Rete del DSO": DSO's grid
- "PdC": connection point
- "Dispositivo generale" **DG**: main switch
- "Parte di impianto … isola": portion of the power system which cannot work in islanded mode
- "Dispositivo d'interfaccia" **DI**: interface switch
- "Parte di impianto … isola": portion of the power system which can work in islanded mode
- "Dispositivo del generatore" **DGG**: generator switch
- "Eventuale Sistema di conversione": possible inverter

CEI 0-21: Reference technical rules for the connection of active and passive users to the LV electrical Utilities

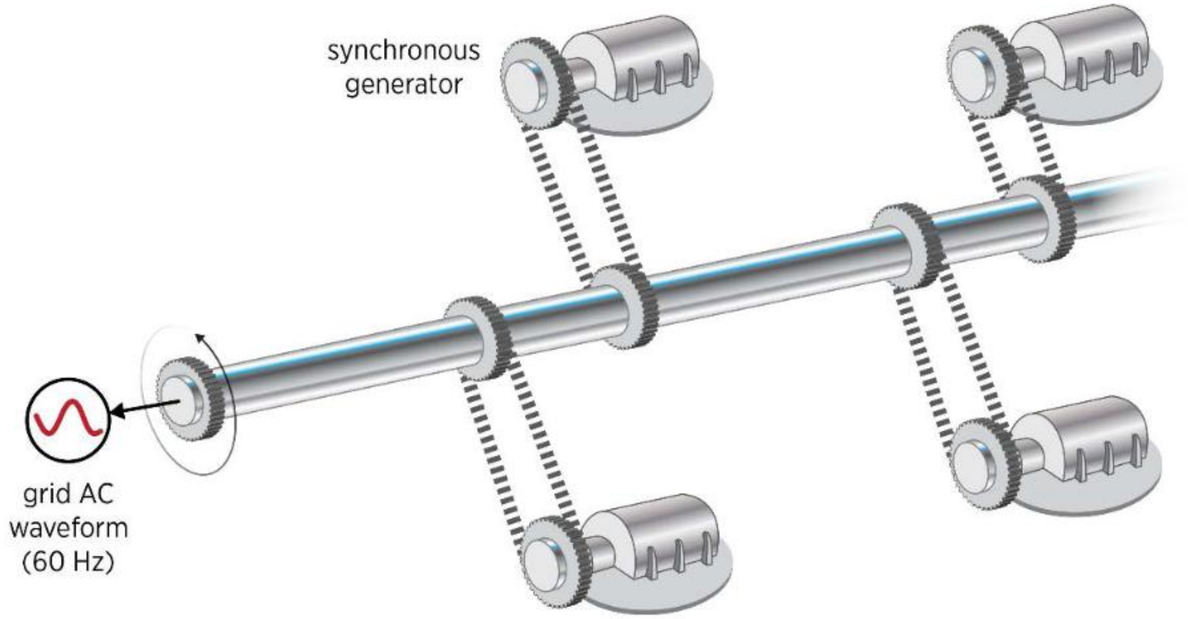
- Frequency variation: 50±5% (100% of the time), 50±2% (95% of the time)
- Voltage “slow” variation: U_n + 10% and U_n - 15%

Power [kW]	Grid voltage level
≤ 100	LV
> 100 and ≤ 200	LV or MV





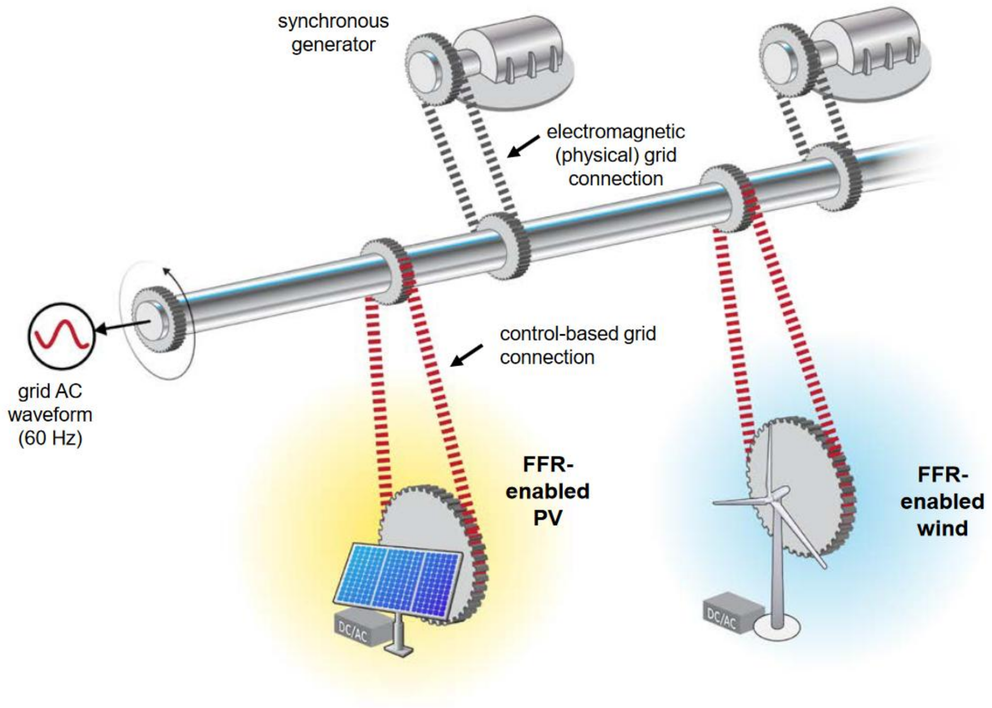
Inertia of the electric power system



Inertia and the Power Grid: A Guide Without the Spin - NREL

- Inertia refers to energy stored in rotating generators
- This energy is valuable when large power plants fail (temporary response – a few seconds)
- Historically inertia was abundant
- With the evolution of the grid (inverter-based sources) questions have emerged (and solution have been found!)

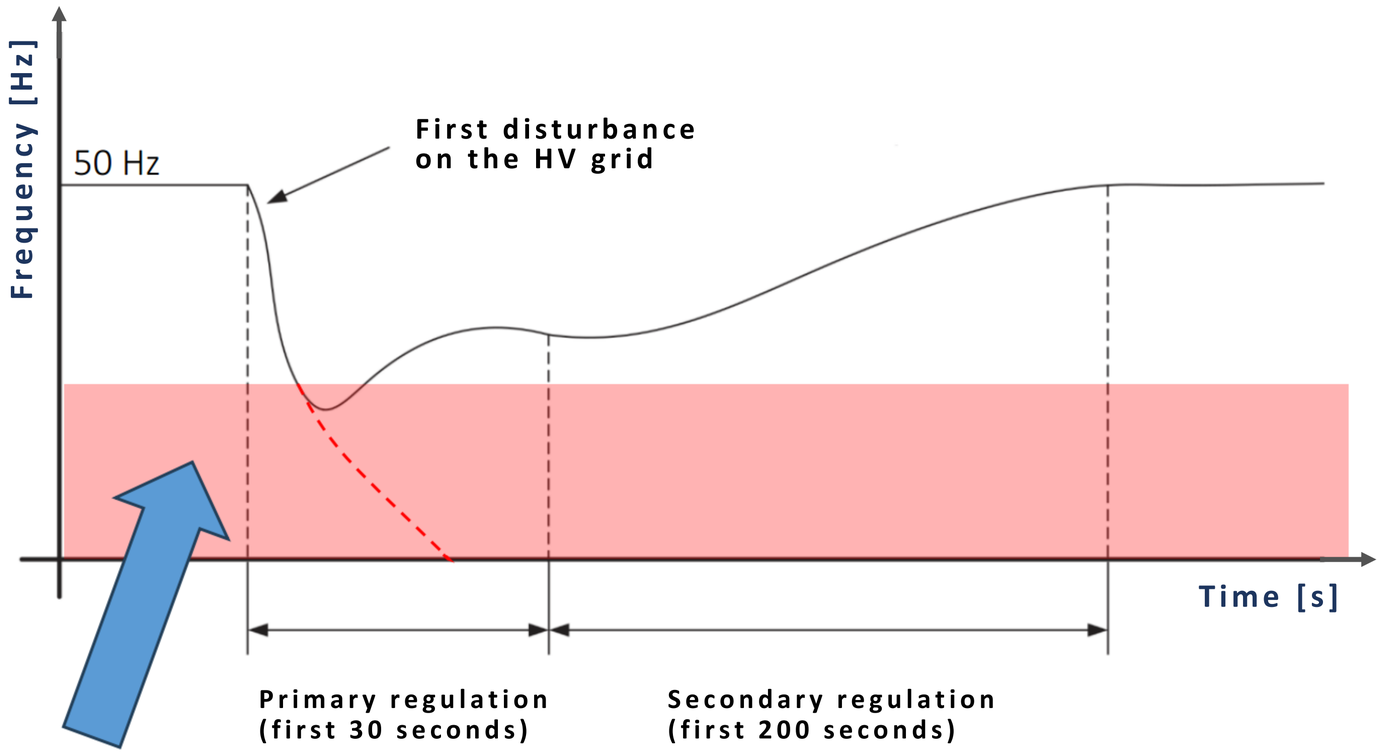
Inertia of the electric power system – Virtual inertia



Inertia and the Power Grid: A Guide Without the Spin - NREL

- Wind, solar and storage can provide frequency-responsive services through inverters
- Using sensors and software that control the response (**virtual inertia**)
- Inverter-based resources including photovoltaic, wind and storage can quickly detect frequency deviations and respond to system imbalances
- The response is much faster than traditional mechanical response

Stability of the power network



1. Local issue on the HV grid (e.g. loss of a generation unit)
2. Frequency fluctuation
3. Intervention of DG protections (under-frequency threshold)
4. DG disconnection
5. Additional power imbalance
6. Worsening of the frequency imbalance
7. Disconnection of additional DG
8. Risk of power outage

The SPI must be able to distinguish the origin of the disturbance (HV vs MV)

Interface protection system (switch)

The interface protection system (SPI) must ensure:

- a reliable connection between the generator and the grid during normal grid operation, even in the presence of disturbances originating from the high-voltage system;
- the fast and reliable disconnection of the generator in case of a fault occurring on the distribution network (to prevent unintentional islanding)

The SPI includes thresholds for:

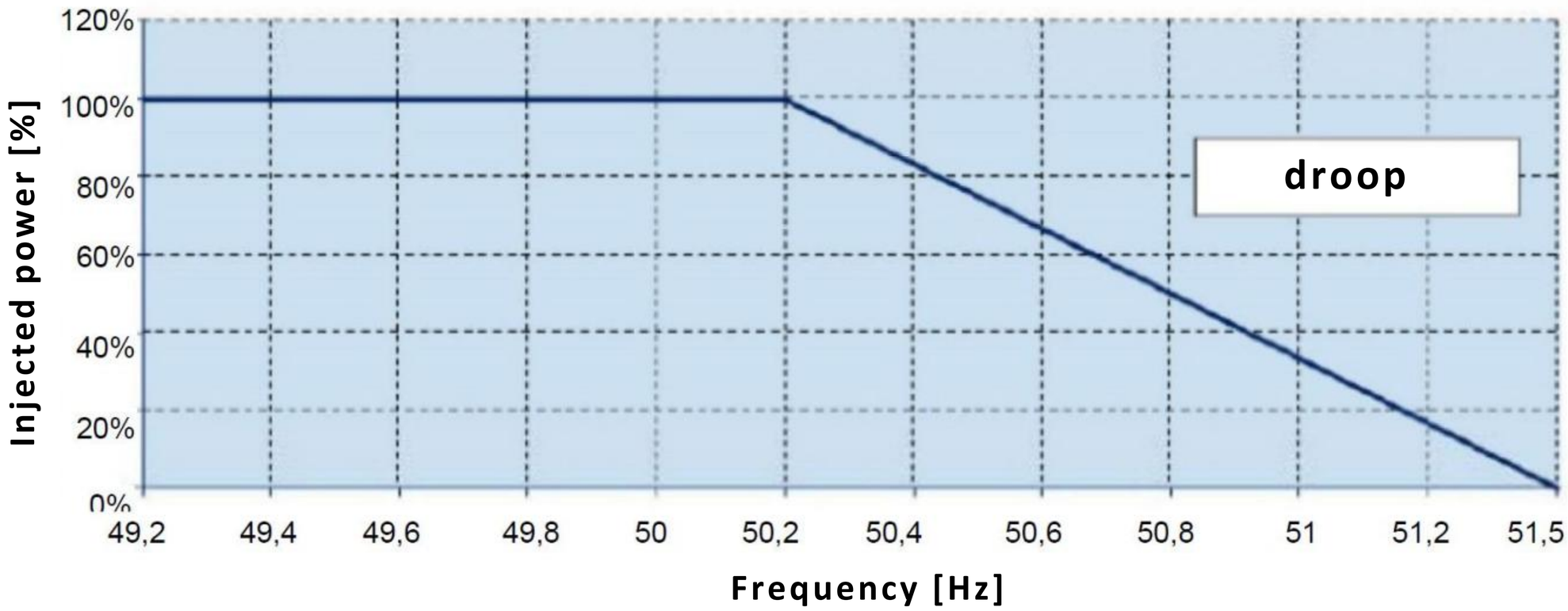
- max/min frequency

- max/min voltage

Conflicting requirements:

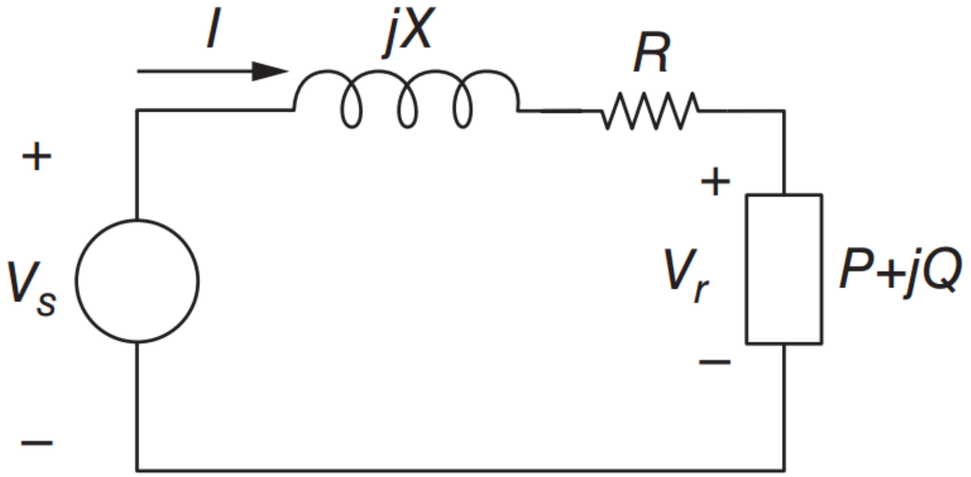
- **widening the thresholds** to make the SPI less sensitive to disturbances originating from the high-voltage grid
- **narrowing the intervention thresholds** to ensure disconnection for a fault on the distribution network

Power regulation under overfrequency conditions

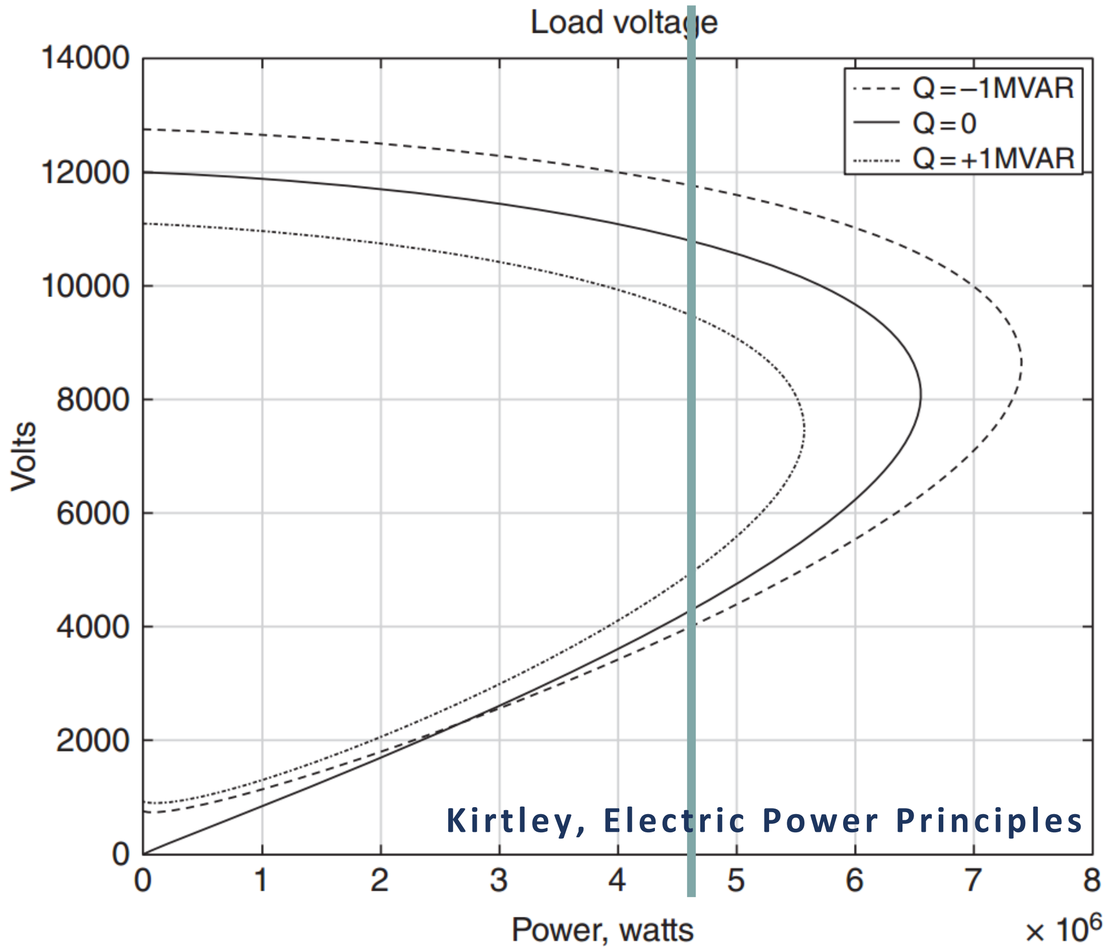


After 300 seconds from the end of the disturbance the DG can return to produce at full power

Voltage regulation



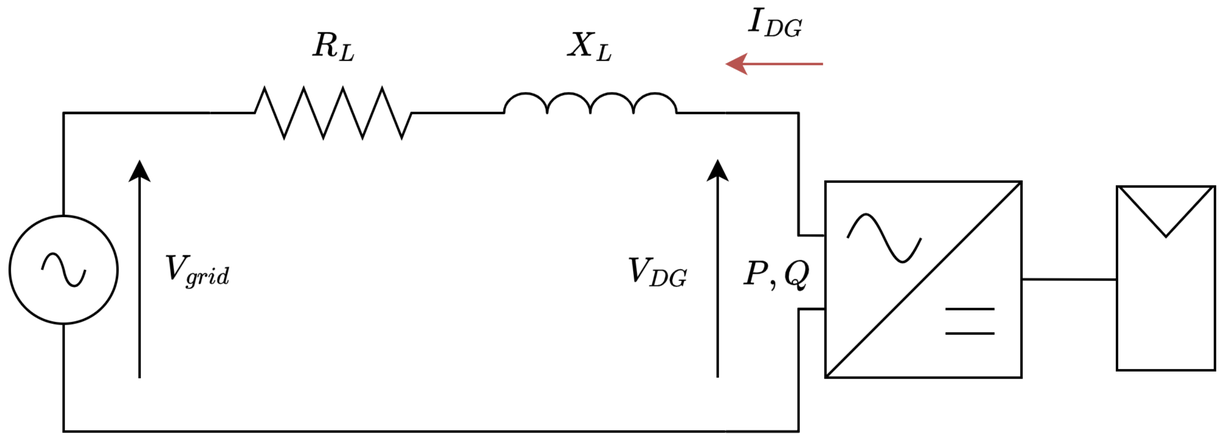
$$\mathrm{P} + \mathrm{j}Q = \frac{1}{2}\bar{V}_r\bar{I}^*$$

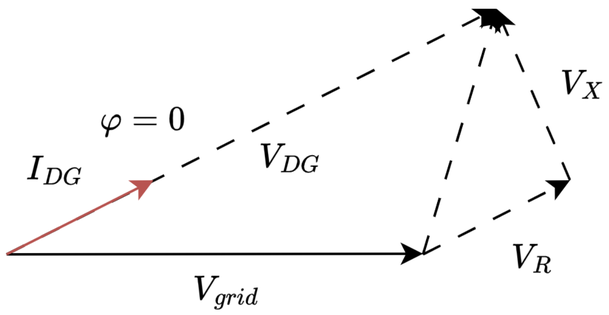


- Inductive reactive power reduces voltage and maximum power transfer
- If Q is constant: ↑P ↓V
- If P is constant: ↑Q ↓V

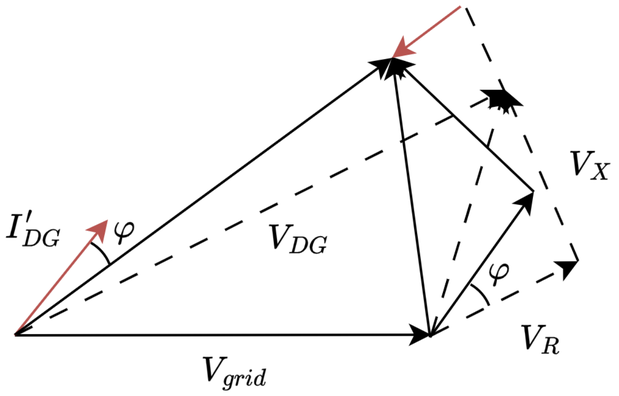
$$V_r^2 = \frac{1}{2}(V_s^2 - 2XQ - 2RP) \pm \sqrt{\left(\frac{1}{2}(V_s^2 - 2XQ - 2RP)\right)^2 - |Z|(P^2 + Q^2)}$$

Participation in voltage regulation





$cos\varphi = 1 \quad (only\, P)$

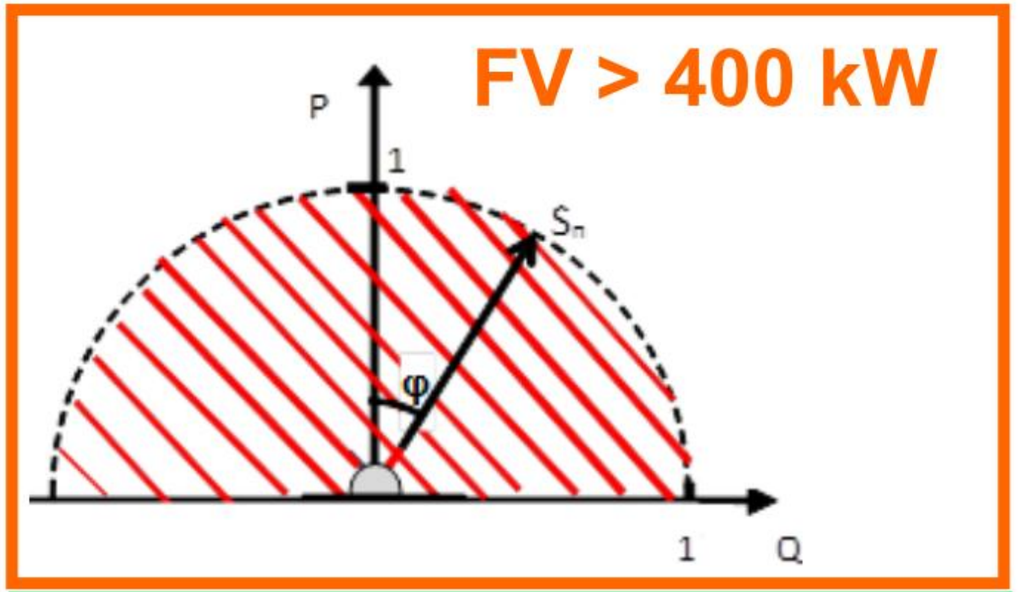


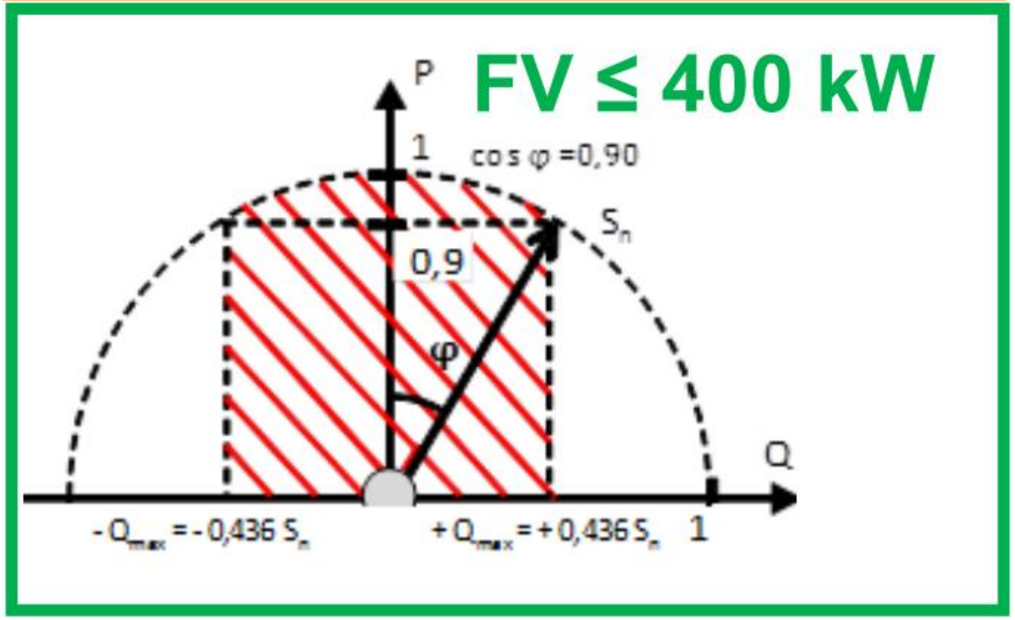
$cos\varphi = 0,9 \quad (P\, and\, Q)$

- The injection of active power by the DG increases the voltage at the connection point and along the line
- To address the issue, the regulations require that DGs must be able to exchange reactive power with the grid
- If Q is not sufficient, the DG must reduce P

Capability

- The operation at power factor different from 1, must be possible according to a specific performance of the inverter
- The capability is function of the voltage level and the size of the plant

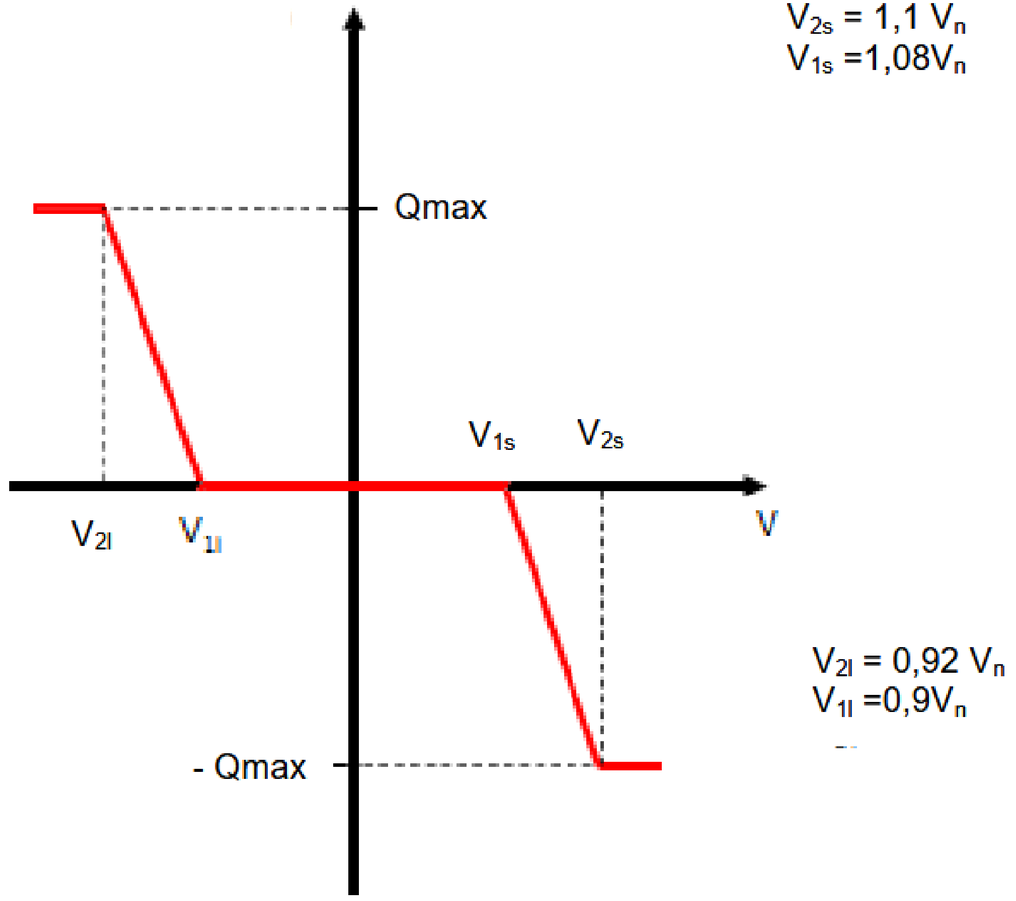




Voltage regulation

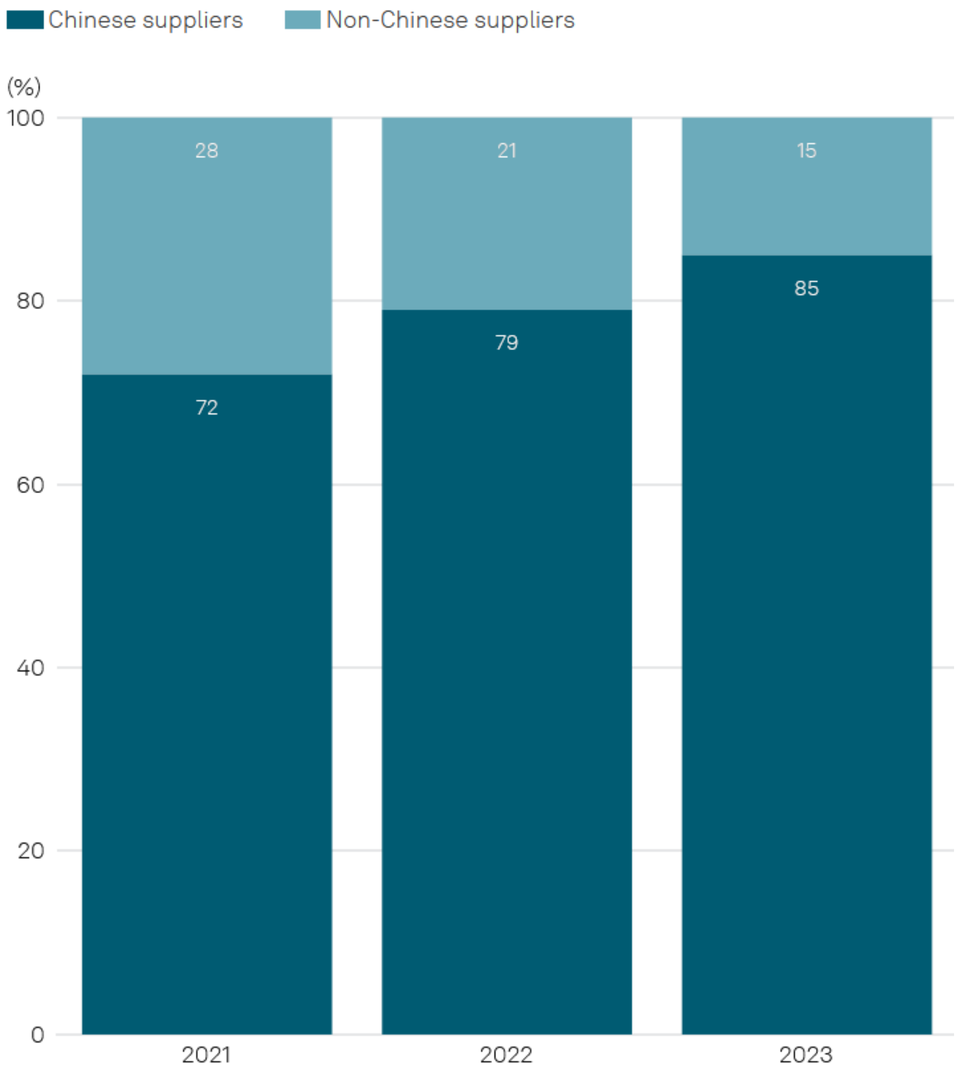
The voltage regulation can be implemented:

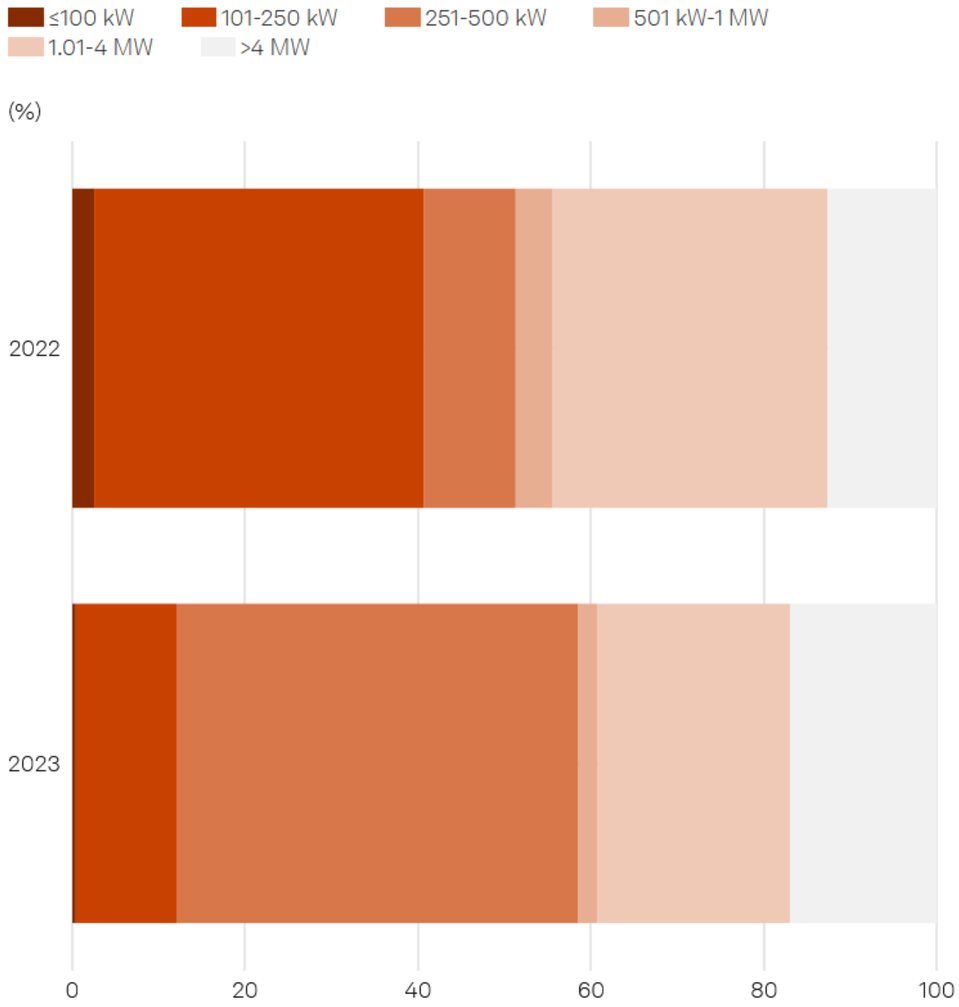
- with local logic, according to specific control laws
- with coordinated logic, in accordance with an external signal sent by the DSO



Inverter suppliers and sizes

S&P Global





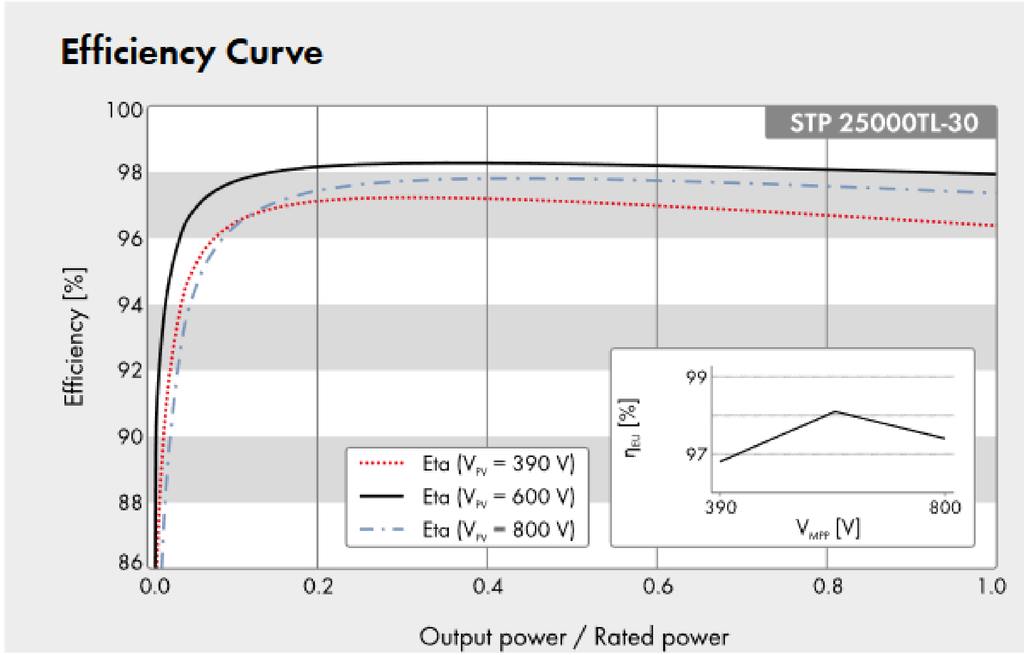
Datasheet of a pv grid-connected inverter

Technical Data	Sunny Tripower 15000TL	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)			
Max. generator power	27000 Wp	36000 Wp	45000 Wp
DC rated power	15330 W	20440 W	25550 W
Max. input voltage	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	240 V to 800 V / 600 V	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A	33 A / 33 A
Max. DC short-circuit current input A/input B	43 A / 43 A	43 A / 43 A	43 A / 43 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3	2 / A:3; B:3
Output (AC)			
Rated power (at 230 V, 50 Hz)	15000 W	20000 W	25000 W
Max. AC apparent power	15000 VA	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V		
AC voltage range	180 V to 280 V		
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz		
Rated power frequency / rated grid voltage	50 Hz / 230 V		
Max. output current / Rated output current	29 A / 21.7 A	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited		
THD	≤ 3%		
Feed-in phases / connection phases	3 / 3		
Efficiency			
Max. efficiency / European Efficiency	98.4% / 98.0%	98.4% / 98.0%	98.3% / 98.1%



$$\eta_{EU} = 0.03 \times \eta_{5\%} + 0.06 \times \eta_{10\%} + 0.13 \times \eta_{20\%} + 0.10 \times \eta_{30\%} + 0.48 \times \eta_{50\%} + 0.20 \times \eta_{100\%}$$

Datasheet of a pv grid-connected inverter

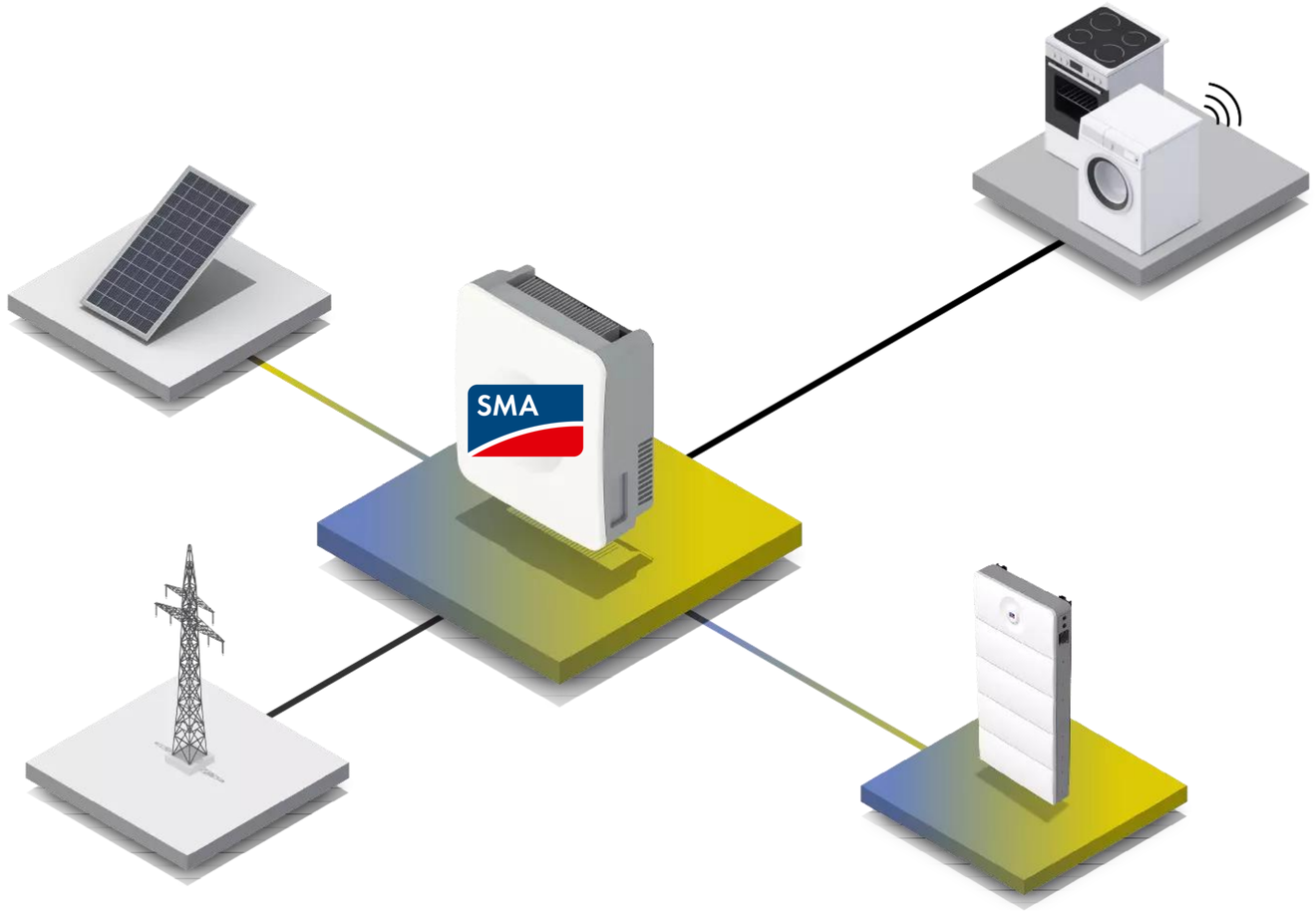




General data

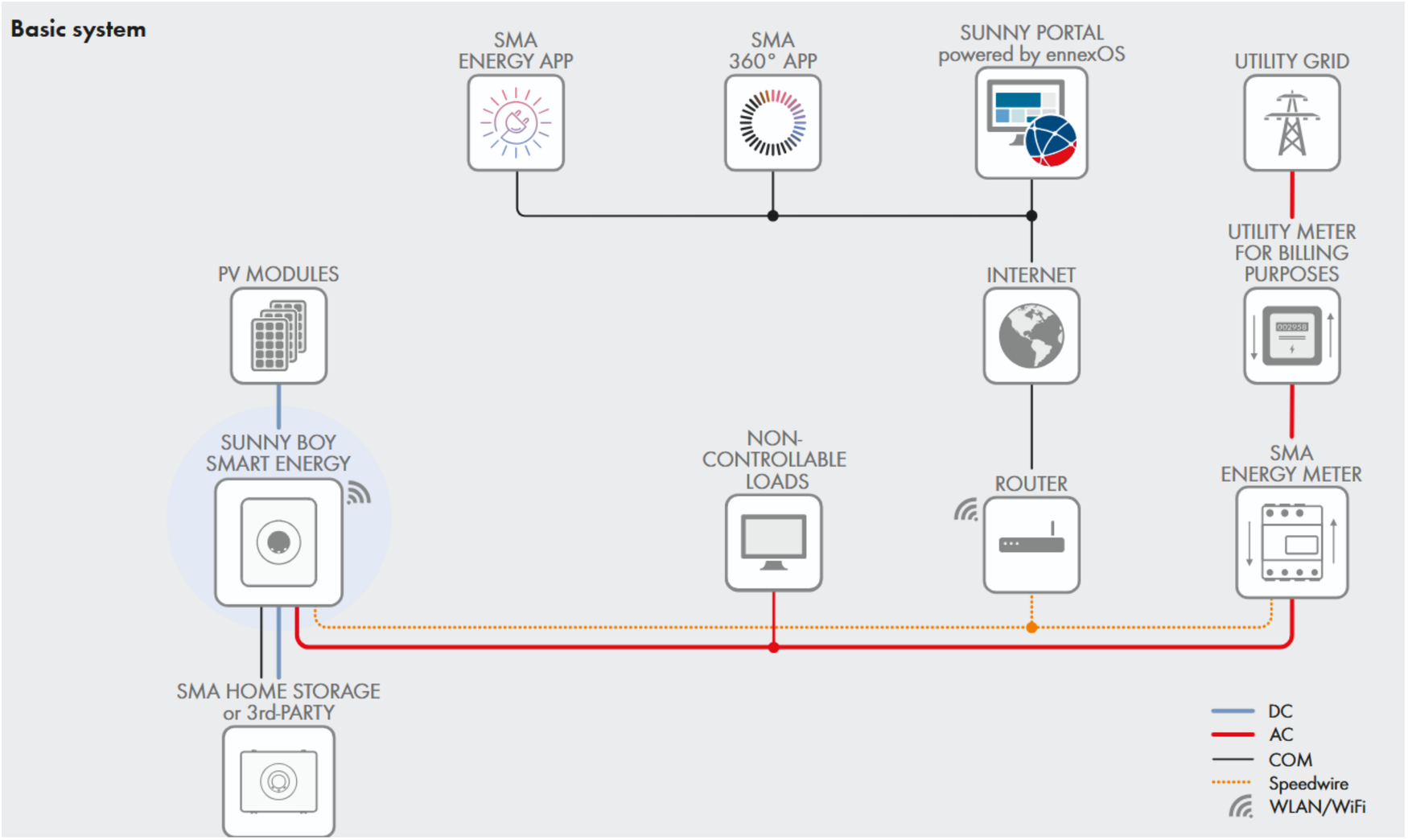
Dimensions (W / H / D)	661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)
Weight	61 kg (134.48 lb)
Operating temperature range	–25 °C to +60 °C (–13 °F to +140 °F)
Noise emission (typical)	51 dB(A)
Self-consumption (at night)	1 W
Topology / cooling concept	Transformerless / Opticool
Degree of protection (as per IEC 60529)	IP65
Climatic category (according to IEC 60721-3-4)	4K4H
Maximum permissible value for relative humidity (non-condensing)	100%

Hybrid Inverter

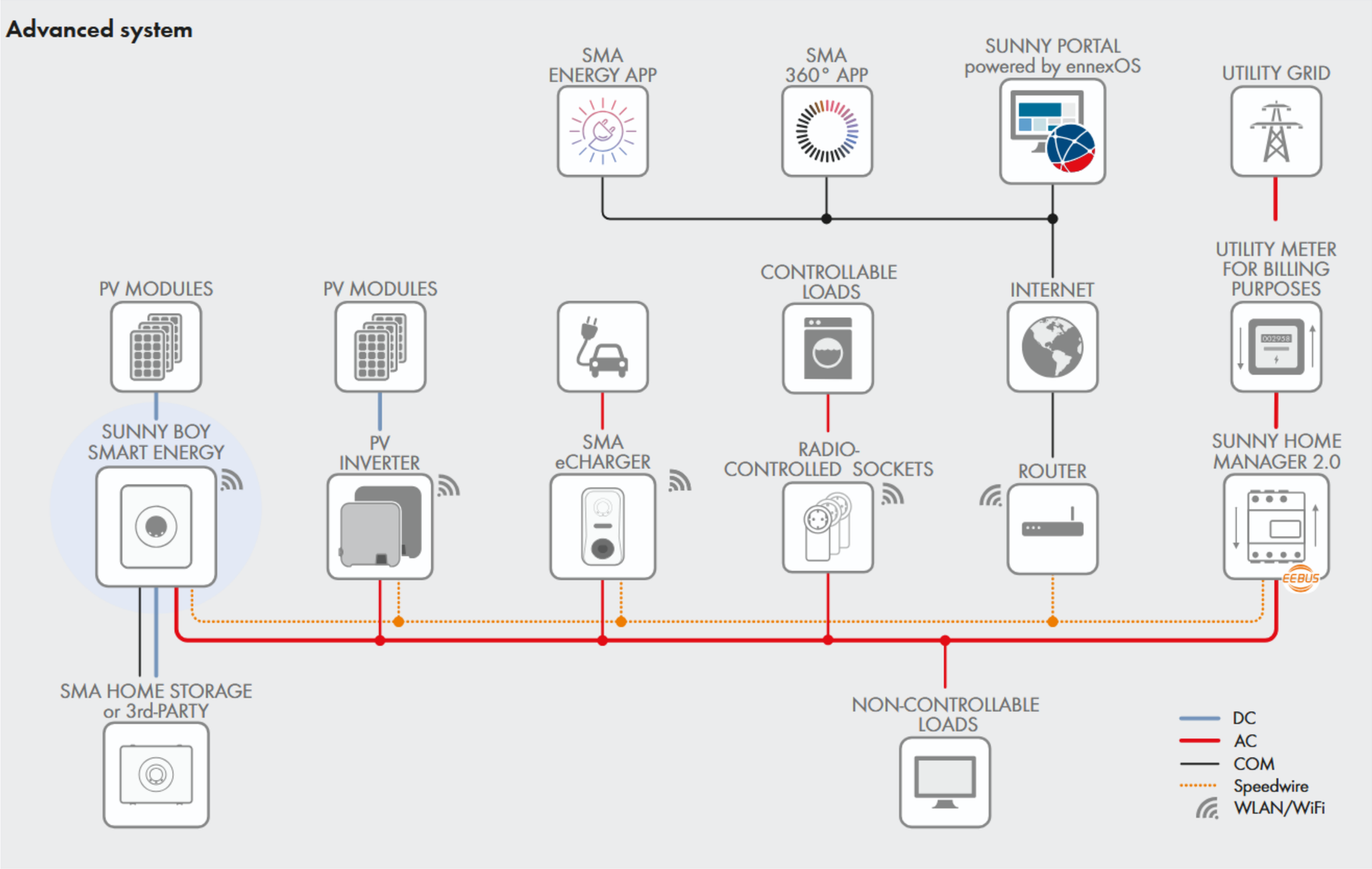


- **Combined functionalities** in one device: battery and photovoltaic
- May ensure access to electricity in case of **blackout**

Hybrid Inverter



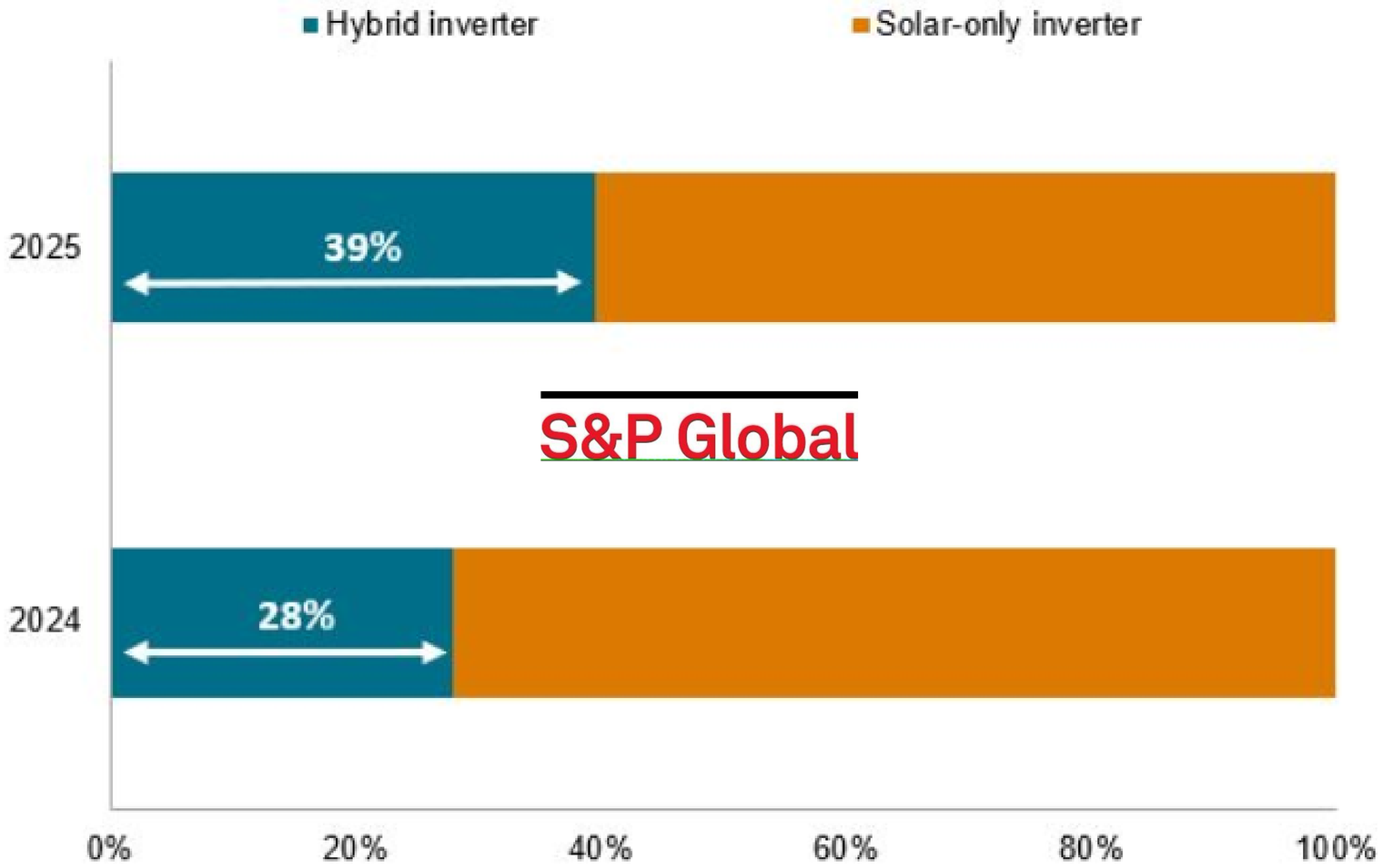
Hybrid Inverter



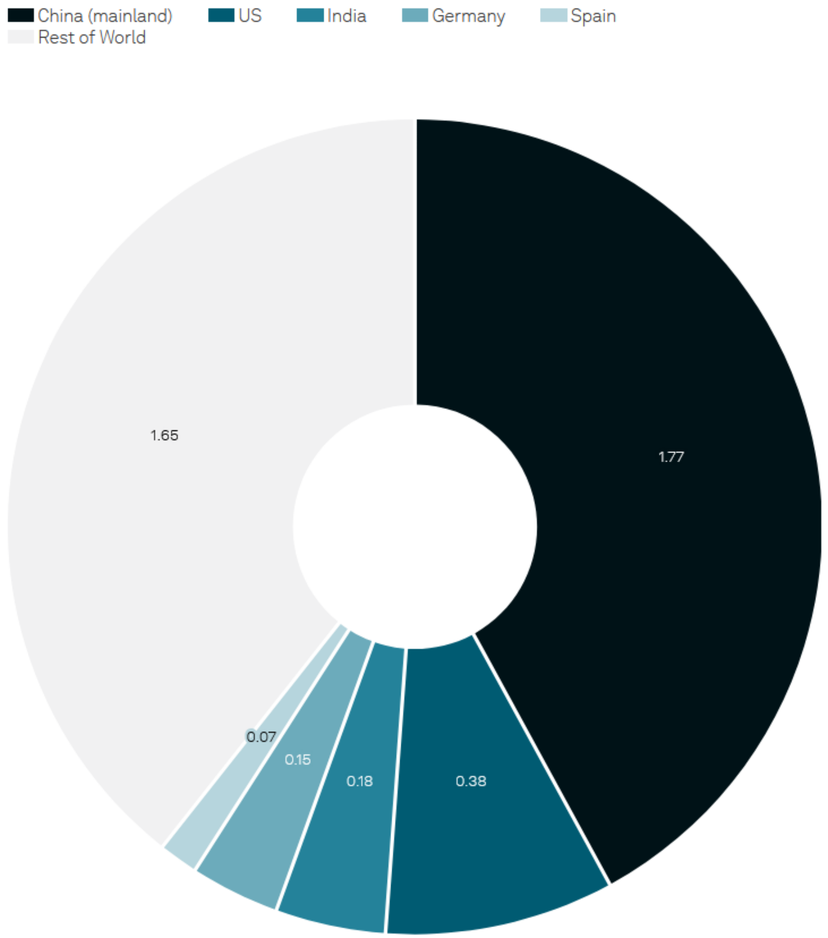
Hybrid Inverter

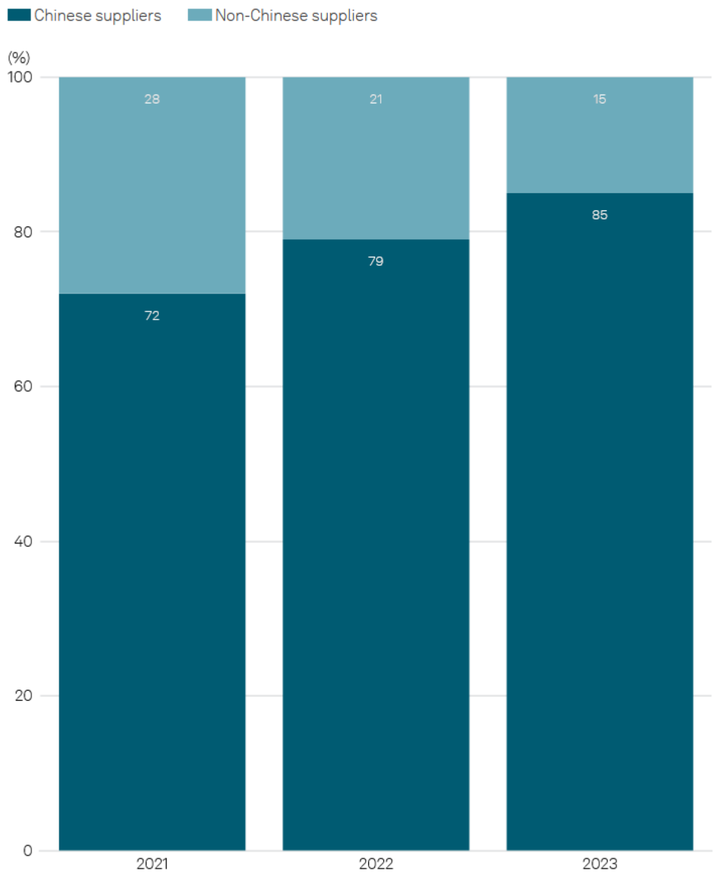
Technical data	Sunny Boy Smart Energy 3.6	Sunny Boy Smart Energy 4.0	Sunny Boy Smart Energy 5.0	Sunny Boy Smart Energy 6.0
Input PV (DC)				
Max. PV array power	7200 Wp	8000 Wp	10000 Wp	12000 Wp
Max. input voltage	600 V			
Min. input voltage	60 V			
MPP voltage range	60 V to 480 V			
Startup input voltage	66 V			
Max. usable input current input A / B / C	15 A			
Max. DC short-circuit current input A / B / C	up to 30 A[5)]			
Number of independent MPP inputs / inputs per MPP	3 / 1			
Connection of MPP inputs in parallel possible	A and B[3)]			
Input battery (DC)				
Battery type	Lithium-Ion batteries[1)]			
Voltage range	90 V to 500 V			
Max. charging current / max. discharging current	30 A / 30 A			
Number of independent battery inputs	1			
Max. charging power	10000 W			
Max. discharging power	3789 W	4211 W	5263 W	6316 W

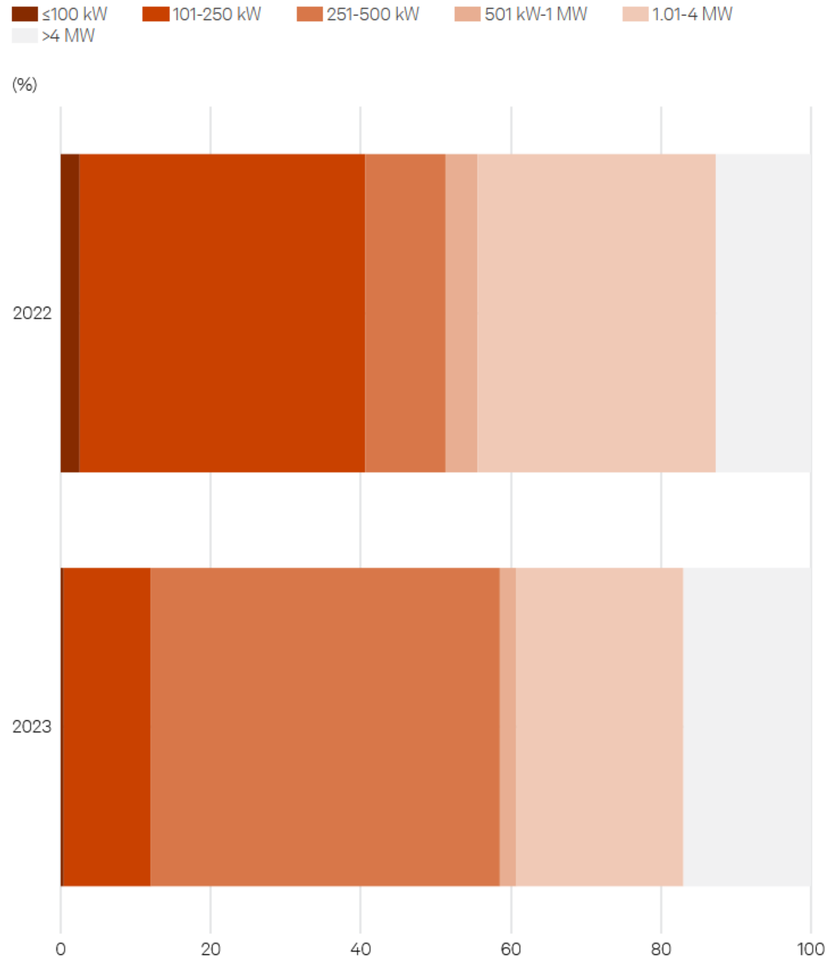
Solar-only and hybrid Inverter



Inverter market 2024





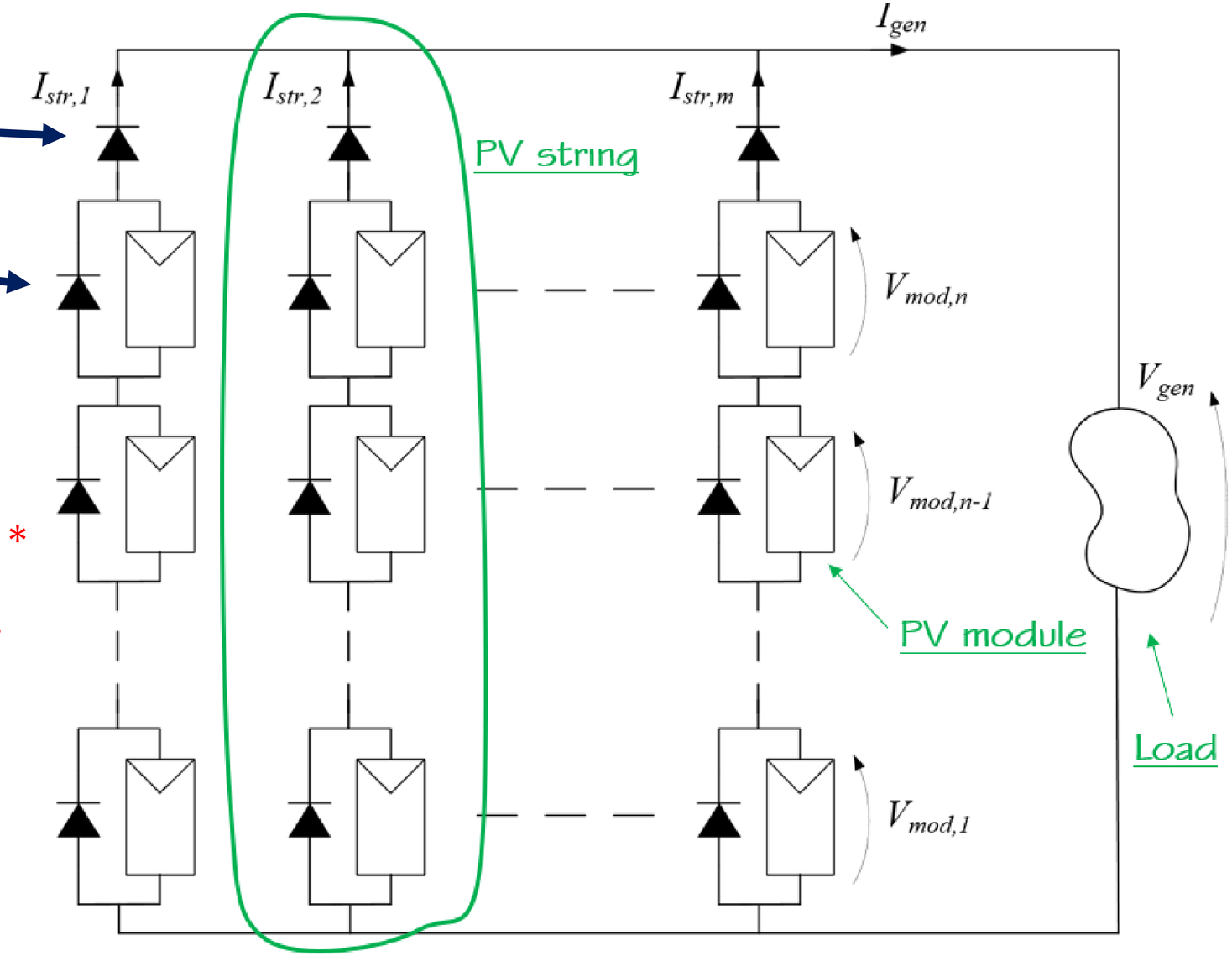


S&P Global

Photovoltaic generator

Blocking diode
Optional
Stand-alone systems

Bypass diode
More than one inside the junction box

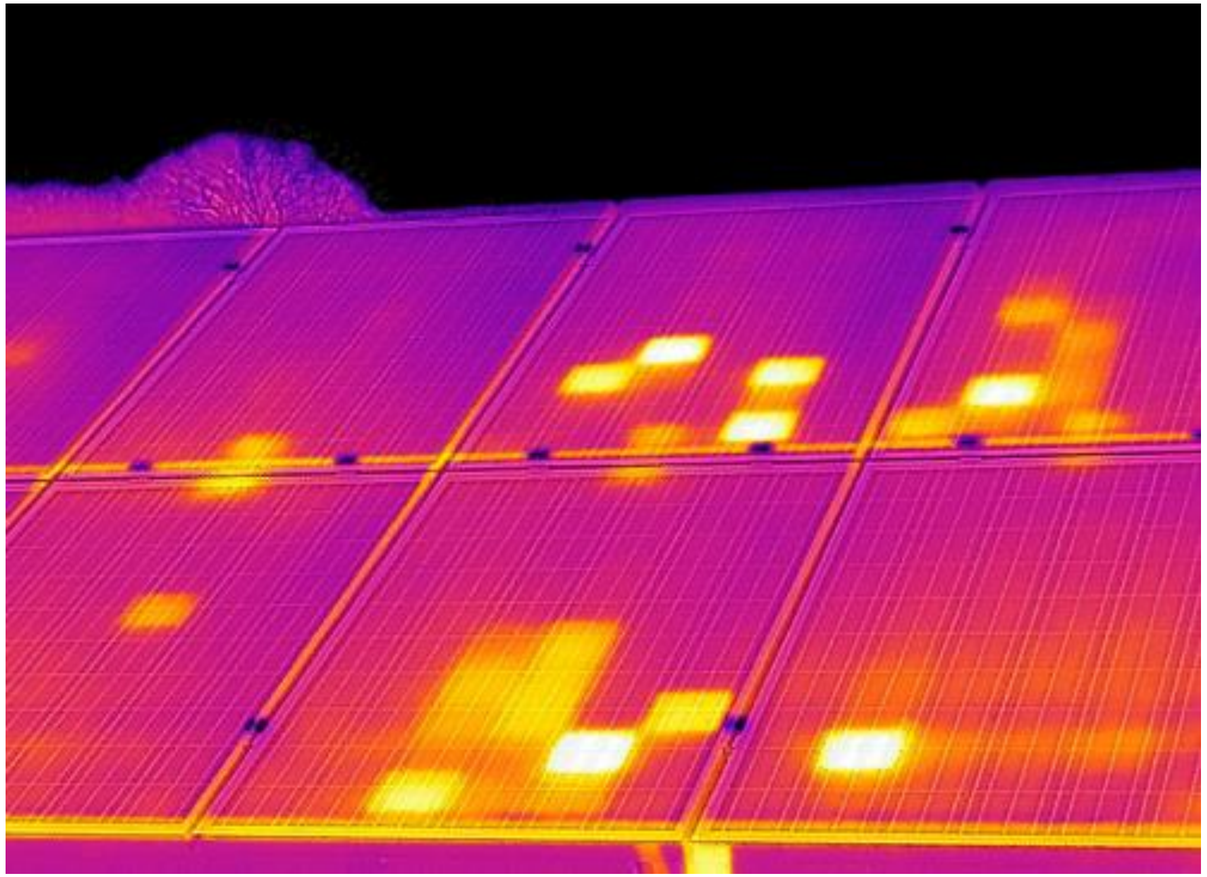


$$I_{str,i} = I^*_{mod} \qquad V_{str} = \sum_{j=1}^{n} V_{mod,j}$$

$$I_{gen} = \sum_{i=1}^{m} I_{str,i} \qquad V_{gen} = V_{str}$$

The hotspot phenomenon

The **hotspot problem** in PV modules refers to a condition where certain cells in a photovoltaic module become **significantly hotter** than others, potentially causing damage to the panel and reducing its overall performance and lifespan.

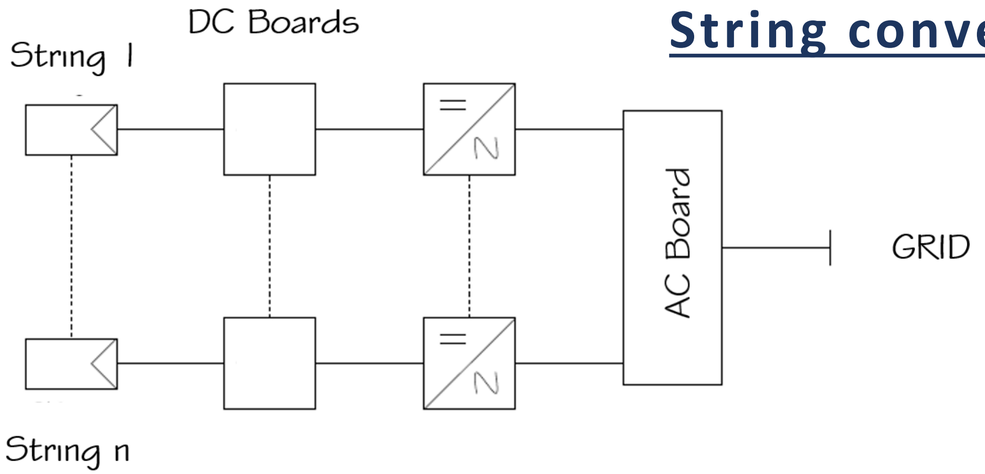


Causes:

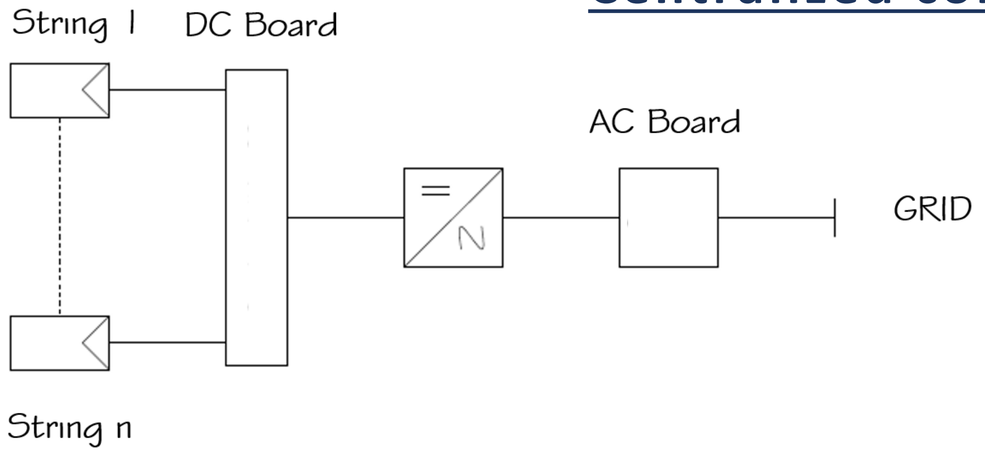
- Partial Shading: when a part of a PV module is shaded
- Current Mismatch: different photogenerated current
- Degradation: different performances

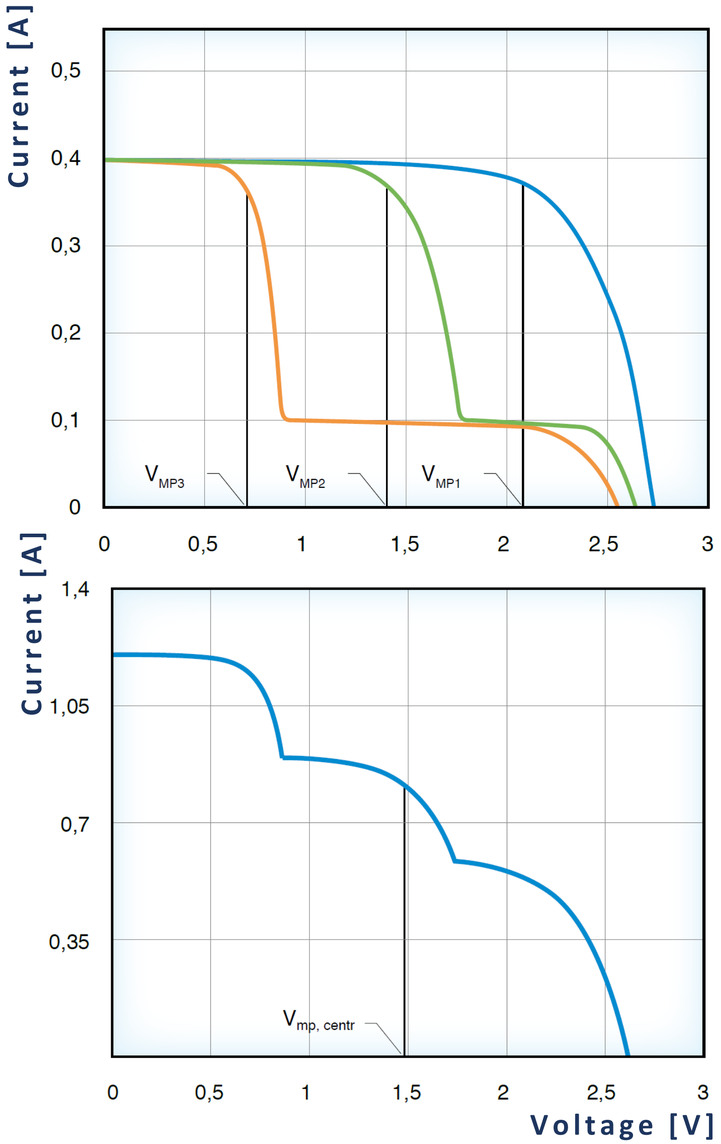
Power conversion

String conversion



Centralized conversion





Coupling inverter and PV field

Nominal power

$$P_{AC,n} > PR \times P_n$$

Maximum DC current

$$I_{SC,mod\ max} = I_{SC}(G) + z \times (T_{max} - 25)$$

$$I_{SC}(G) = \frac{G}{1000} \times I_{SC,STC}$$

$$I_{DC\ max} > m \times I_{SC,mod\ max}$$

Minimum MPP voltage

$$V_{MP,mod\ min} = V_{MP} + w \times (T_{max} - 25)$$

$$V_{MP\ min} < n \times V_{MP,mod\ min}$$

Maximum MPP voltage

$$V_{MP,mod\ max} = V_{MP} + w \times (T_{min} - 25)$$

$$V_{MP\ max} > n \times V_{MP,mod\ max}$$

Maximum DC voltage

$$V_{OC,mod\ max} = V_{OC} + w \times (T_{min} - 25)$$

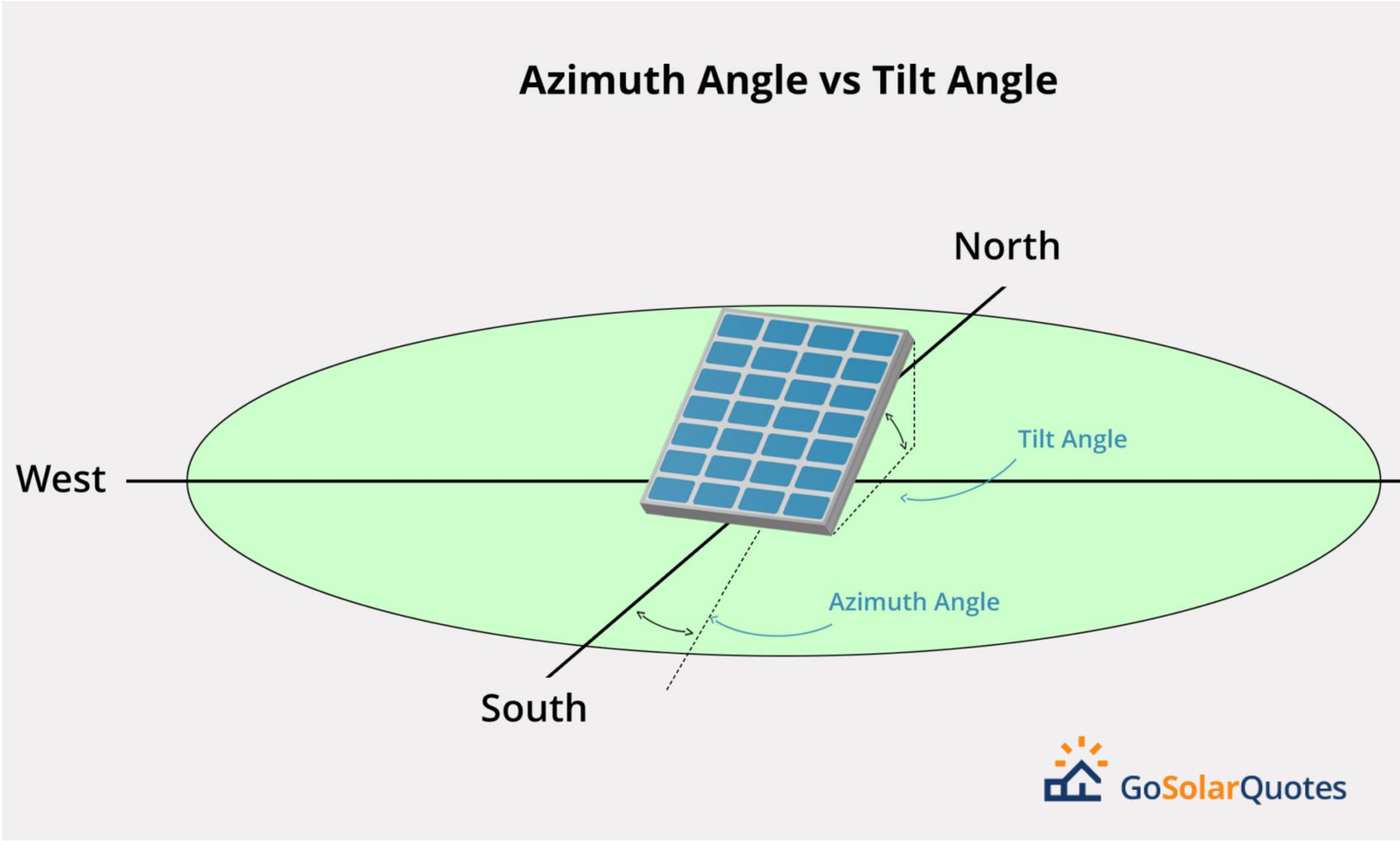
$$V_{DC\ max} > n \times V_{OC,mod\ max}$$

Mounting options

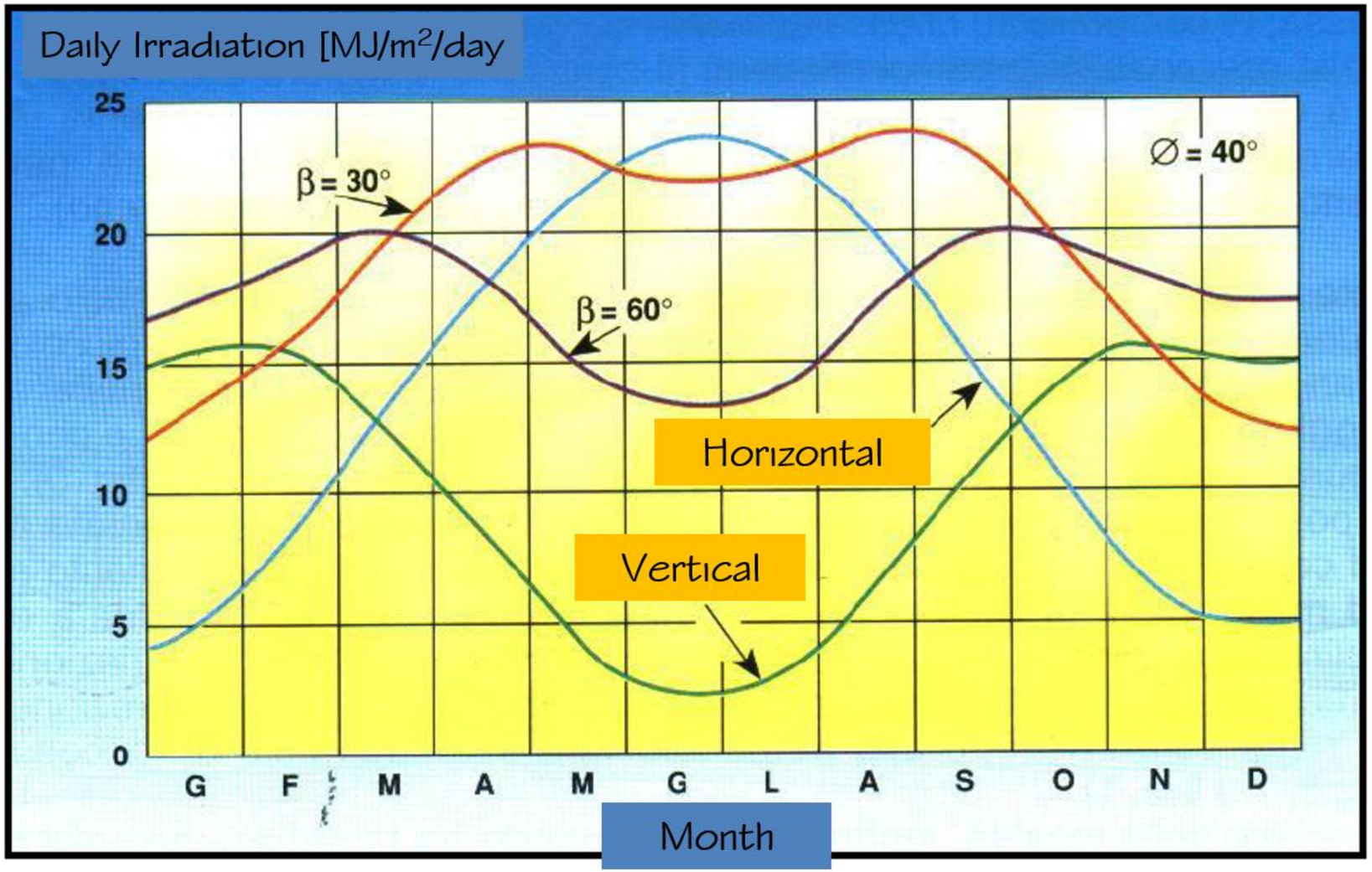
Type of system: fixed or tracking, free standing or BIPV

Tilt angle: slope of the photovoltaic module
β [0° - 90°]

Azimuth angle: orientation of the photovoltaic module
α [-180° - + 180°]



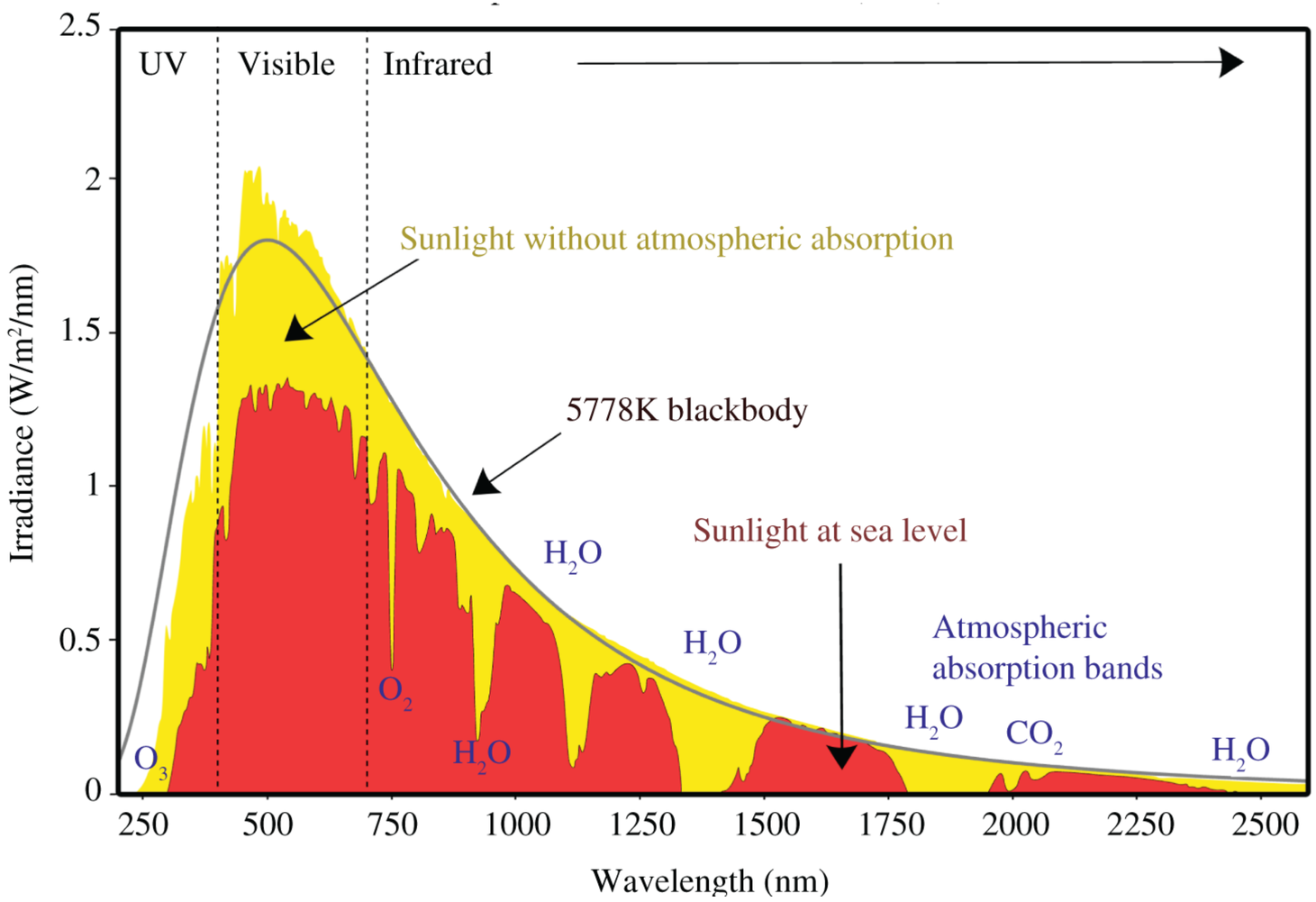
Optimizing the tilt angle



Definitions

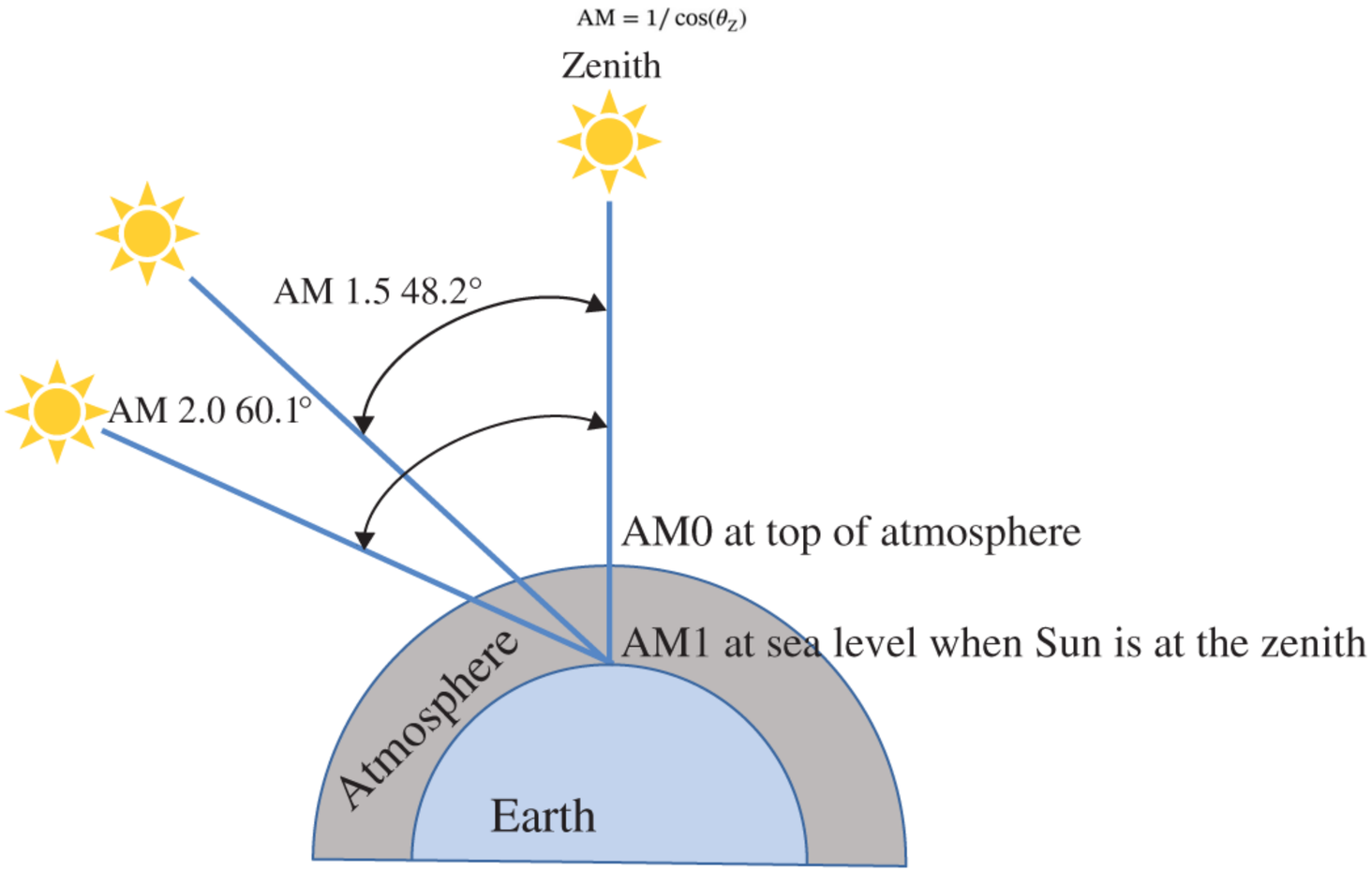
- ✓ **Solar radiation**: general meaning
- ✓ **Irradiation** [Wh/m2]: energy received per unit area
- ✓ **Irradiance** [W/m2]: power received per unit area
- ✓ **Yield** [kWh/kWp]: yearly output energy referred to the nominal power
- ✓ **Solar constant**: energy received from the Sun per unit of time per unit of area on a theoretical surface perpendicular to the Sun's rays and at Earth's mean distance from the Sun, roughly 1,367W/m2

Spectral content of sunlight



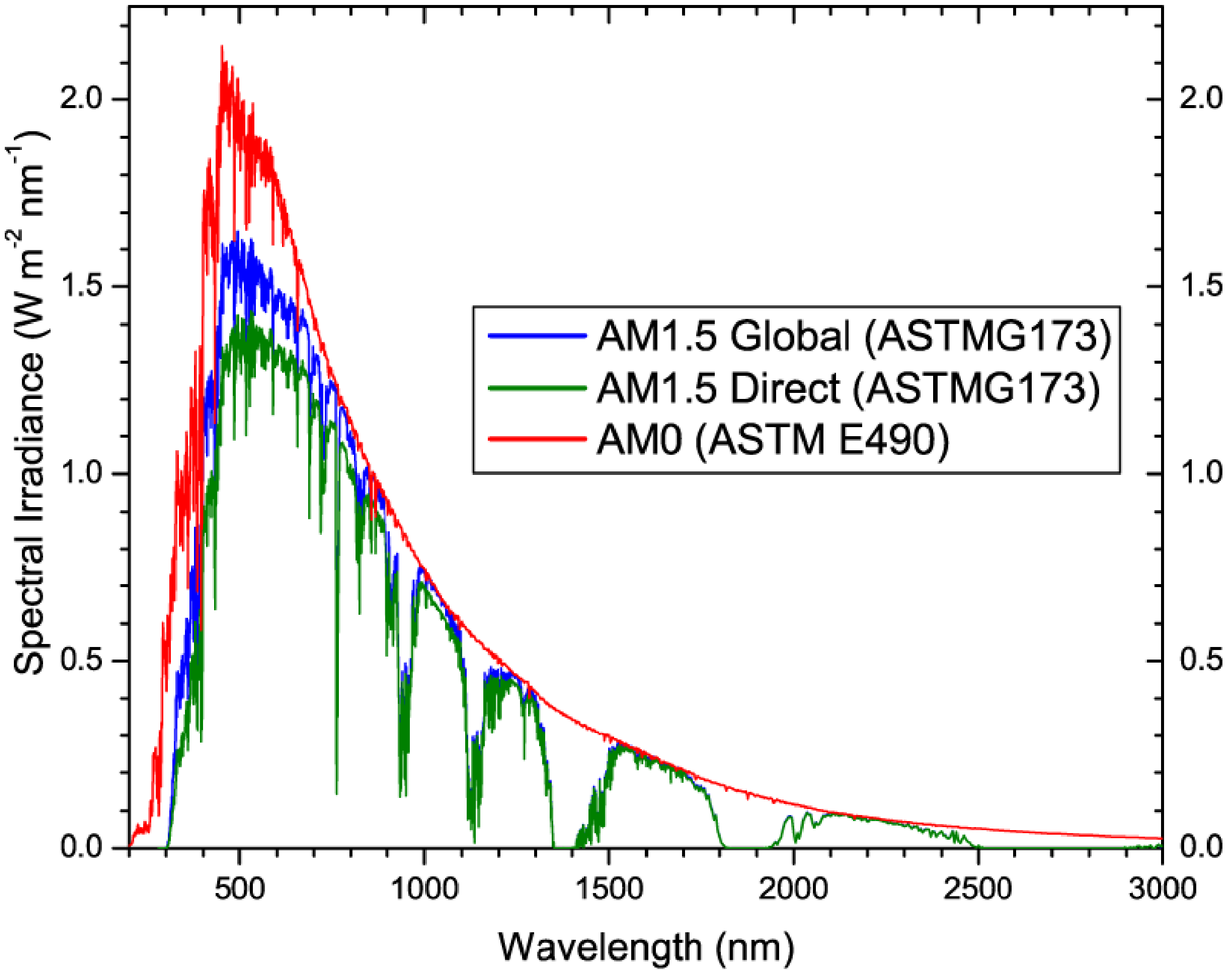
Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

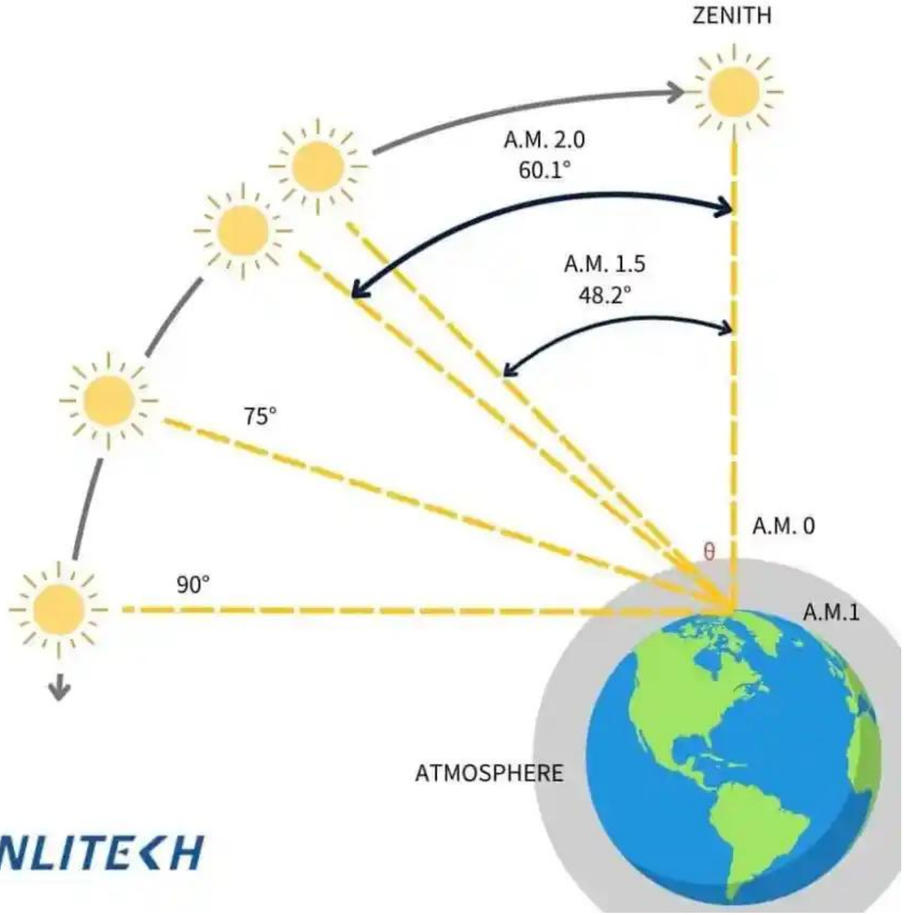
Spectral content of sunlight



Photovoltaic Solar Energy: From Fundamentals to Applications, Volume 2, Wiley 2024

Air Mass

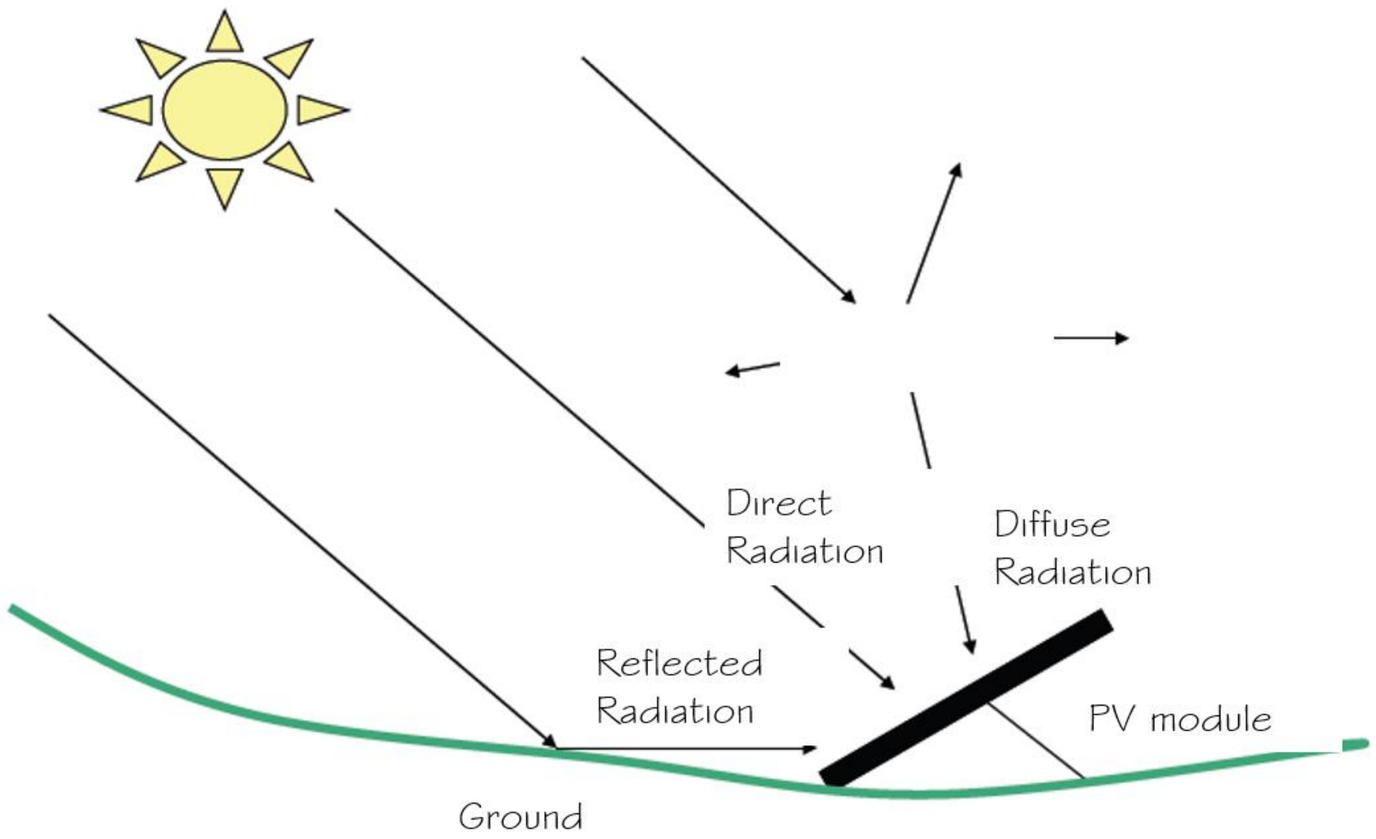




ENLITECH

https://www.youtube.com/watch?v=vXEwiGKlcG8

Solar radiation components



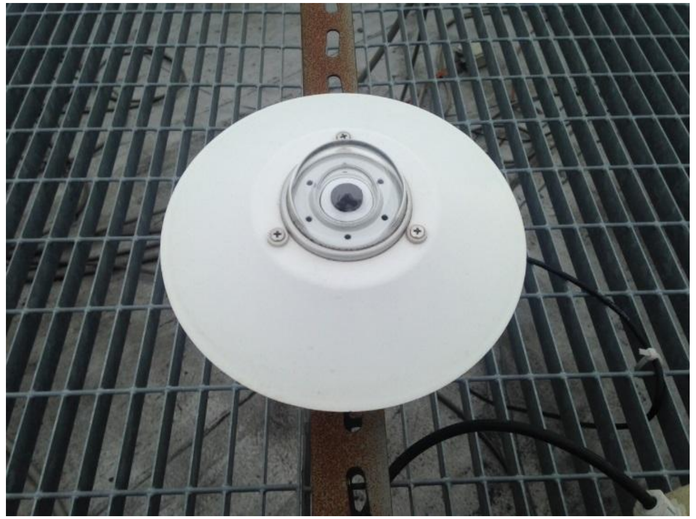
1. **Solar radiation** G
2. **Direct radiation** I
3. **Diffuse radiation** D
4. **Reflected radiation** R

G = I + D + R = f (geometric parameters, time, meteorology, shading)

Solarimeters







Geometric parameters

PV GENERATOR

- ✓ Tilt Angle ß: slope of the PV modules
- ✓ Azimuth Angle α: orientation of the PV modules

LOCATION

- ✓ Latitude L [0 – 90°]: specify the north-south position of a point on the Earth's surface
- ✓ Solar Elevation [0 – 90°]: is the altitude of the sun

$$\sin\gamma = \sin L \times \sin\delta + \cos L \times \cos\delta \times \cos\omega$$

Time parameters

Hour angle: converts the local solar time into the number of degrees which the sun moves across the sky

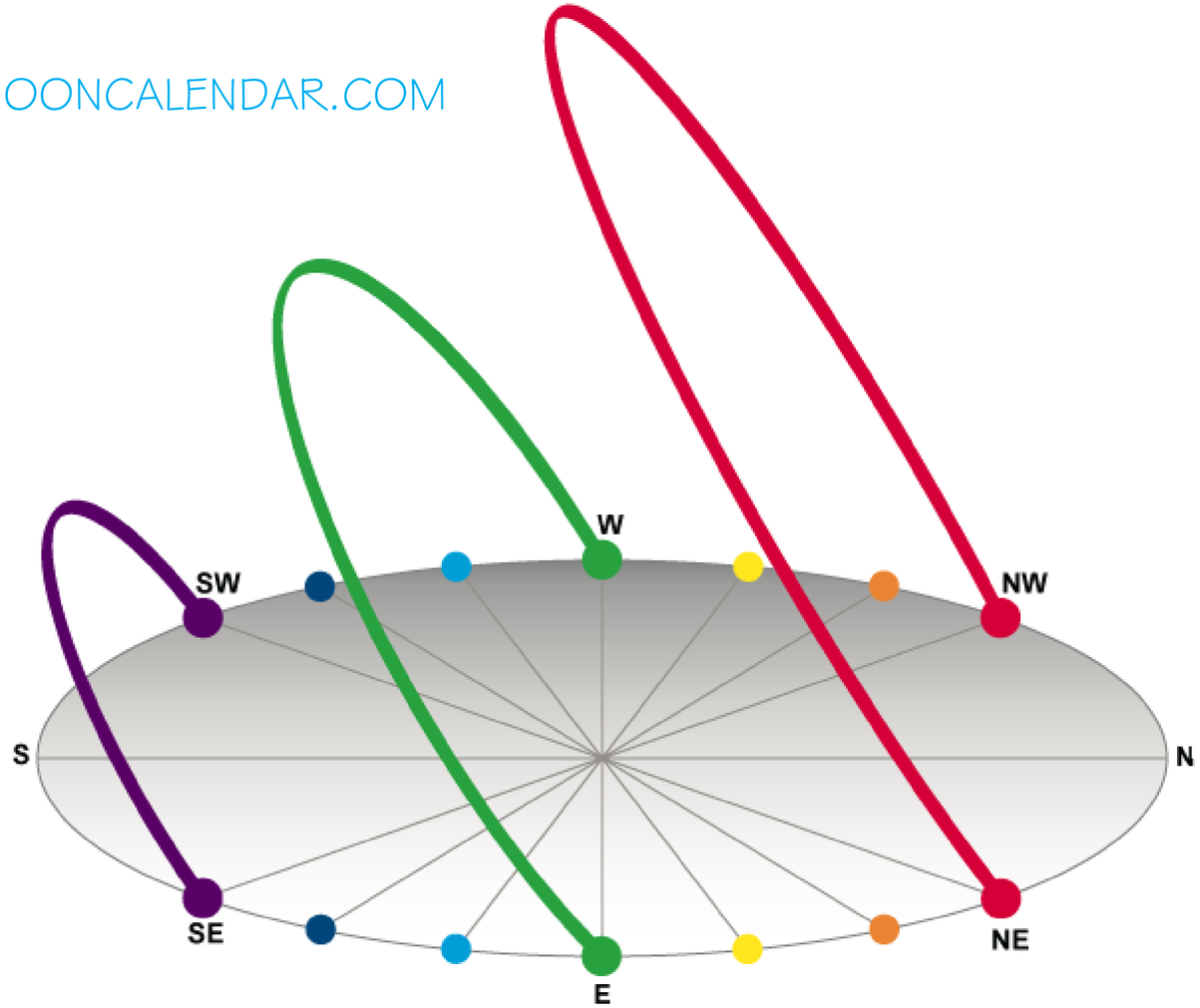
$$\omega = 15 \times (12 - t_s)$$

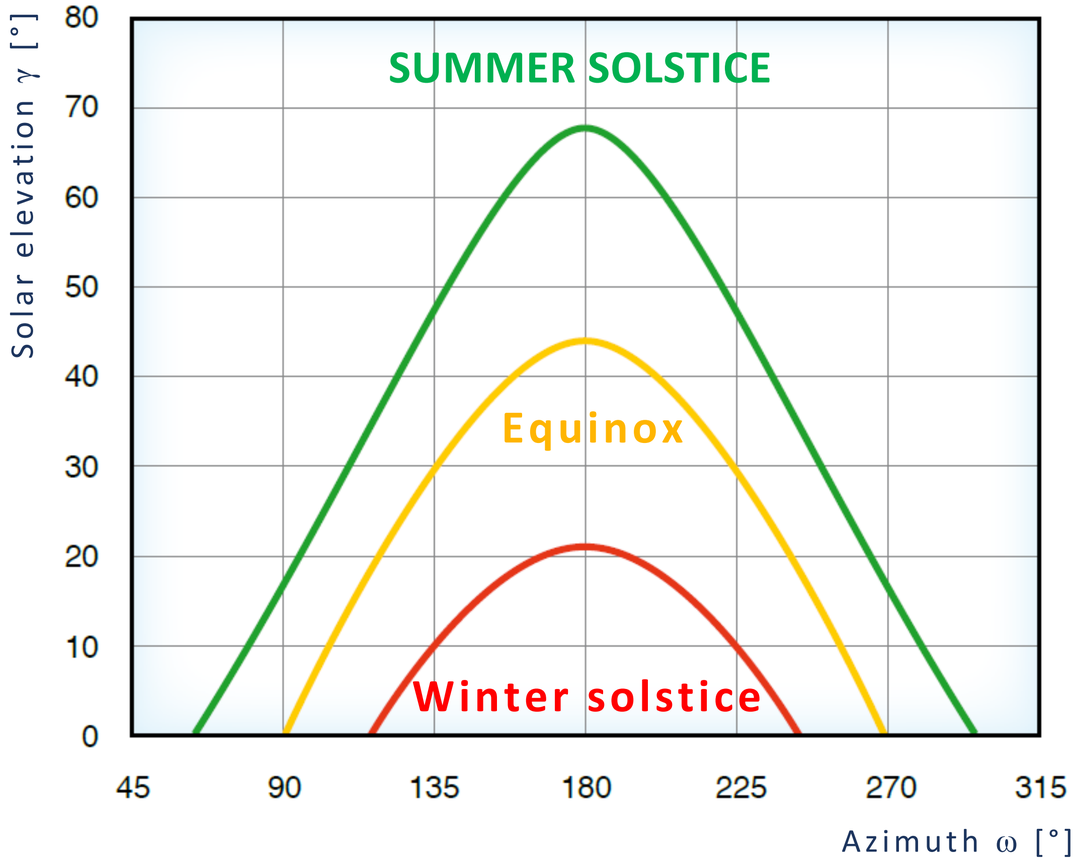
Declination of the Sun: is the angle between the equator and a line drawn from the center of the Earth to the center of the sun

$$\delta = 23,45 \sin\left(360 \times \frac{284 + n}{365}\right)$$

Trajectories of the sun

SUNMOONCALENDAR.COM

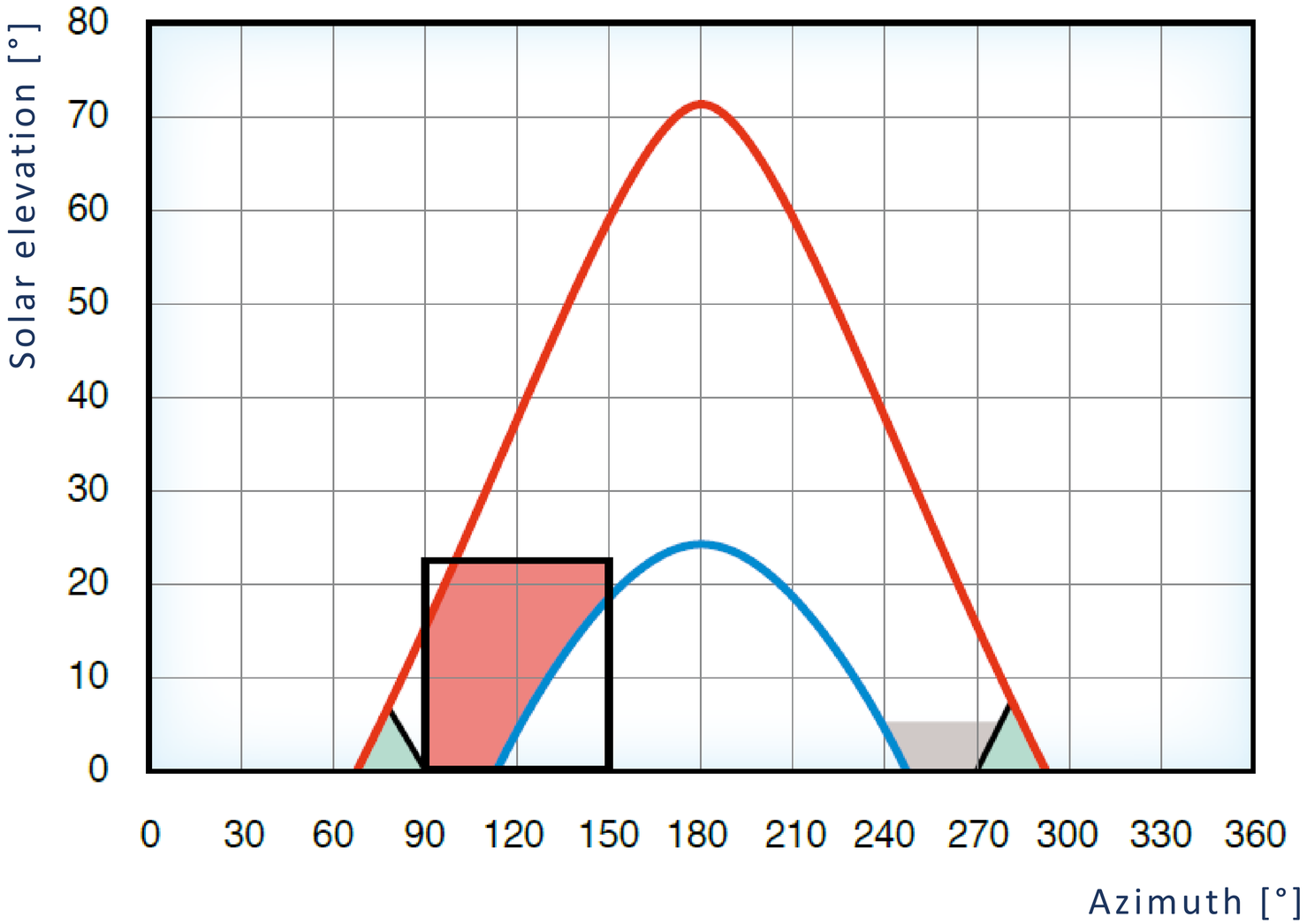




	20/03	21/06	21/12
γ [°]	44	68	21
ω_a [°]	90	64	116
ω_t [°]	270	296	244

https://www.earthspacelab.com/app/solar-time/

Shading – Clinometric profile

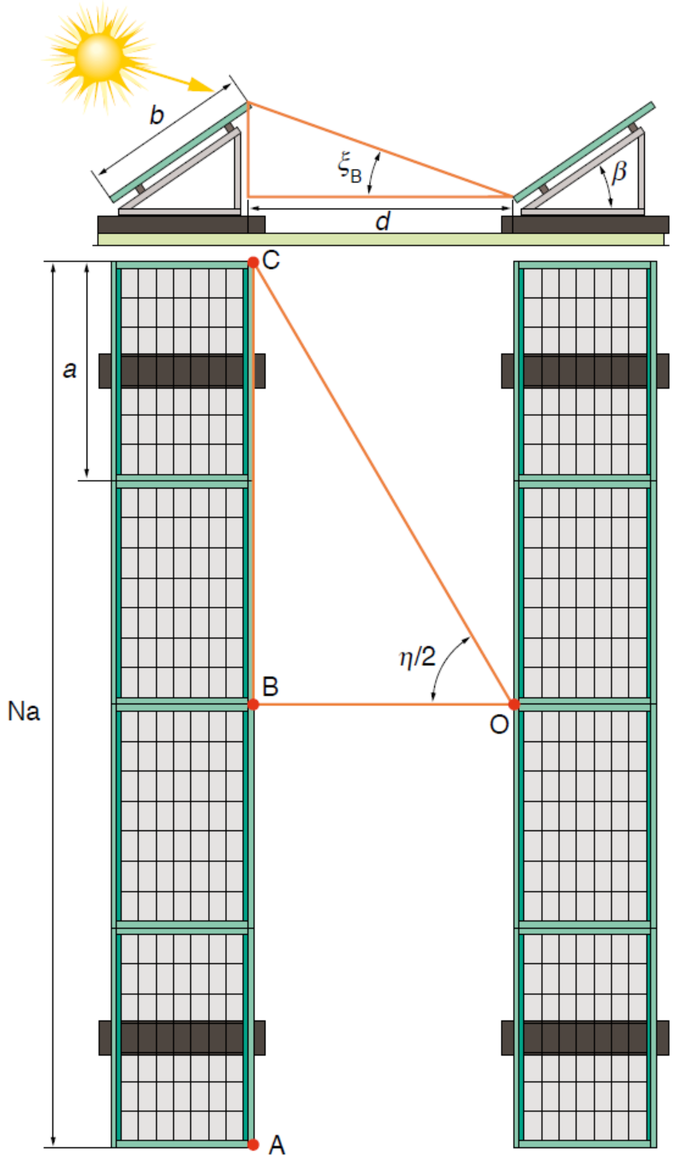


Parallel rows

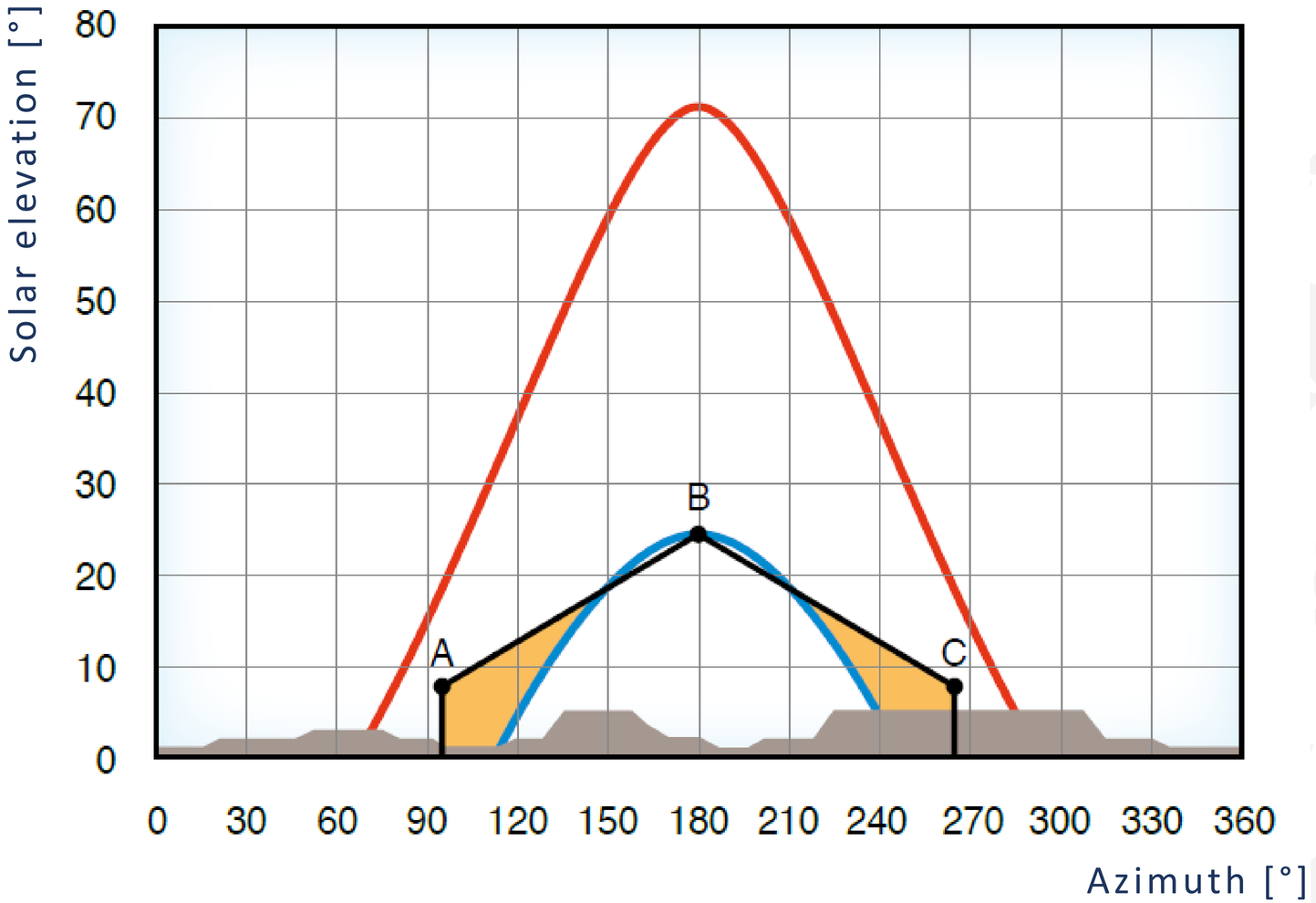
$$\xi_B < \gamma_{21dic,12:00}$$

$$\gamma_{12:00} = \sin^{-1}(\sin L \times \sin \delta + \cos L \times \cos \delta)$$

$$d = \frac{b \times \sin \beta}{\tan \xi_B}$$



Shading - Parallel rows



Solar radiation components

ANGLE OF INCIDENCE

$$\cos\mu = \sin\delta \times \sin L \times \cos\beta - \sin\delta \times \cos L \times \sin\beta \times \cos\alpha +$$

$$\cos\delta \times \cos L \times \cos\beta \times \cos\omega + \cos\delta \times \sin L \times \sin\beta \times \cos\alpha \times \cos\omega +$$

$$\cos\delta \times \sin\beta \times \sin\omega \times \sin\alpha$$

The direct, diffuse and reflected components are

$$I = I_{OR} \times \cos\mu$$

$$D = D_{OR} \times (1 + \cos\beta)/2$$

$$R = G_{OR} \times \rho_g \times (1 - \cos\beta)/2$$

GROUND SURFACE	ALBEDO P_G
Water	0.70
Dry leaves	0.30
Green Grass	0.26
Concrete	0.22
Dark wall	0.27
Bright wall	0.60

Some models as the **Liu and Jordan model** take into account the presence of clouds

Average daily irradiation

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

Cursor:

Selected: 45.650, 13.771

Elevation (m): 15

PVGIS ver. 5.2

Use terrain shadows:

- [x] Calculated horizon
- [ ] Upload horizon file

csv | json

Sfoglia... Nessun file selezionato.

Switch to version 5.1

AVERAGE DAILY IRRADIANCE DATA

Solar radiation database*: PVGIS-SARAH2

Month*: June

- ( ) UTC time
- (•) Local time

On fixed plane:

- [x] Irradiance
- [ ] Clear-sky irradiance

Slope [°]: 35

Azimuth [°]: 0

On sun-tracking plane:

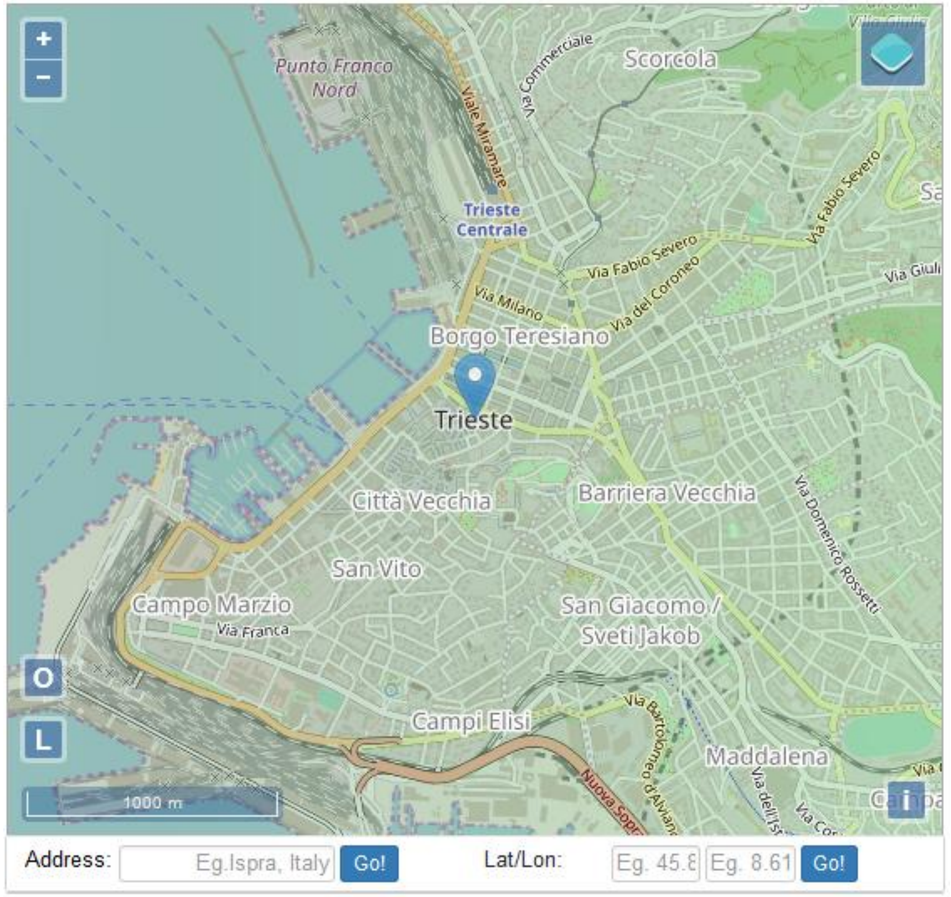
- [ ] Irradiance
- [ ] Clear-sky irradiance

Temperature:

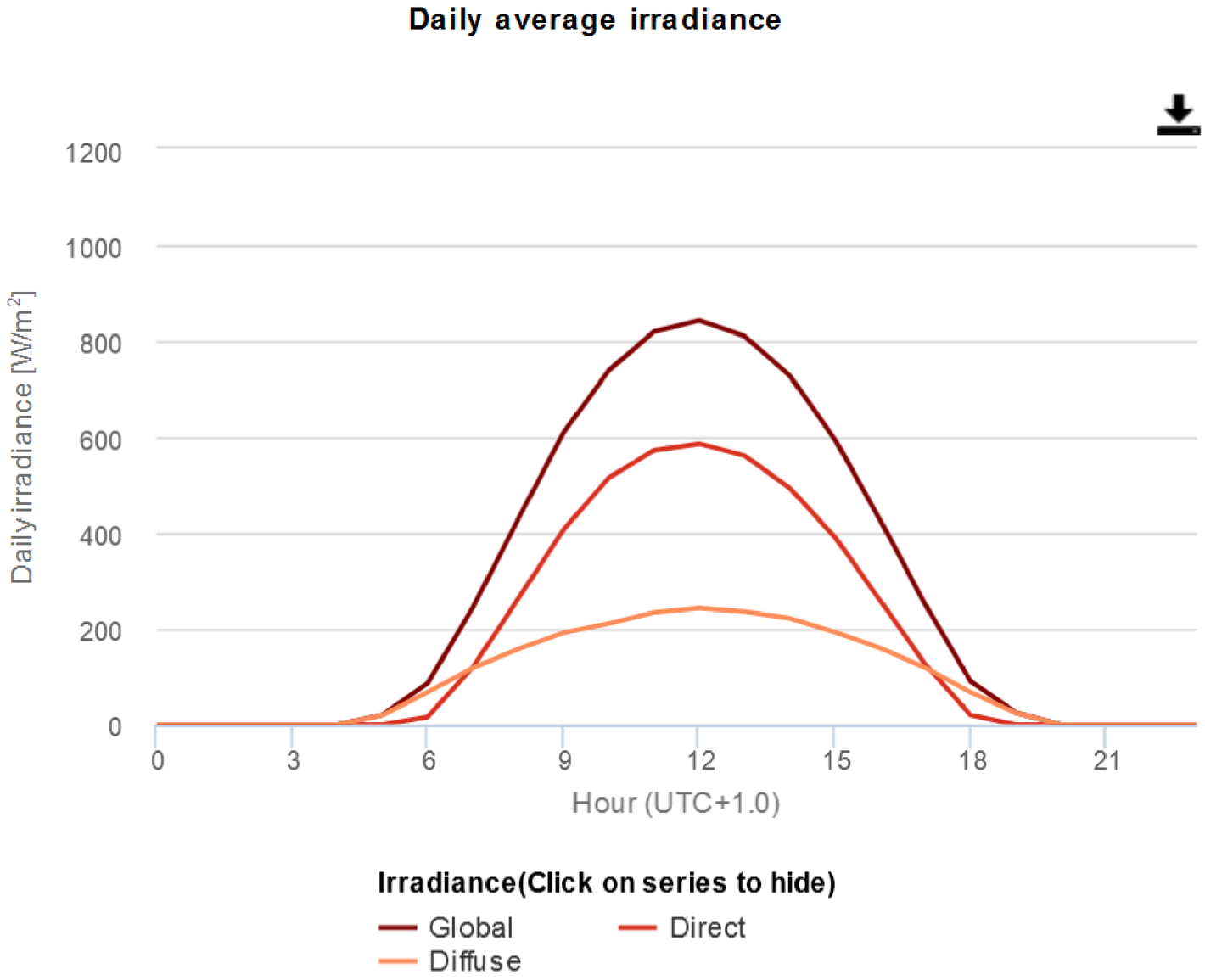
- [x] Daily temperature profile

PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM

European Commission



Results


Daily average irradiance
Daily irradiance [W/m²]
1200
1000
800
600
400
200
0
0
3
6
9
12
15
18
21
Hour (UTC+1.0)
Irradiance(Click on series to hide)
Global
Direct
Diffuse

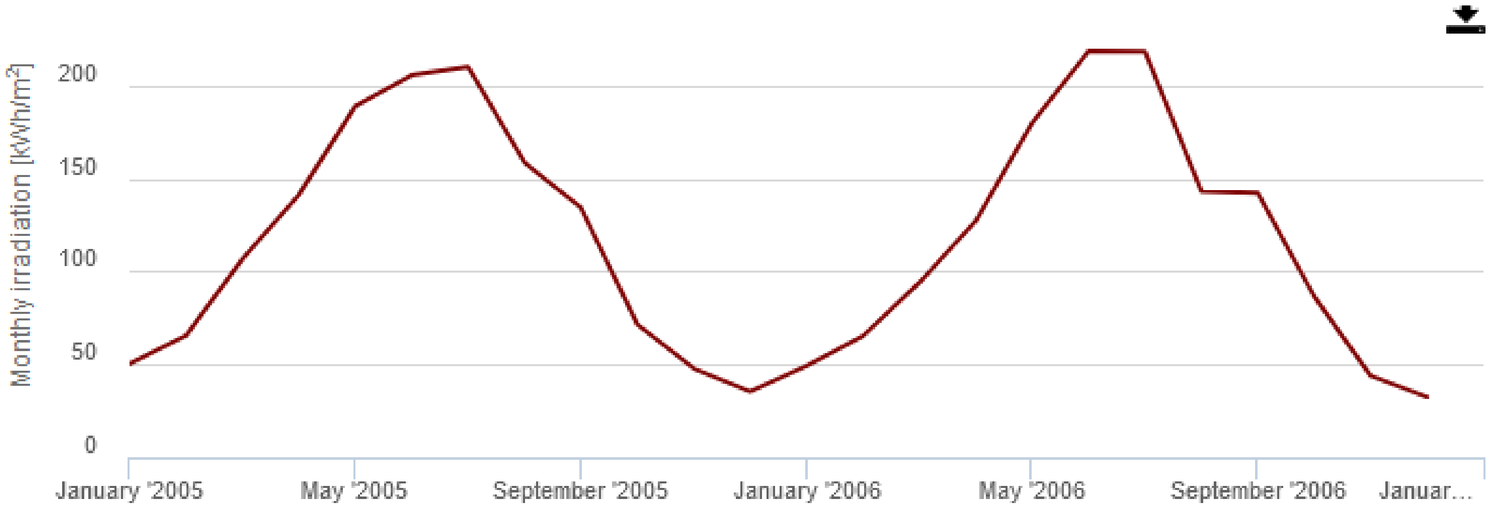
Results

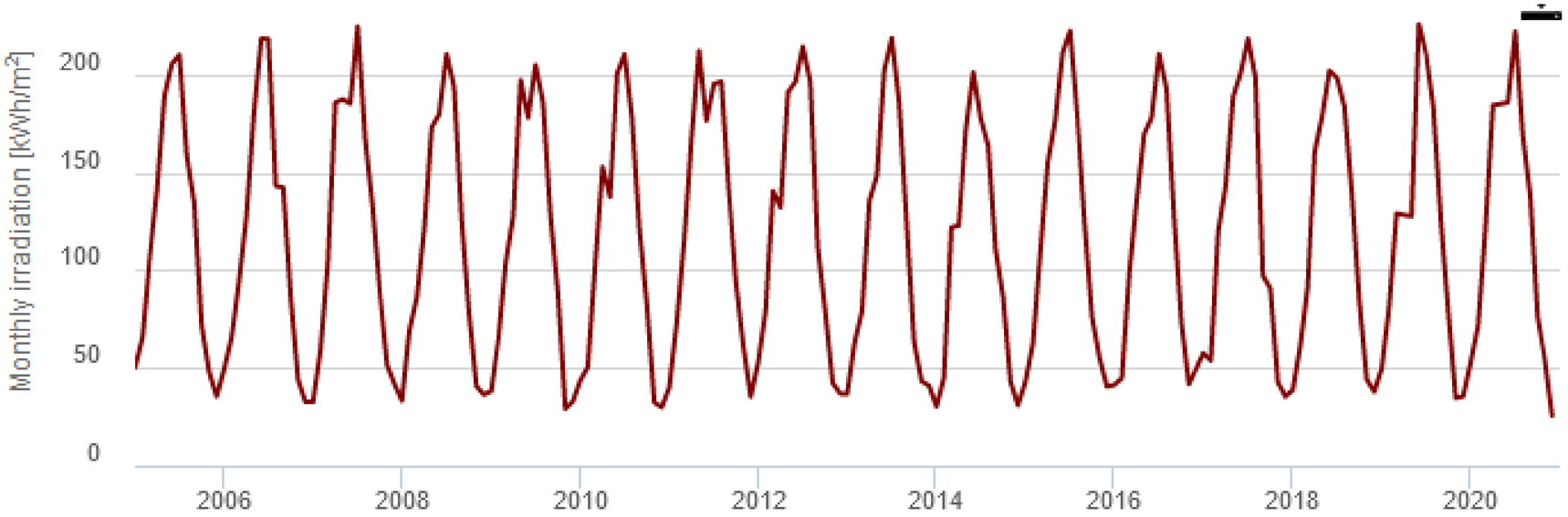
Irradiance on a fixed plane

Time	00:45	01:45	02:45	03:45	04:45	05:45	06:45	07:45	08:45	09:45	10:45	11:45	12:45	13:45	14:45	15:45	16:45	17:45	18:45	19:45	20:45	21:45	22:45	23:45
G(i)	0	0	0	0	0	20	87	245	428	609	738	819	842	810	728	594	426	249	90	25	0	0	0	0
Gb(i)	0	0	0	0	0	0	16	121	263	406	514	572	585	561	493	391	259	125	20	0	0	0	0	0
Gd(i)	0	0	0	0	0	20	68	119	158	192	211	234	243	235	222	193	159	119	67	24	0	0	0	0

G(i): Global irradiance on a fixed plane [W/m2].
Gb(i): Direct irradiance on a fixed plane [W/m2].
Gd(i): Diffuse irradiance on a fixed plane [W/m2].

Monthly data

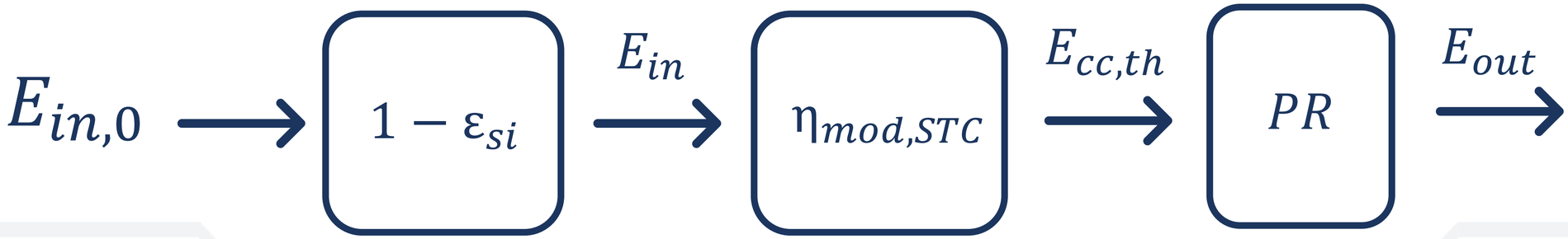




Hourly data

A	B	
Latitude (decimal degrees):45.650		
Longitude (decimal degrees):13.771		
Elevation (m):15		
Radiation database:PVGIS-SARAH2		
Slope: 37 deg. (optimum)		
Azimuth: 0 deg.		
time	G(i)	H
20050101:0010	0	
20050101:0110	0	
20050101:0210	0	
20050101:0310	0	
20050101:0410	0	
20050101:0510	0	
20050101:0610	0	
20050101:0710	0	
20050101:0810	29.22	
20050101:0910	559.99	
20050101:1010	743.13	
20050101:1110	813.44	
20050101:1210	823.96	
20050101:1310	729.48	
20050101:1410	533.07	
20050101:1510	18.91	
20050101:1610	0	
20050101:1710	0	
20050101:1810	0	
20050101:1910	0	
20050101:2010	0	

Yield of a photovoltaic system



$$E_{out} = E_{in,0} \cdot (1 - \varepsilon_{si}) \cdot \eta_{mod,STC} \cdot PR$$

- PR: Performance Ratio
- ε_{si}: solar irradiance losses

Yield of a photovoltaic system

$$E_{out} = 365 \times P_n \times PR \times G_{md} \times (1 - \varepsilon_{si})$$

- P_n: nominal power
- PR: Performance Ratio
- G_{md}: daily global mean irradiation
- ε_{si}: solar irradiance losses

$$PR = \left[(1 - \varepsilon_{pu}) \times (1 - \varepsilon_{gen}) \times (1 - \varepsilon_j) \times (1 - \varepsilon_{inv})\right]$$

- ε_{pu}: pick up losses (geometry, shading, soiling, albedo)
- ε_{gen}: generator losses (temperature, mismatch)
- ε_j: Joule losses
- ε_{inv}: inverter losses

System losses

Pick up losses

$$\varepsilon_{pu} = \varepsilon_{alb} + \varepsilon_{soi}$$

Generator losses

$$\varepsilon_{gen} = \varepsilon_T + \varepsilon_{mis} \qquad \varepsilon_T = p \times (T_{CG} - 25)$$

$$\varepsilon_T = p \times \left(T_a + \frac{T_{NOCT} - 20}{800} \times G - 25 \right)$$

p – power-temperature coefficient

T_{CG} – cell temperature

T_a – ambient temperature

T_{NOCT} – Nominal Operating Cell Temperature

G – Solar Irradiance

System losses and yield

Shading	2%
Albedo and Soiling	2%
Temperature	5.5%
Mismatch	2%
Joule	2%
Inverter	3%
PR	85%

The yield of a 1kWp PV plant in Trieste with optimal tilt and azimuth angles (solar irradiance losses 4%) is

$$E_{out} = 365 \times 0.85 \times 1 \times 4.56 \times (1 - 0.04) = 1{,}358 kWh/year$$

Yield in Trieste

PERFORMANCE OF GRID-CONNECTED PV

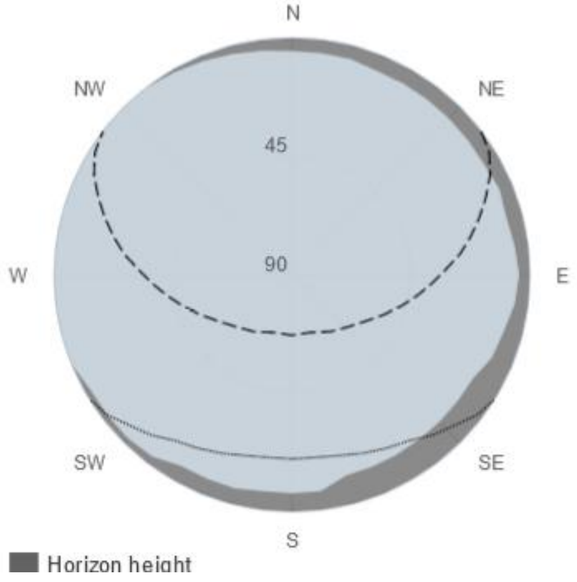
Solar radiation database*	PVGIS-SARAH2
PV technology*	Crystalline silicon
Installed peak PV power [kWp]*	1
System loss [%]*	15

Fixed mounting options

Mounting position *	Free-standing
Slope [°]*	35
Azimuth [°]*	0

☐ Optimize slope

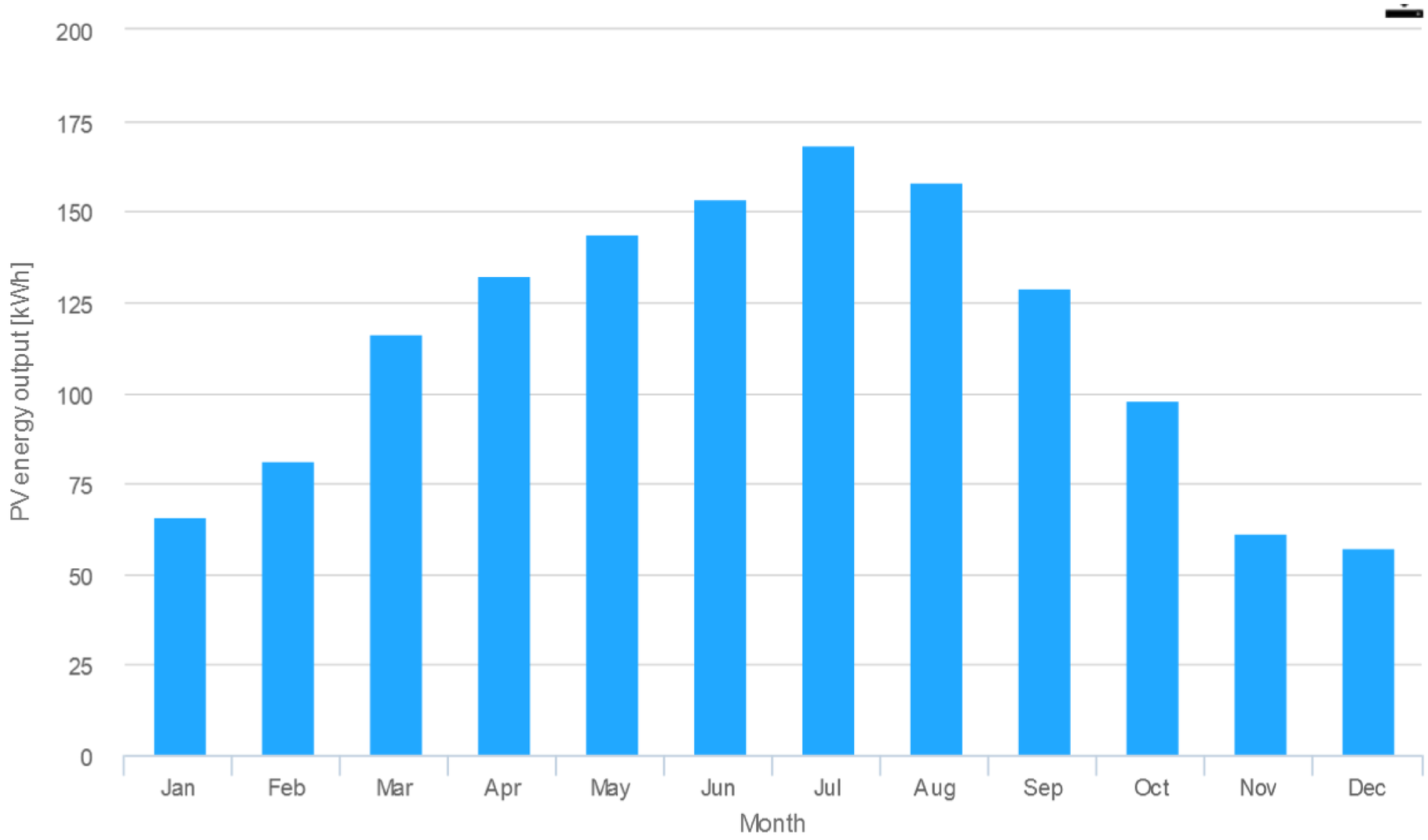
☐ Optimize slope and azimuth



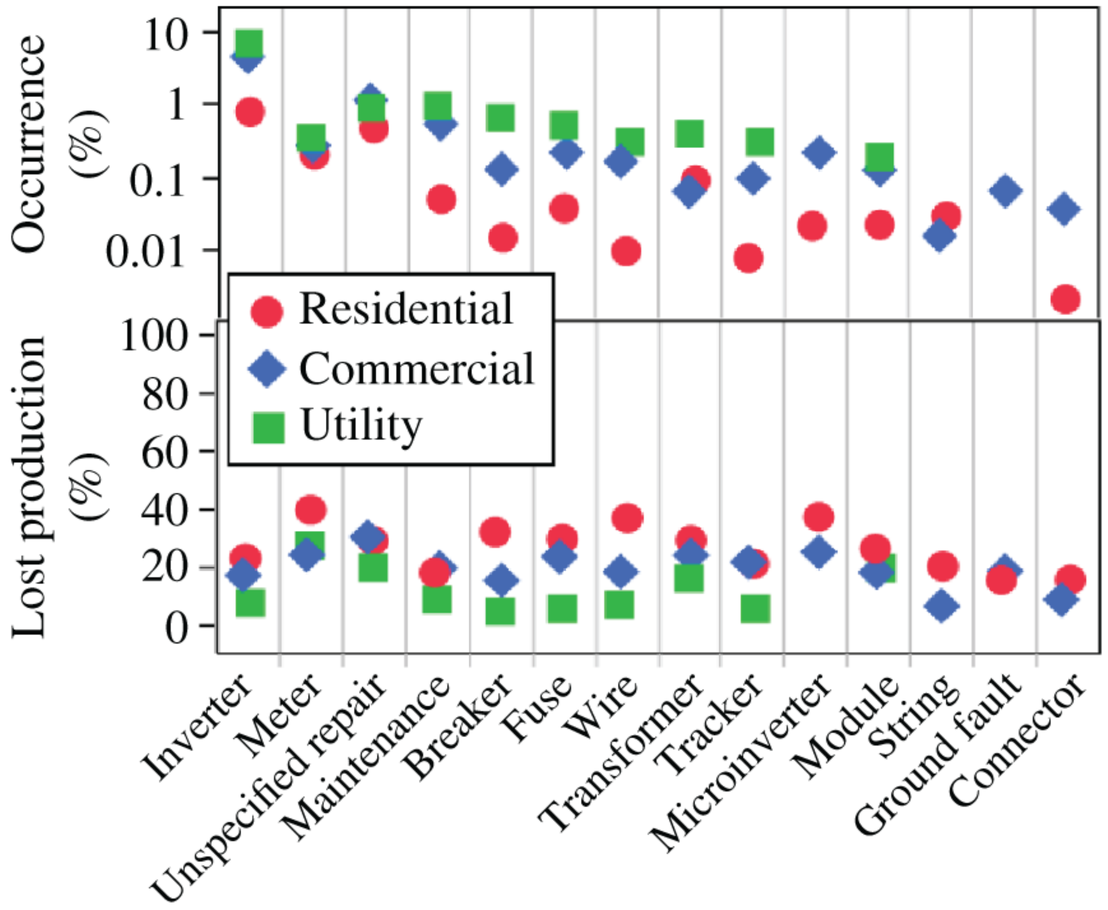
Simulation outputs:

Slope angle [°]:	35
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	1364.95
Yearly in-plane irradiation [kWh/m^2]:	1664.64
Year-to-year variability [kWh]:	75.10
Changes in output due to:	
Angle of incidence [%]:	-2.7
Spectral effects [%]:	1.15
Temperature and low irradiance [%]:	-1.99
Total loss [%]:	-18

Yield in Trieste



Failure and availability



Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

Levelized Cost of Energy

$$LCOE = VO\&MC + \frac{OCS \times CRF + FO\&MC}{8760 \times CF}$$

$$CRF = \frac{WACC \times (WACC + 1)^N}{(WACC + 1)^N - 1} \qquad WACC = \frac{E}{E + D} \times K_e + \frac{D}{E + D} \times K_d$$

- VO&MC [€/kWh]: variable operation and maintenance costs
- OCS [€/kWp]: overnight capital cost
- CRF [ ]: capital recovery factor
- FO&MC [€/kWp]: fixed operation and maintenance costs
- CF [ ]: capacity factor
- WACC [%]: weighted average cost of capital
- N [ ]: number of annuities received
- E [€]: equity – D [€]: dept
- Ke [%]: the return of equity – Kd [%]: the cost of dept

Photovoltaic Levelized Cost of Energy

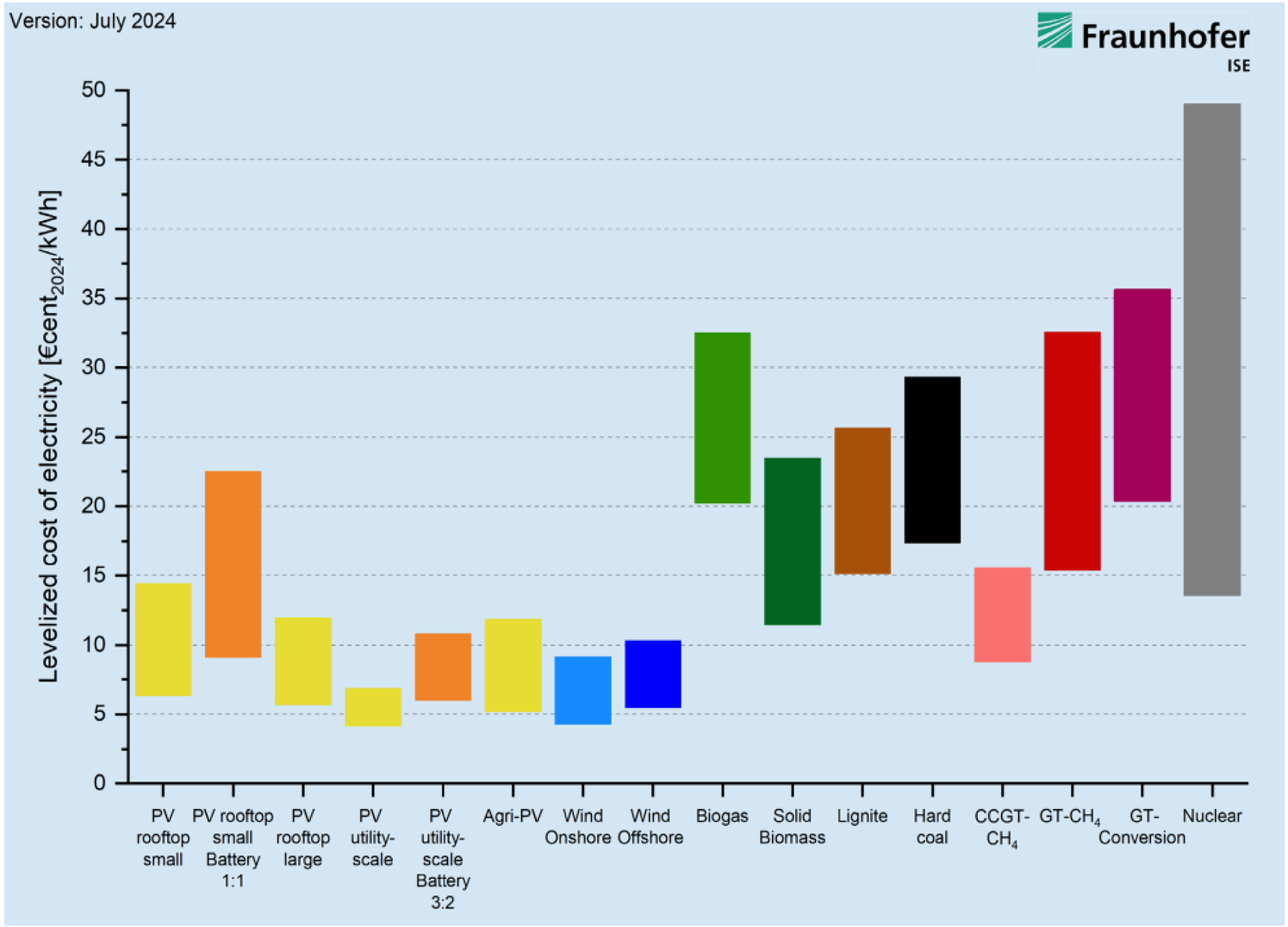
$$LCOE = \frac{OCS \times CRF \times (1 + FO\&MC)}{\frac{E_0}{N} \times \sum_{k=1}^{N} \left(1 - \frac{d_r \times (k-1)}{100}\right)}$$

- OCS [€/kWp]: overnight capital cost
- CRF [ ]: capital recovery factor
- FO&MC [%]: fixed operation and maintenance costs
- E0 [kWh/kWp/year]: yield of the plant over the first year of operations
- N [ ]: is the number of annuities received
- dr [%/year]: degradation rate of the PV modules

Photovoltaic Levelized Cost of Energy

Photovoltaic Levelized Cost of Energy

Levelized Cost of Energy for different technologies



Net Present Value (NPV)

$$NPV = -(OCS \times P_n) + \sum_{k=1}^{N} ICF_k \times \frac{(1+g)^k \times (1+e)^k}{(1+i)^k} - \sum_{k=1}^{N} OCF_k \times (1+g)^k$$

$$ICF_k = E_0 \times P_n \times \left[1 - \frac{d_r \times (k-1)}{100}\right] \times \left[P_{uf} \times sc + FiT \times (1-sc)\right] \qquad OCF_k = OCS \times P_n \times FO\&MC$$

- OCS [€/kWp]: Overnight capital cost
- ICFk [€]: Input Cash Flow
- g [%]: Inflation rate
- e [%]: Energy inflation rate
- i [%]: Interest rate
- OCFk [€]: Output Cash Flow
- E0 [kWh/kWp/year]: yield of the plant over the first year of operations
- Puf [€/kWh]: Electricity price
- FiT [€/kWh]: Feed-in tariff
- sc [ ]: Self-consumption
- Pn [kWp]: nominal power of the plant

Net Present Value

Payback time (PBT) and Internal Rate of Return (IRR)

$$NPV = -(OCS \times P_n) + \sum_{k=1}^{N} ICF_k \times \frac{(1+g)^k \times (1+e)^k}{(1+i)^k} - \sum_{k=1}^{N} OCF_k \times (1+g)^k$$

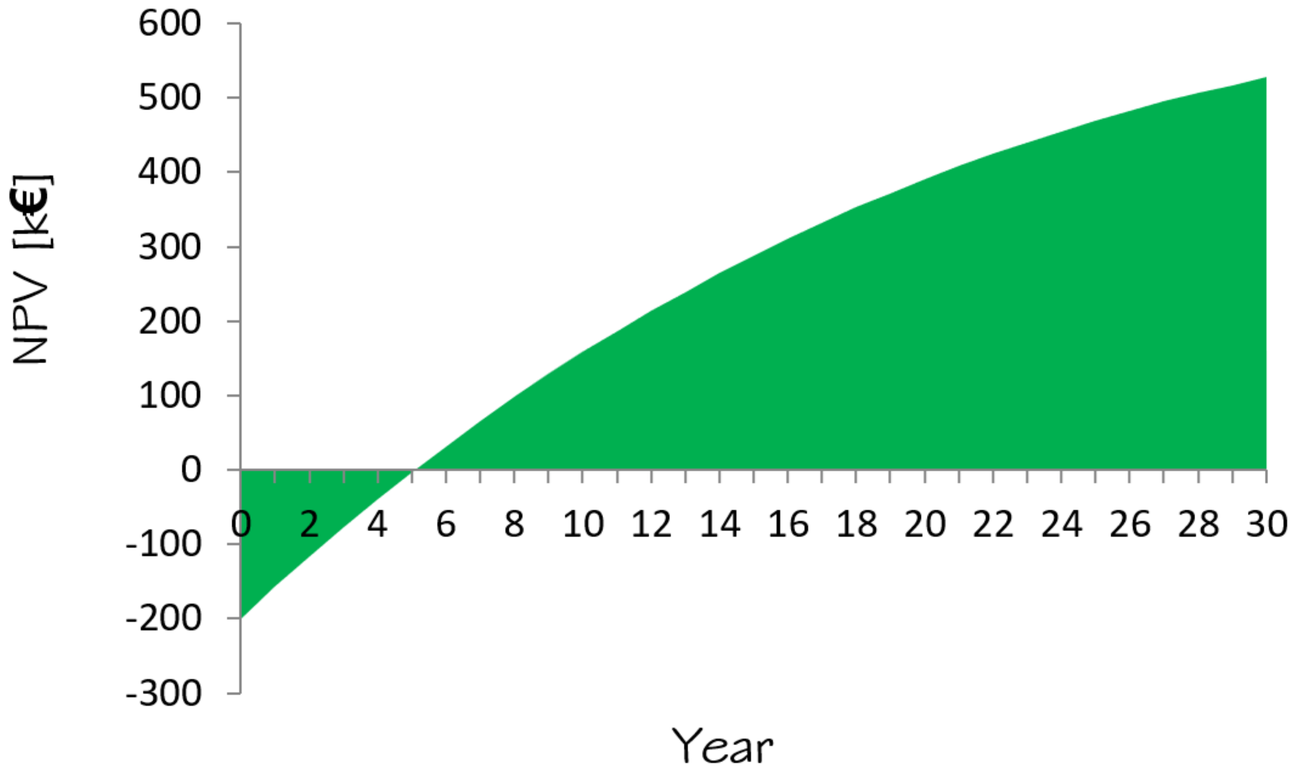
- The **payback time (PBT)** is the time corresponding to a net present value equal to zero
- The **internal rate of return (IRR)** is calculated as:

$$\frac{1}{30 \times OCS} \times \left[\sum_{k=1}^{30} ICF_k \times \frac{(1+g)^k \times (1+e)^k}{(1+i)^k} - \sum_{k=1}^{30} OCF_k \times (1+g)^k \right]$$

C&I – Debt only – Self-consumption 100%
"Old" electricity price

Power	200 kWp
OCS	1,000 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	/
E	/
Kd	8%
D	100%
EP	160 €/MWh
FiT	47 €/MWh
Sc	100%
E0	1,500
dr	0.6%

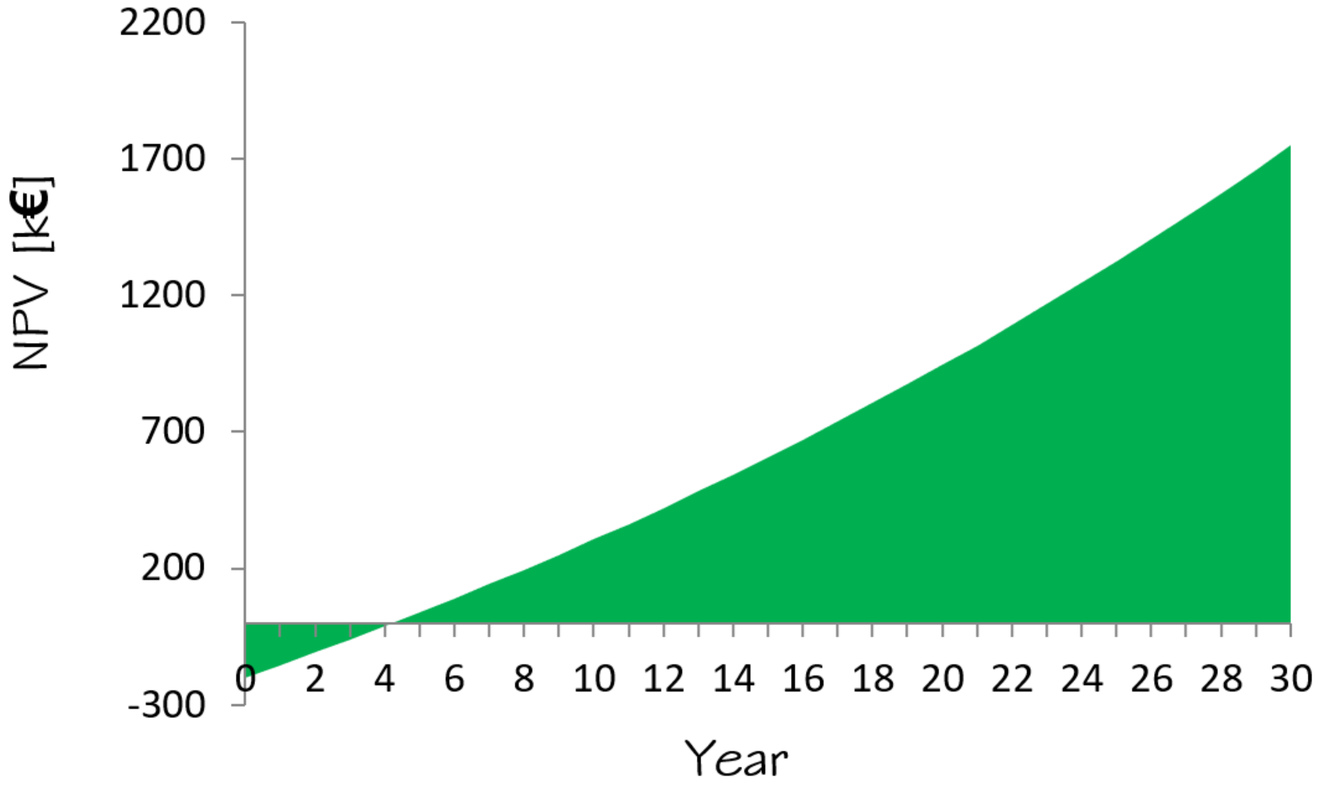
LCOE	6.62 €/kWh
PBT	5 years
IRR	12%



C&I – Equity only – Self-consumption 100%
"Old" electricity price

Power	200 kWp
OCS	1,000 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	2%
E	100%
Kd	/
D	/
EP	160 €/MWh
FiT	47 €/MWh
Sc	100%
E0	1,500
dr	0.6%

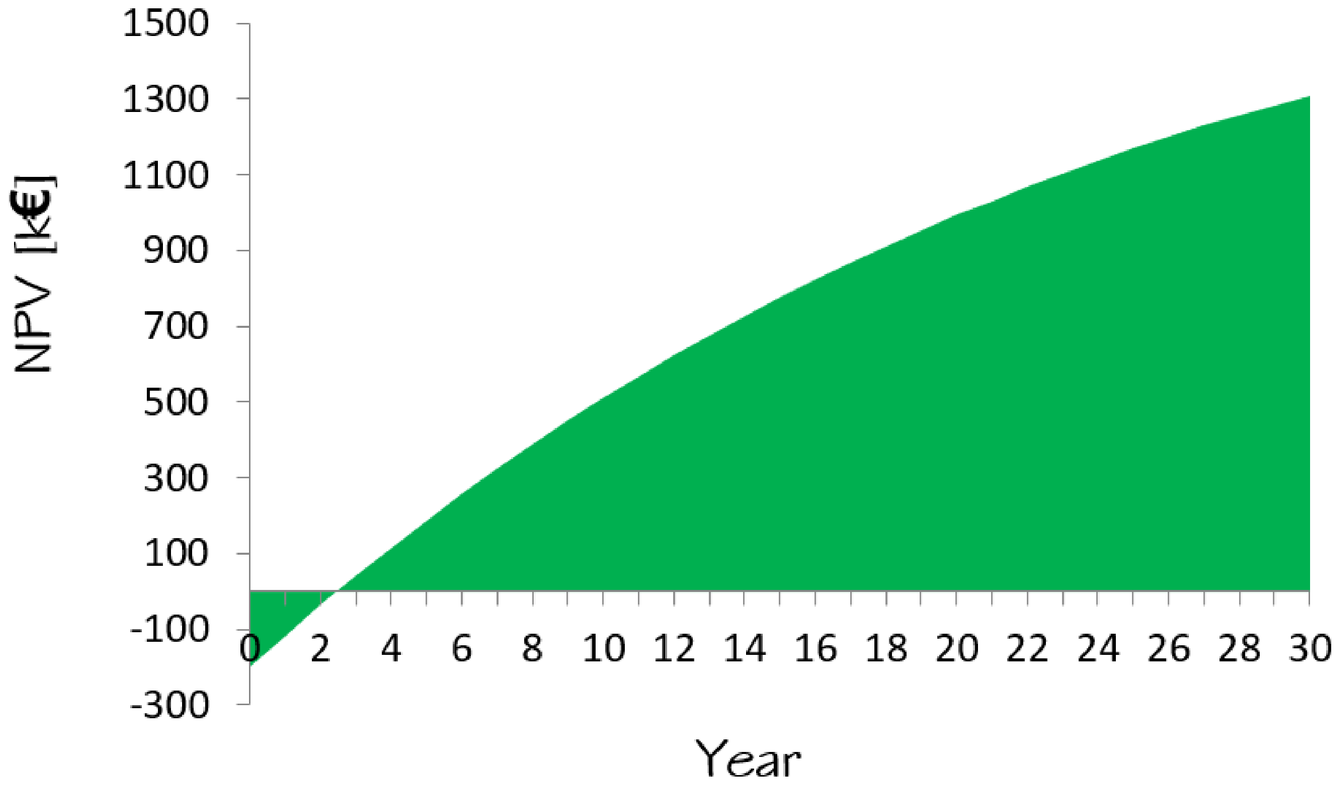
LCOE	3.33 €/kWh
PBT	4.2 years
IRR	33%



C&I – Debt only – Self-consumption 100%
Average electricity price

Power	200 kWp
OCS	1,000 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	/
E	/
Kd	8%
D	100%
EP	300 €/MWh
FiT	47 €/MWh
Sc	100%
E0	1,500
dr	0.6%

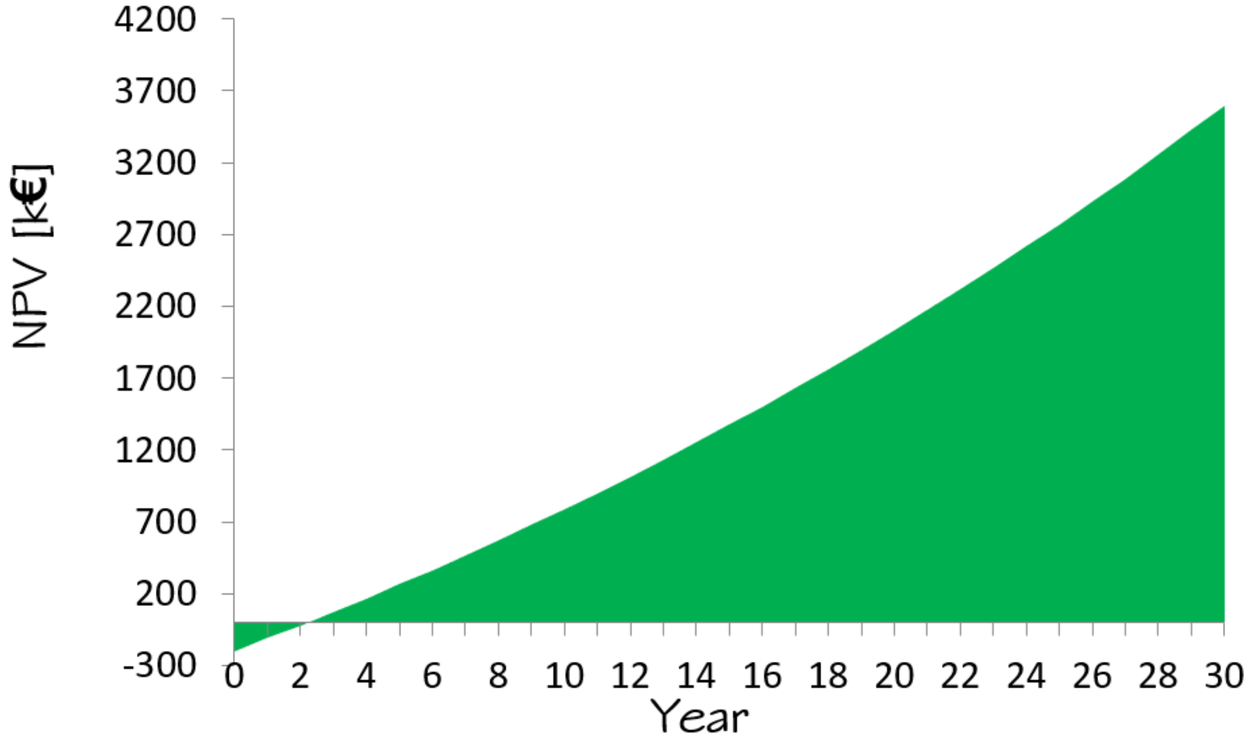
LCOE	6.62 €/kWh
PBT	2.5 years
IRR	25%



C&I – Equity only – Self-consumption 100%
Average electricity price

Power	200 kWp
OCS	1,000 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	2%
E	100%
Kd	/
D	/
EP	300 €/MWh
FiT	47 €/MWh
Sc	100%
E0	1,500
dr	0.6%

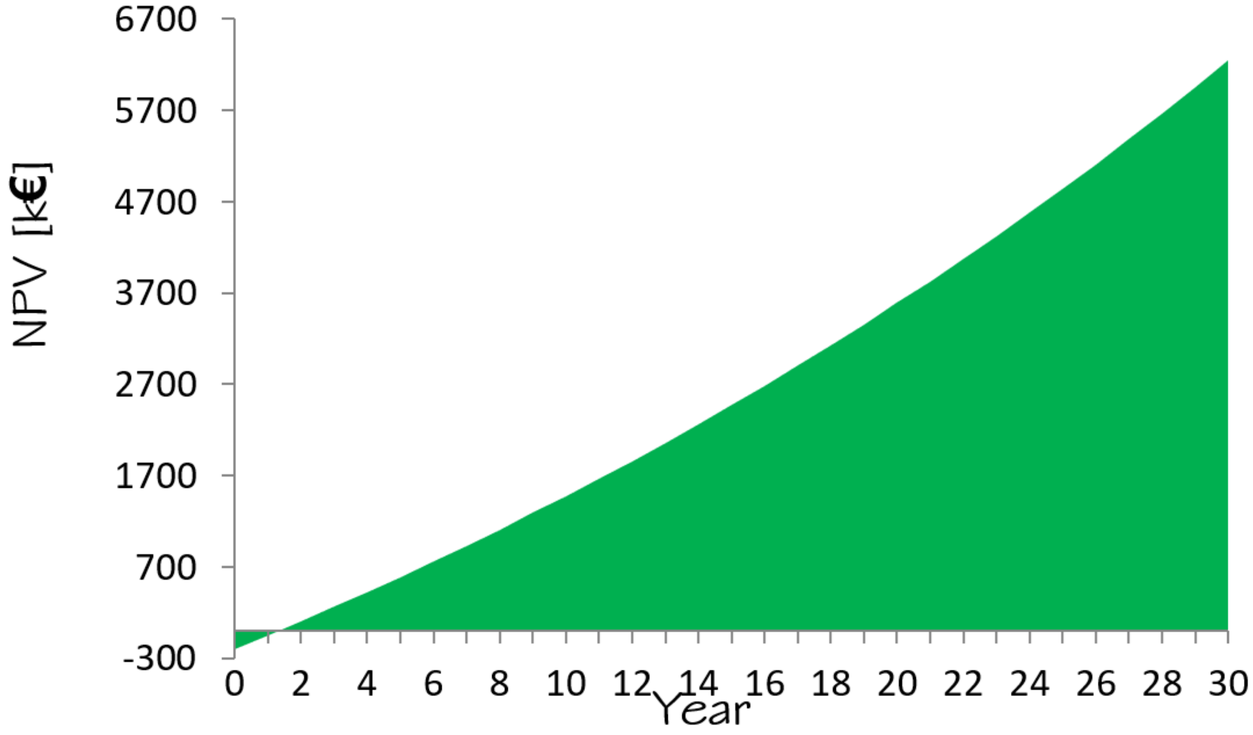
LCOE	3.33 €/kWh
PBT	2.2 years
IRR	63%



C&I – Equity only – Self-consumption 100%
High electricity price

Power	200 kWp
OCS	1,000 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	2%
E	100%
Kd	/
D	/
EP	500 €/MWh
FiT	47 €/MWh
Sc	100%
E0	1,500
dr	0.6%

LCOE	3.33 €/kWh
PBT	1.4 years
IRR	107%



Residential – Equity only – Self-consumption 40%
Average electricity price – IRPEF 50%

Power	3 kWp
OCS	2,200 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	0%
E	/
Kd	0%
D	/
EP	300 €/MWh
FiT	47 €/MWh
Sc	40%
E0	1,500
dr	0.6%

LCOE	7.32 €/kWh
PBT	5 years
IRR	29%

