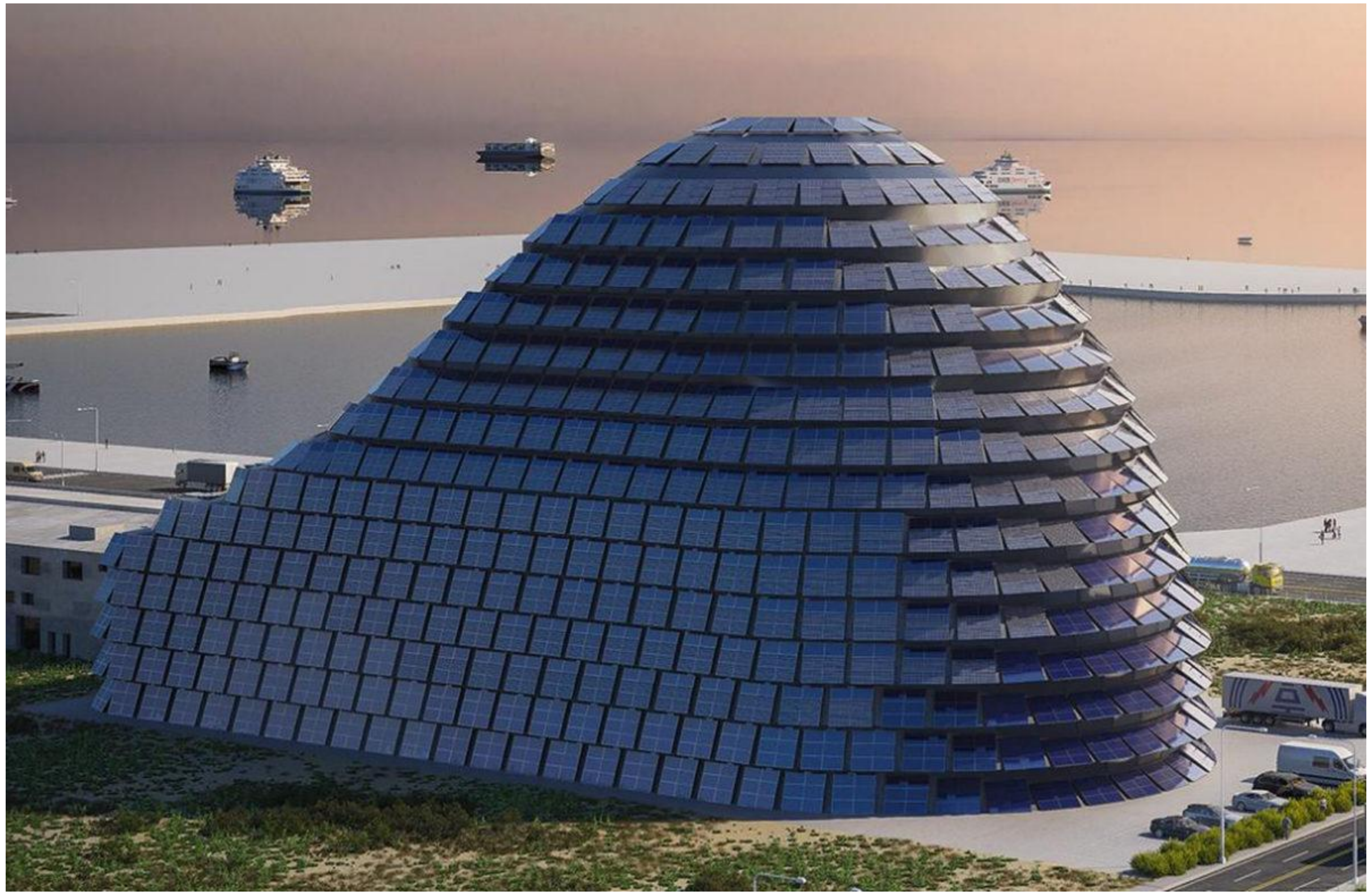
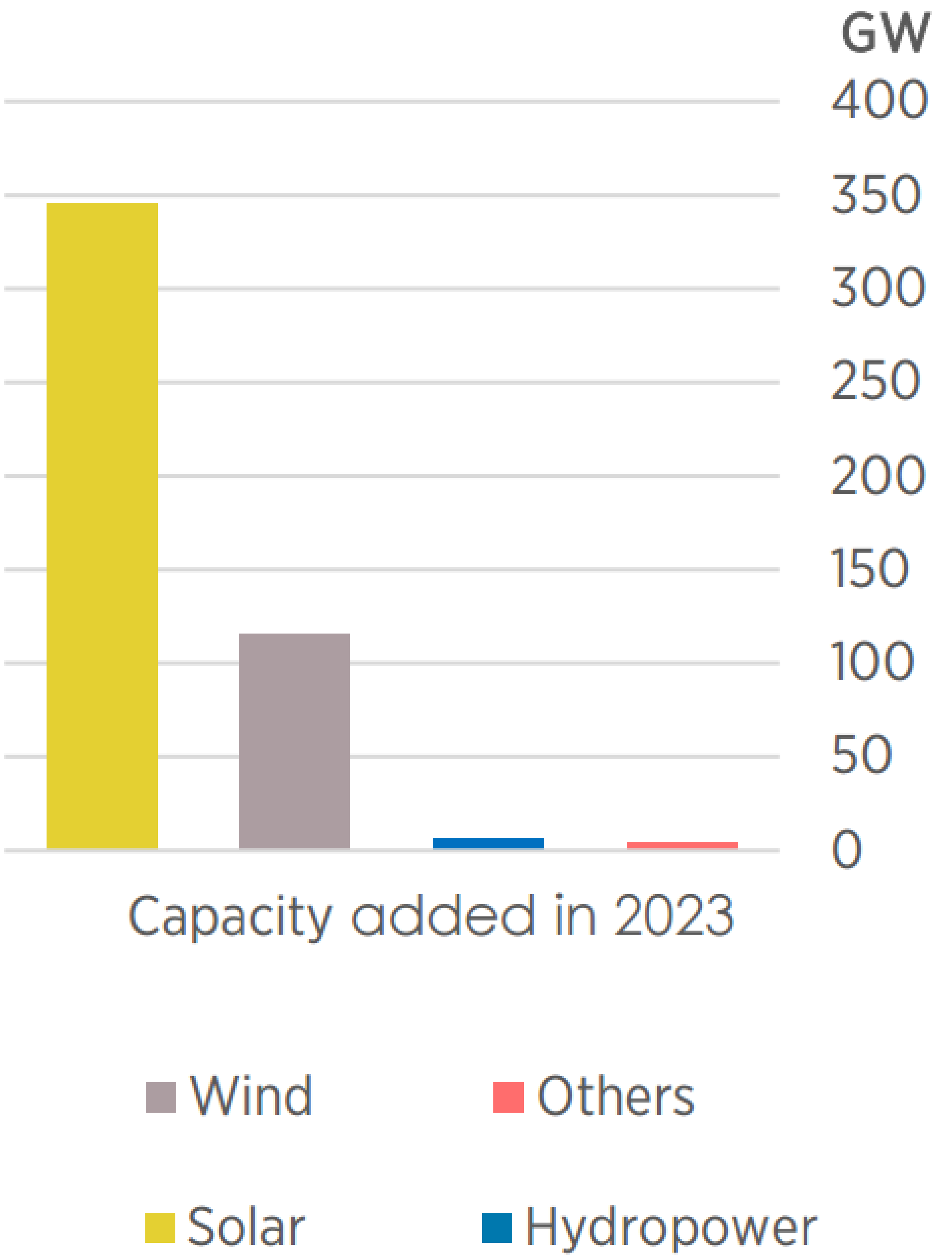
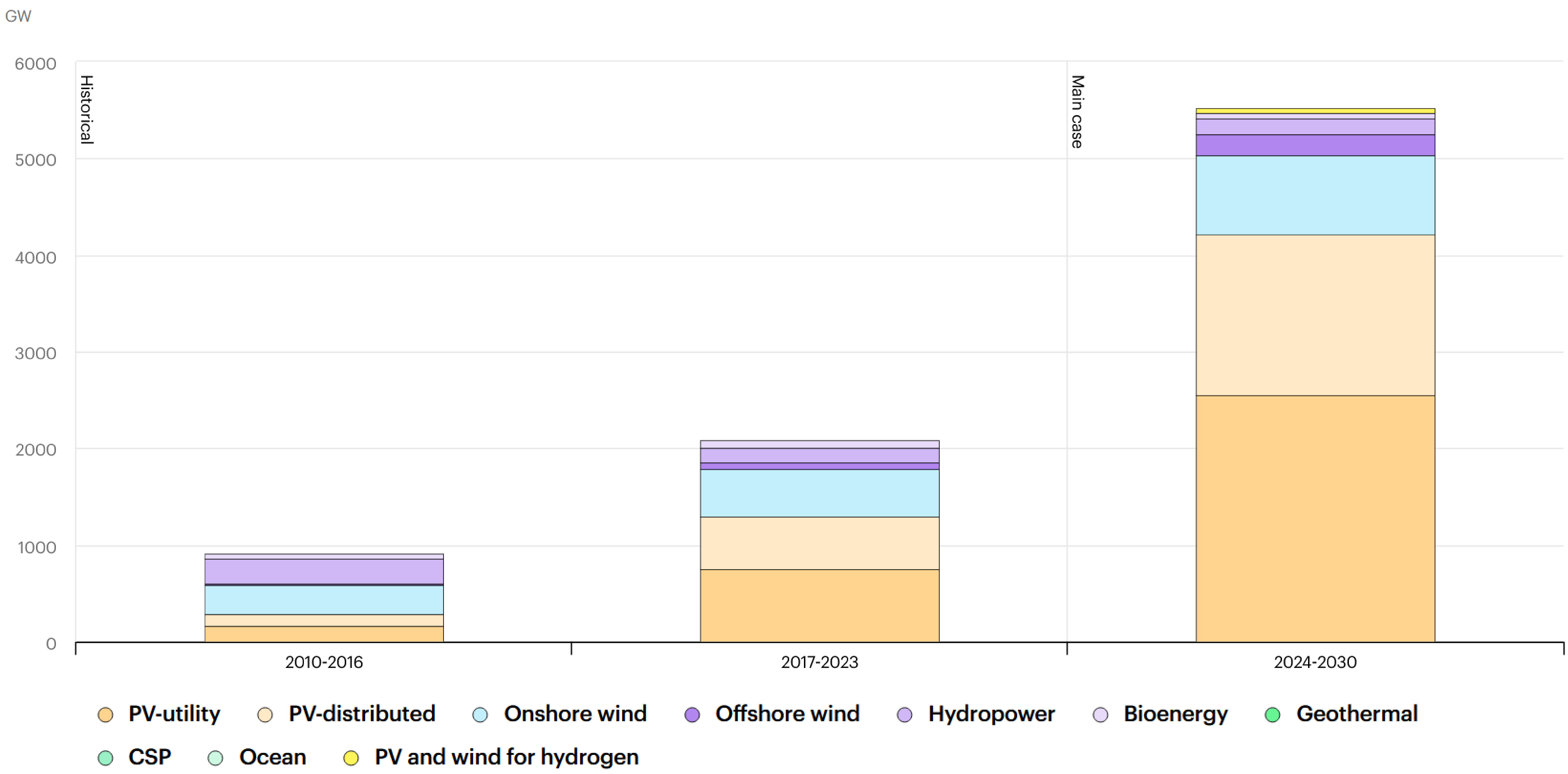
PHOTOVOLTAIC SYSTEMS



The role of photovoltaics





A vision from the past

G. Ciamician

SCIENCE

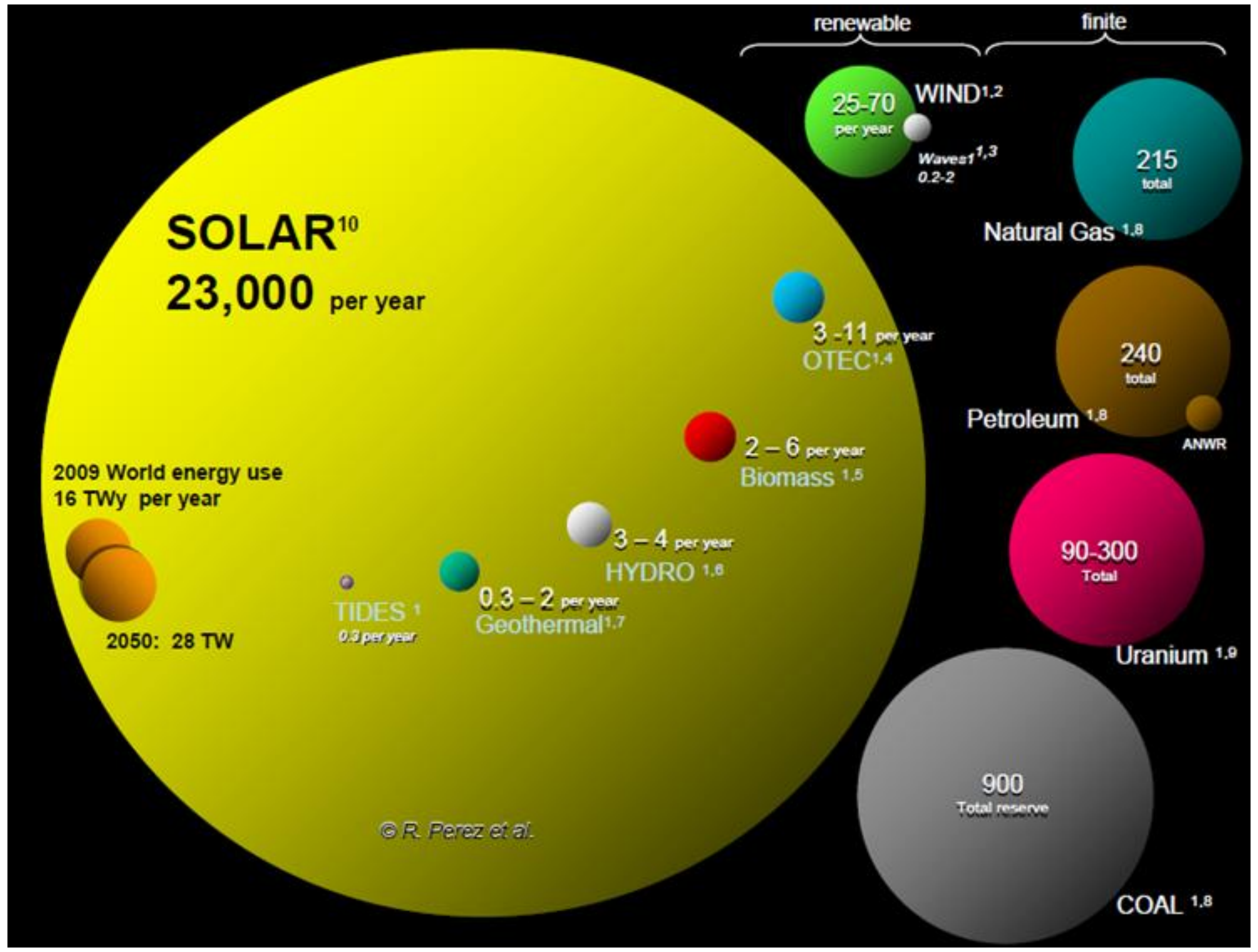
FRIDAY, SEPTEMBER 27, 1912

CONTENTS

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.

Why photovoltaics?

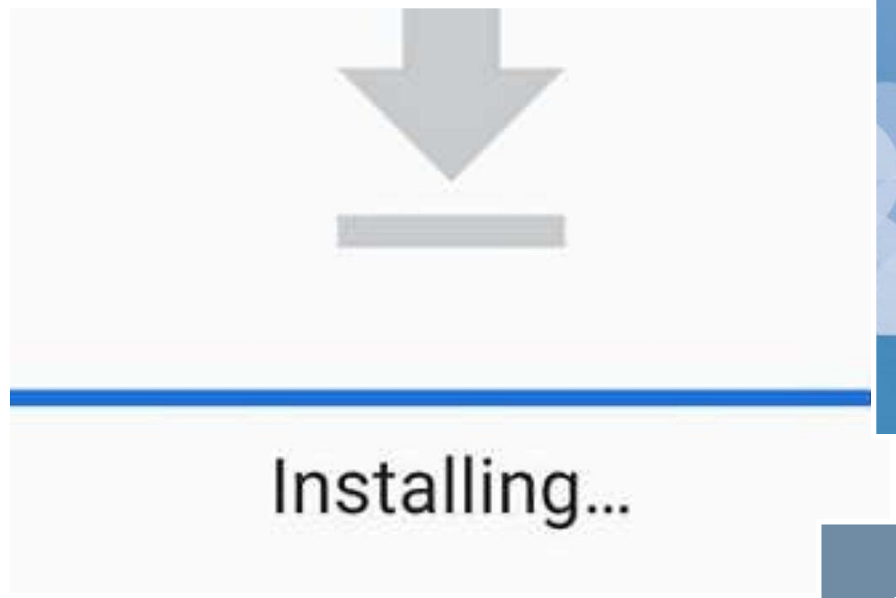


Solar is now 'cheapest electricity in history', confirms IEA

Fuel source is vast and essentially infinite

Low costs

Why photovoltaics?



Reliable and durable

Easy and quick installation

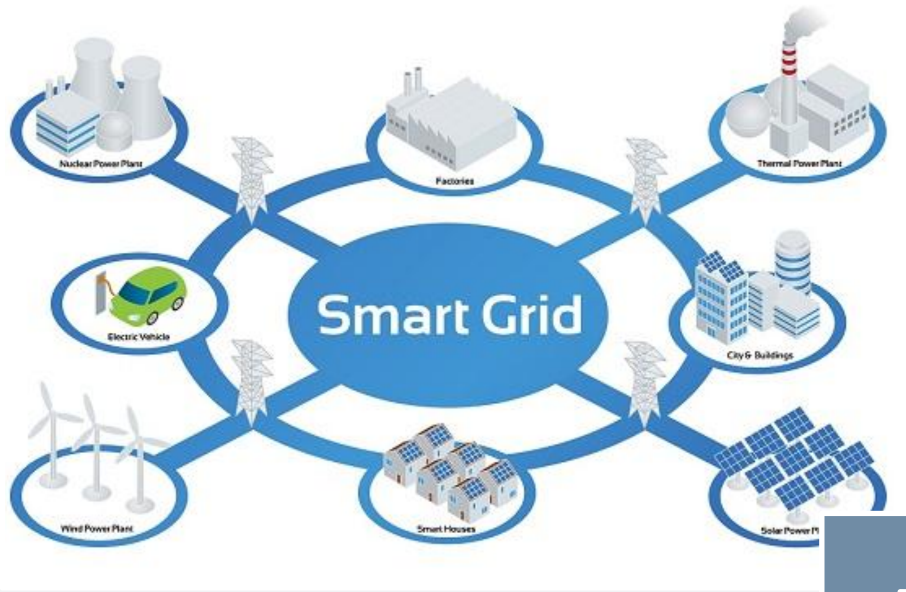
Why photovoltaics?

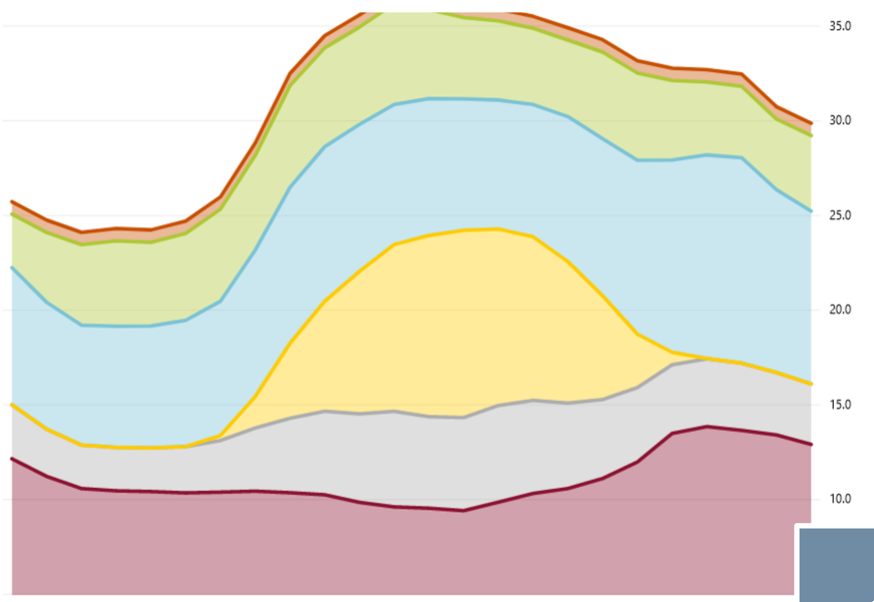
Modular technology

No moving parts, no noise

(no emissions)

Why photovoltaics?

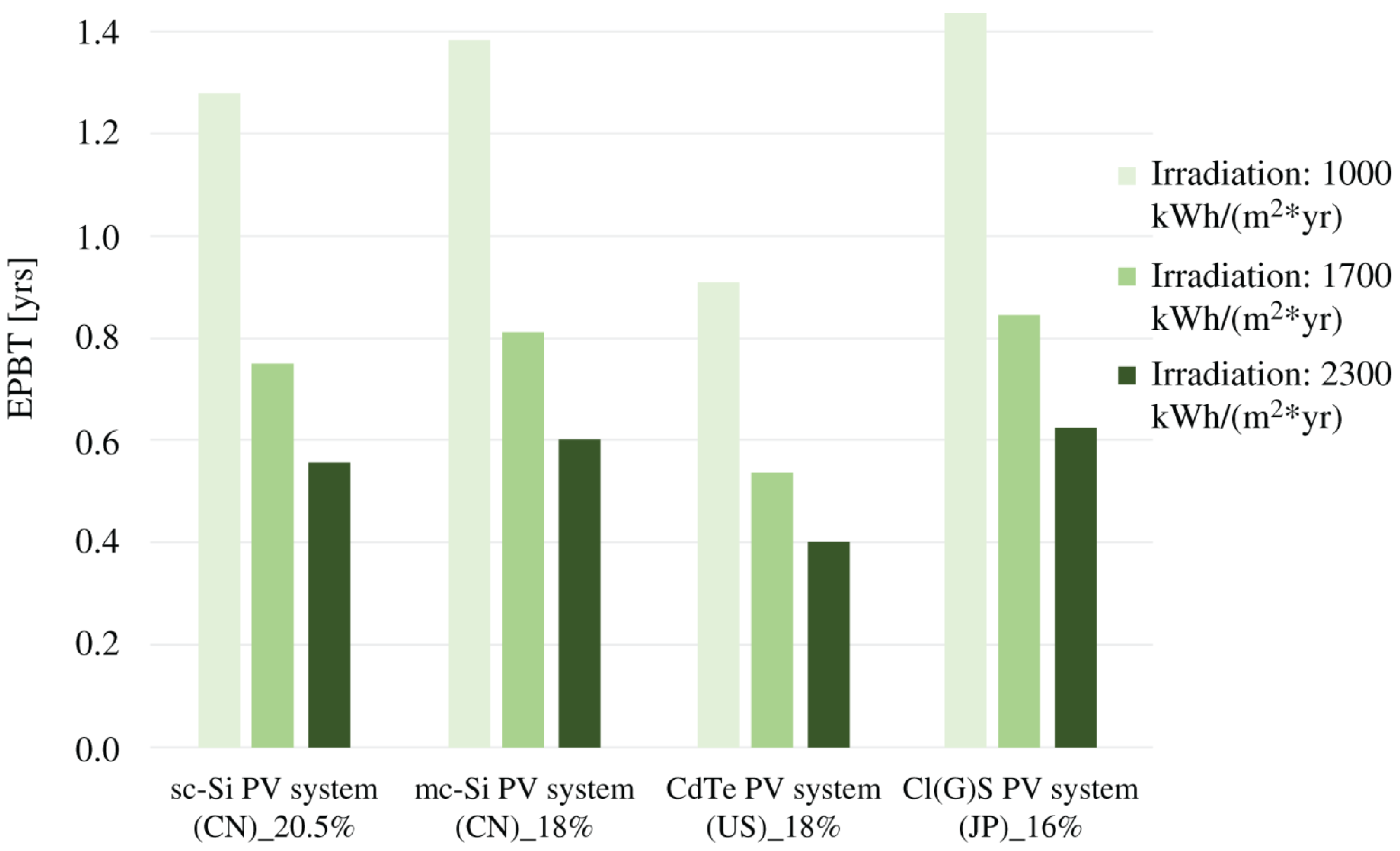




Distributed generation

Daily output peak can match the local demand

Energy Payback Time



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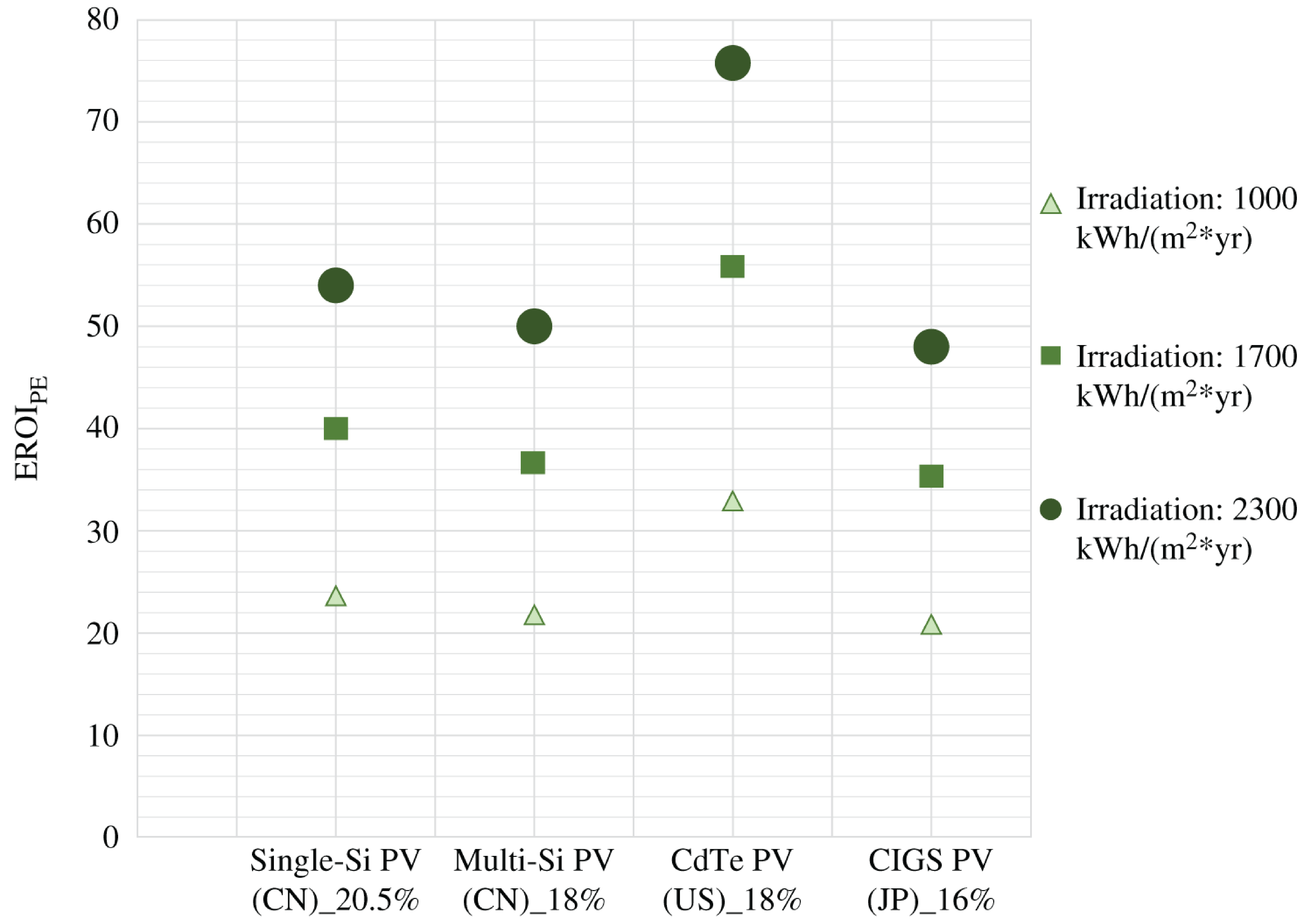
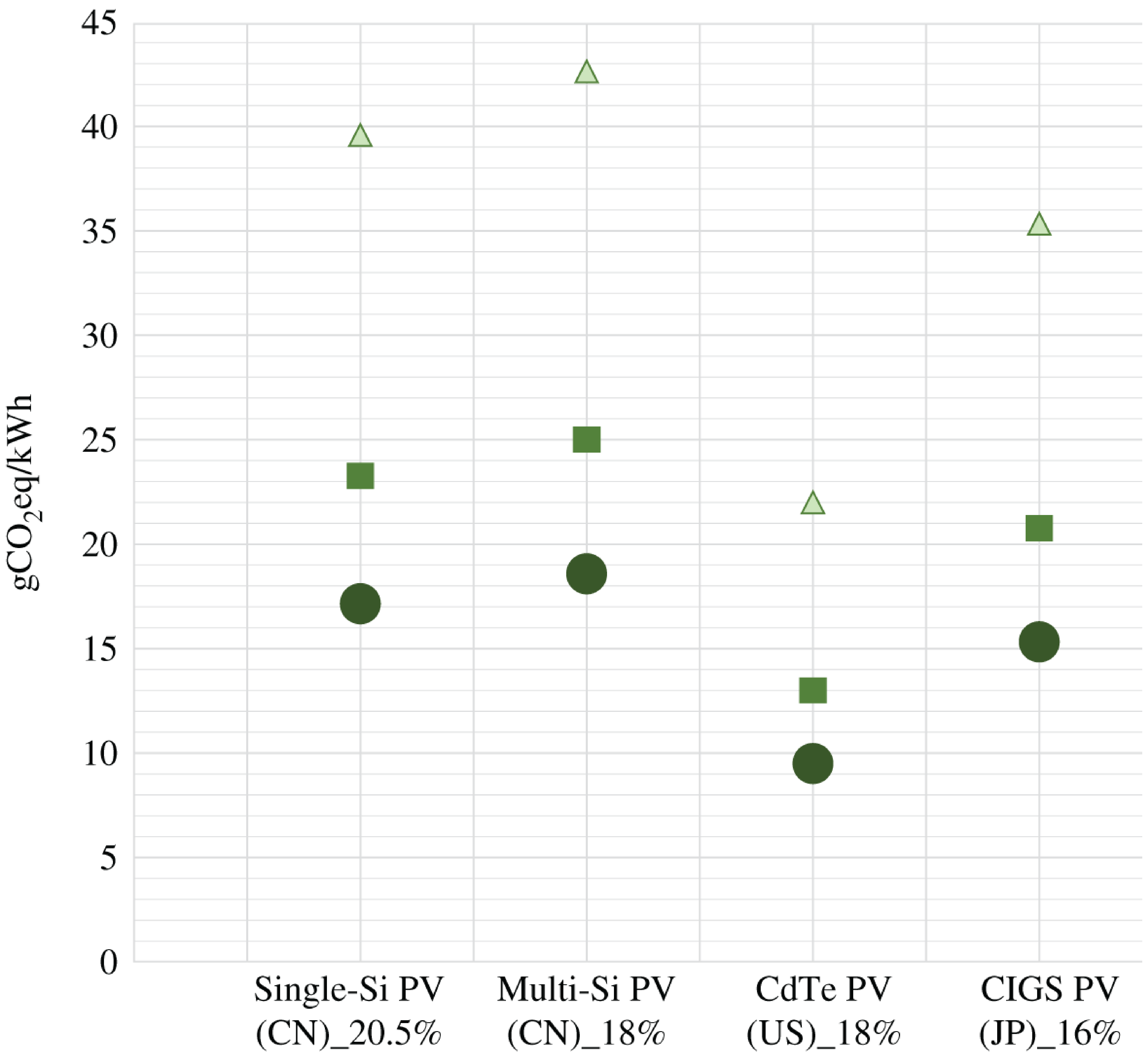
EROI and CO2 emissions





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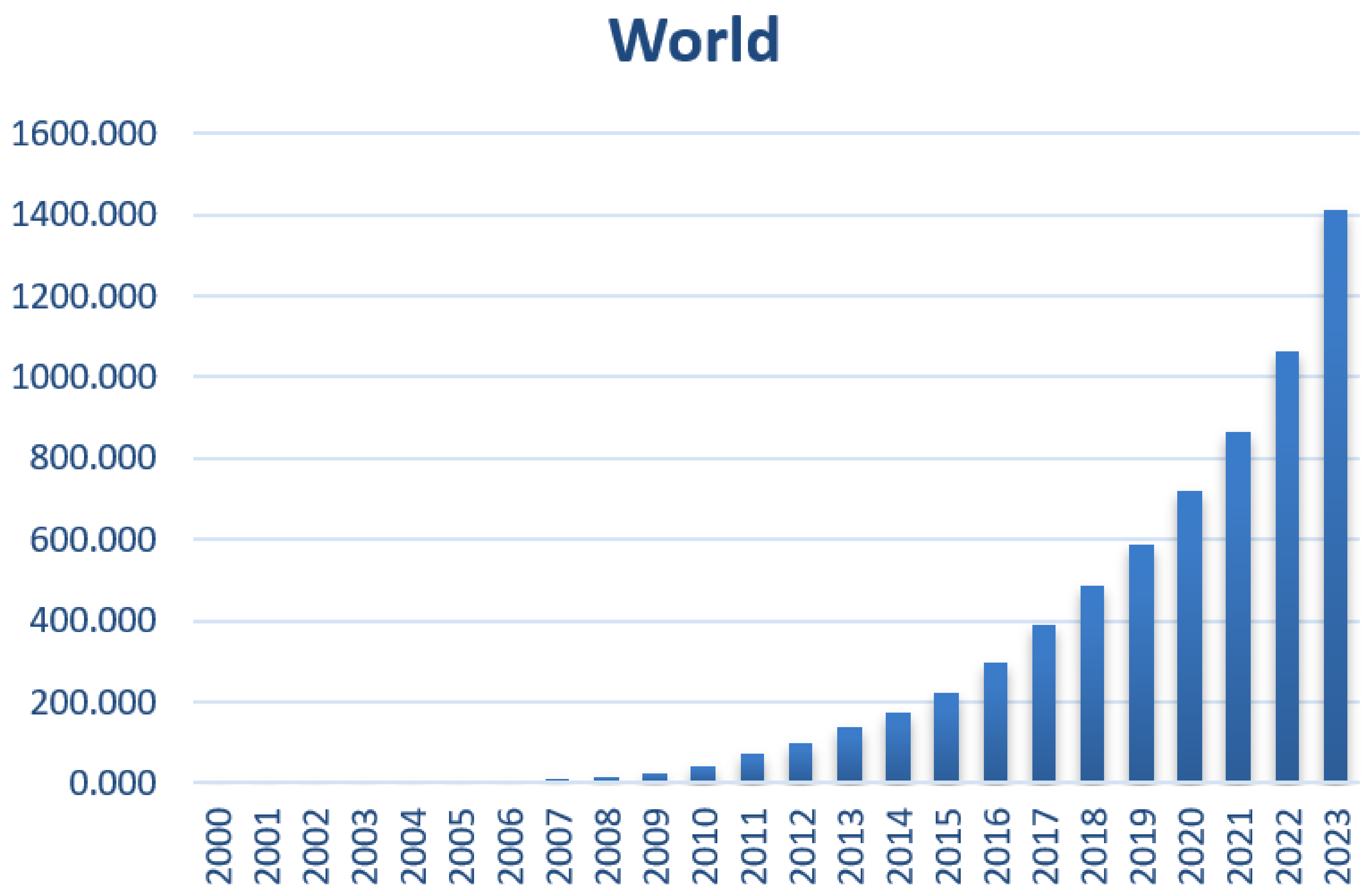
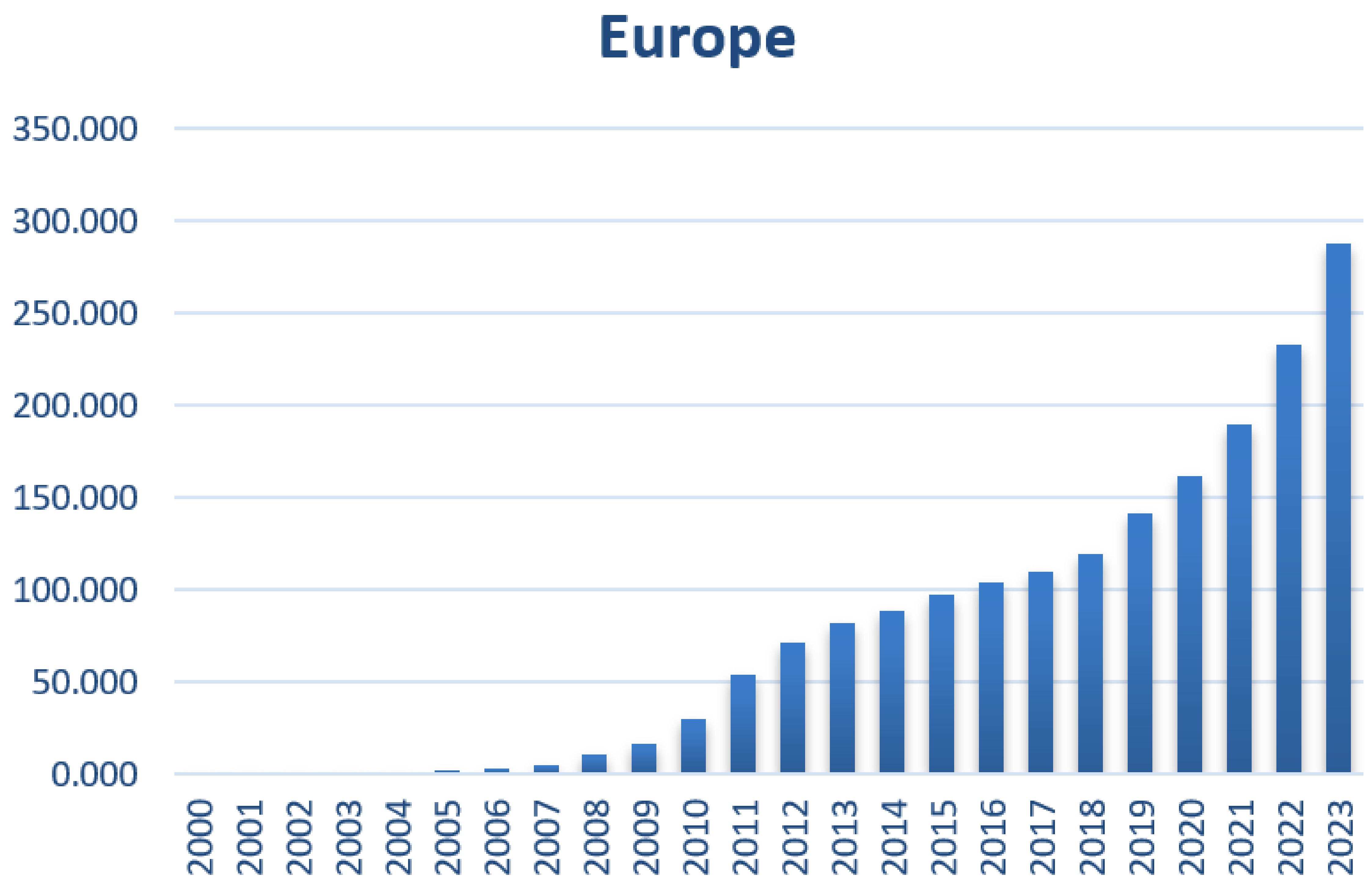
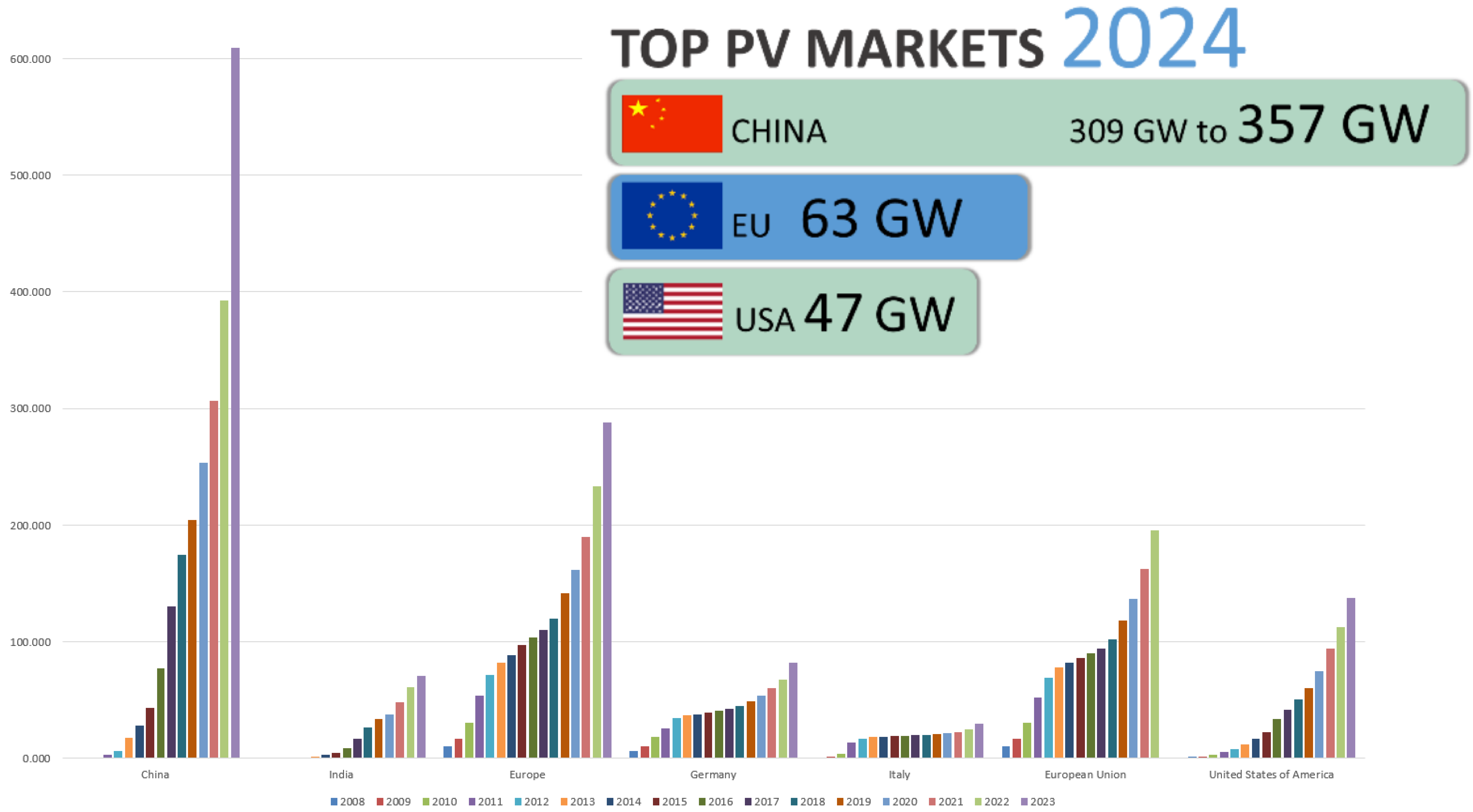
Cumulative installed power (MWp)

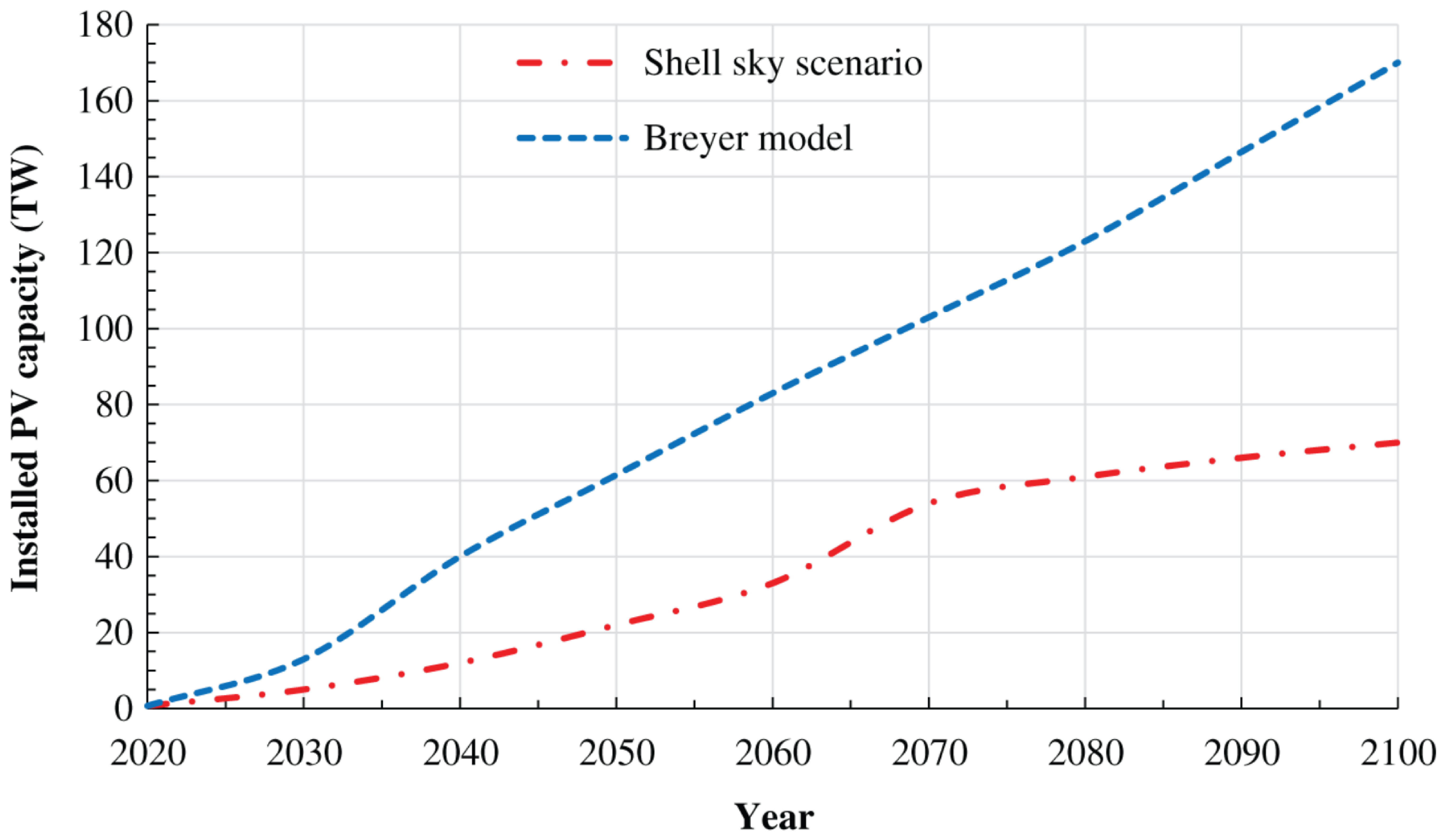


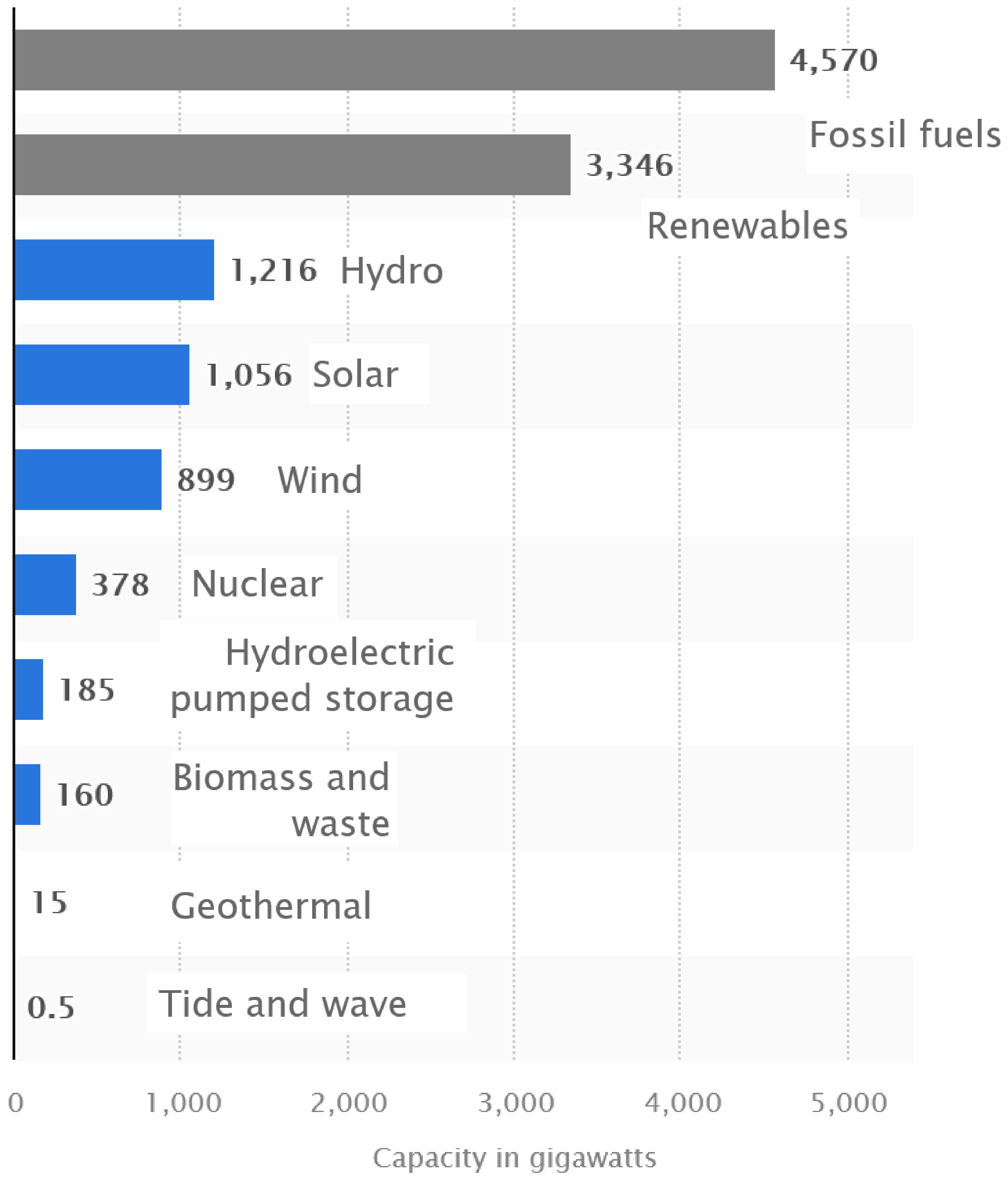


Cumulative installed power (MWp)



Modeled cumulative installed capacity





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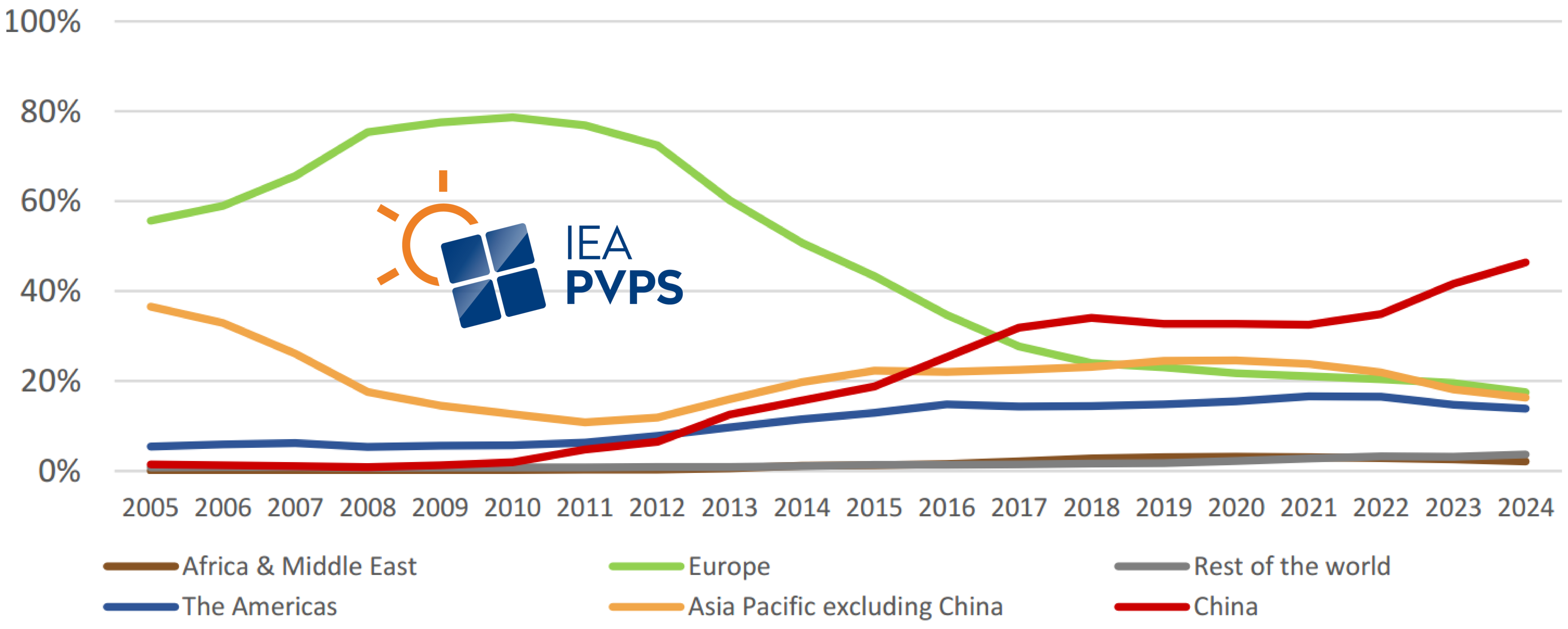
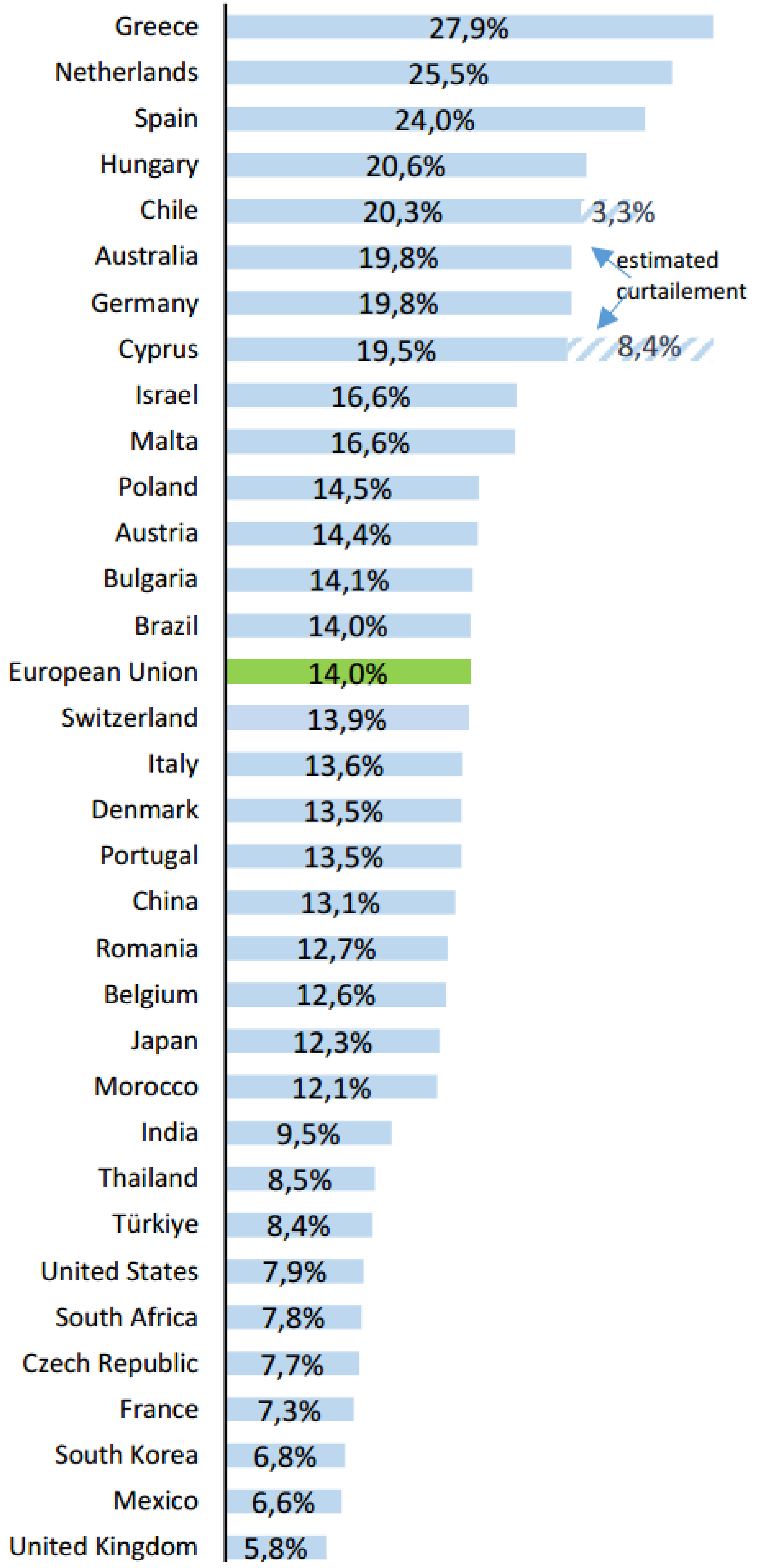
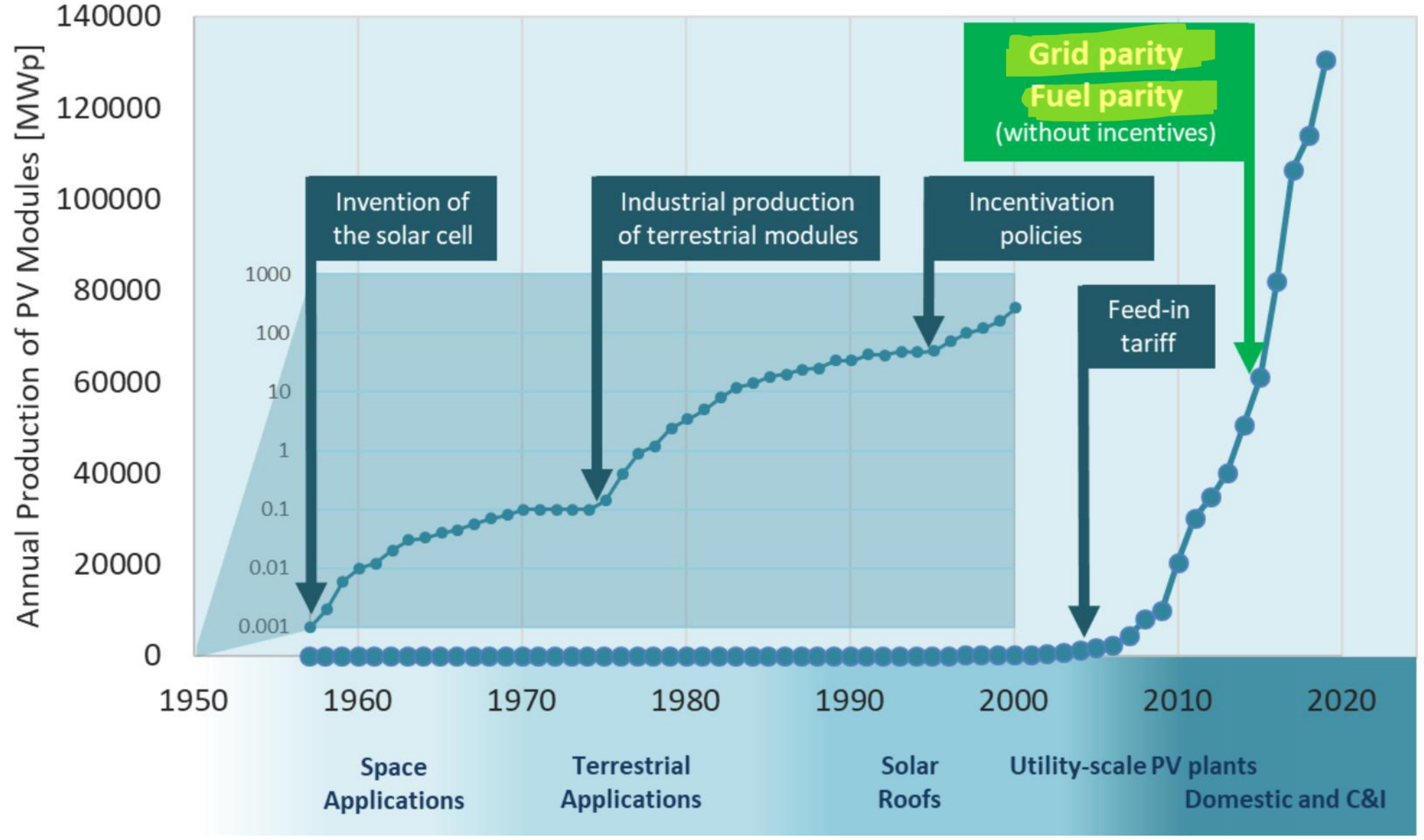
Evolution of global market



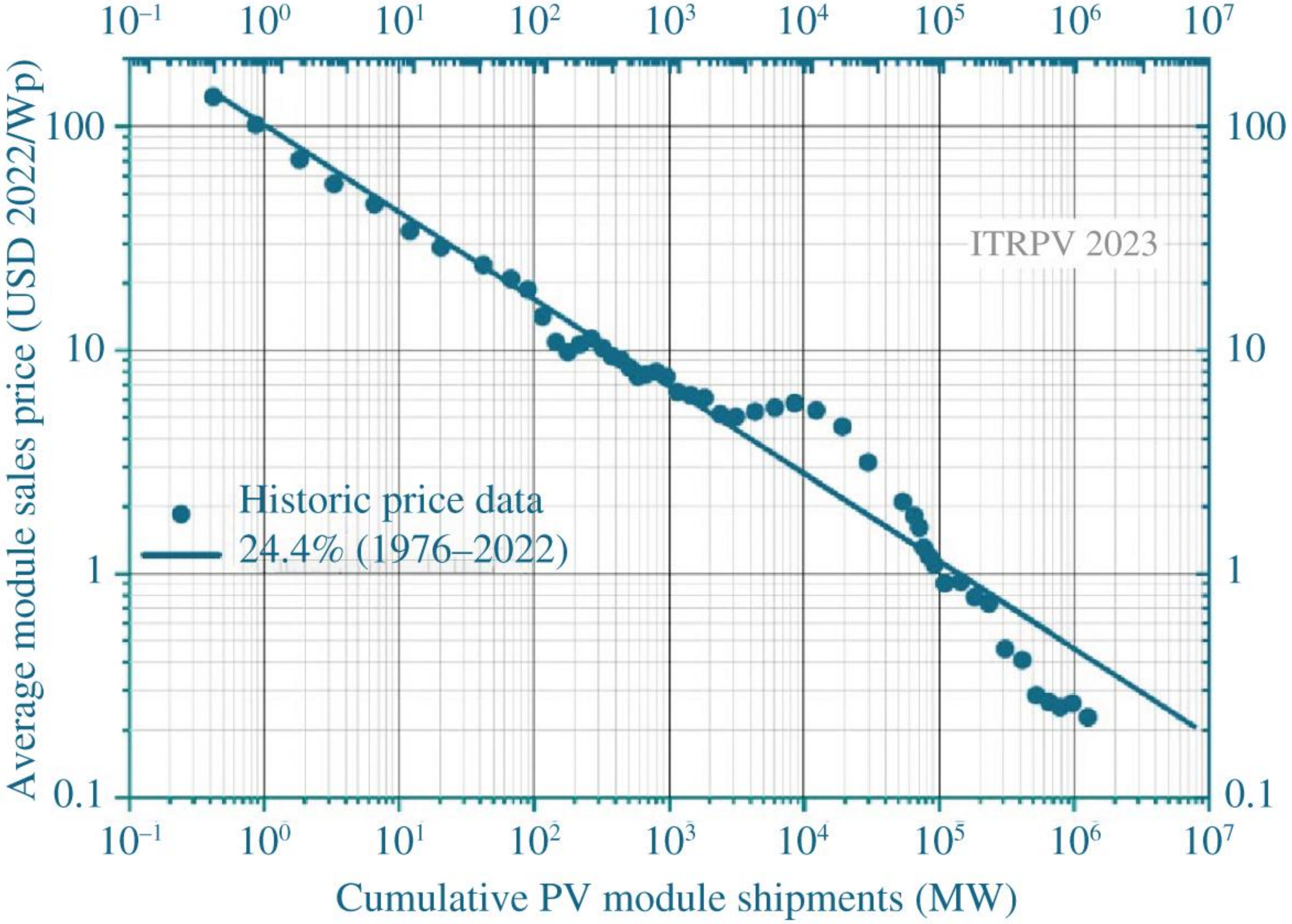
Electricity production in 2023



It’s just the beginning: the first clue



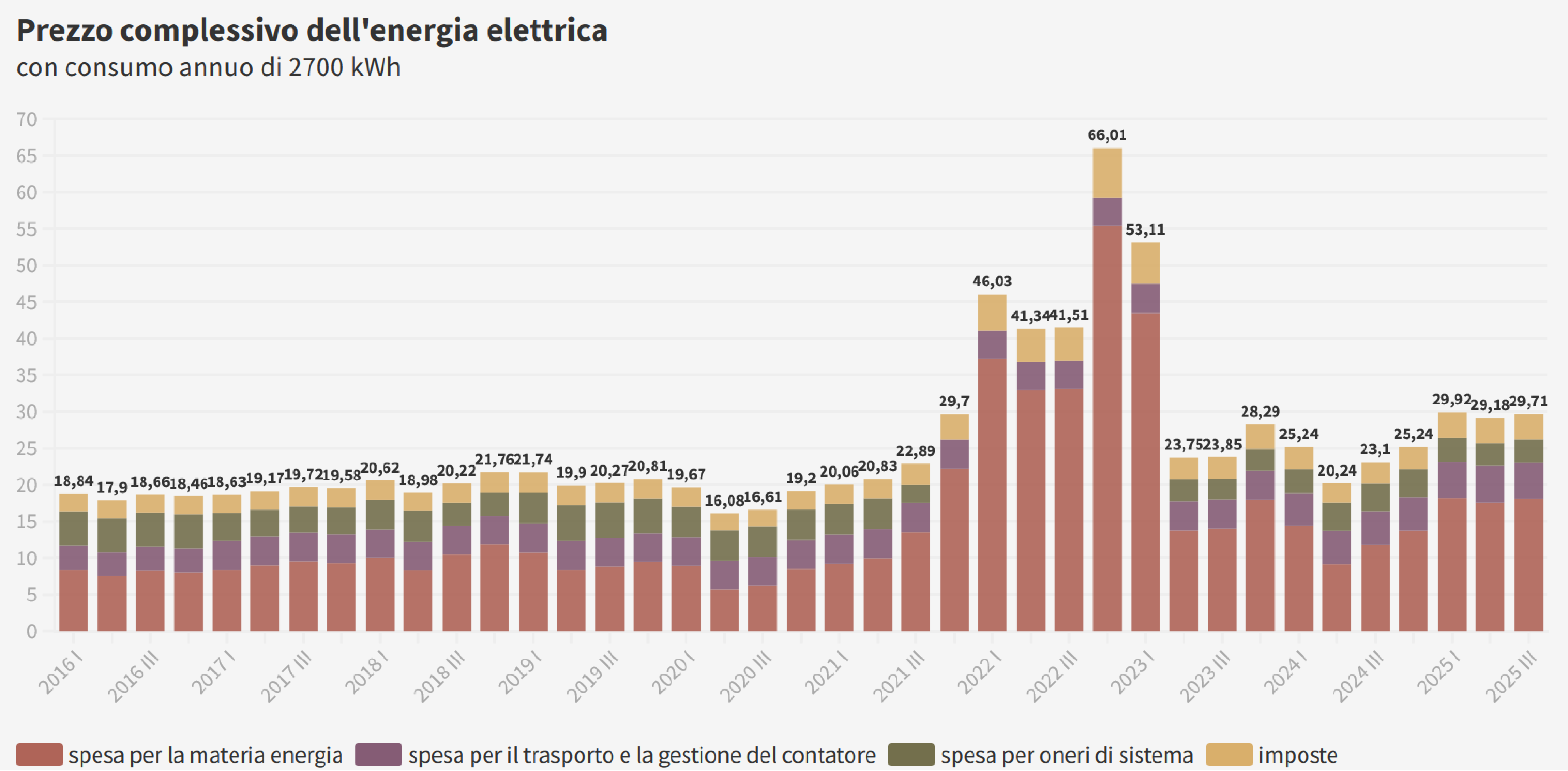
ITRPV (2023)/International Technology Roadmap for Photovoltaics



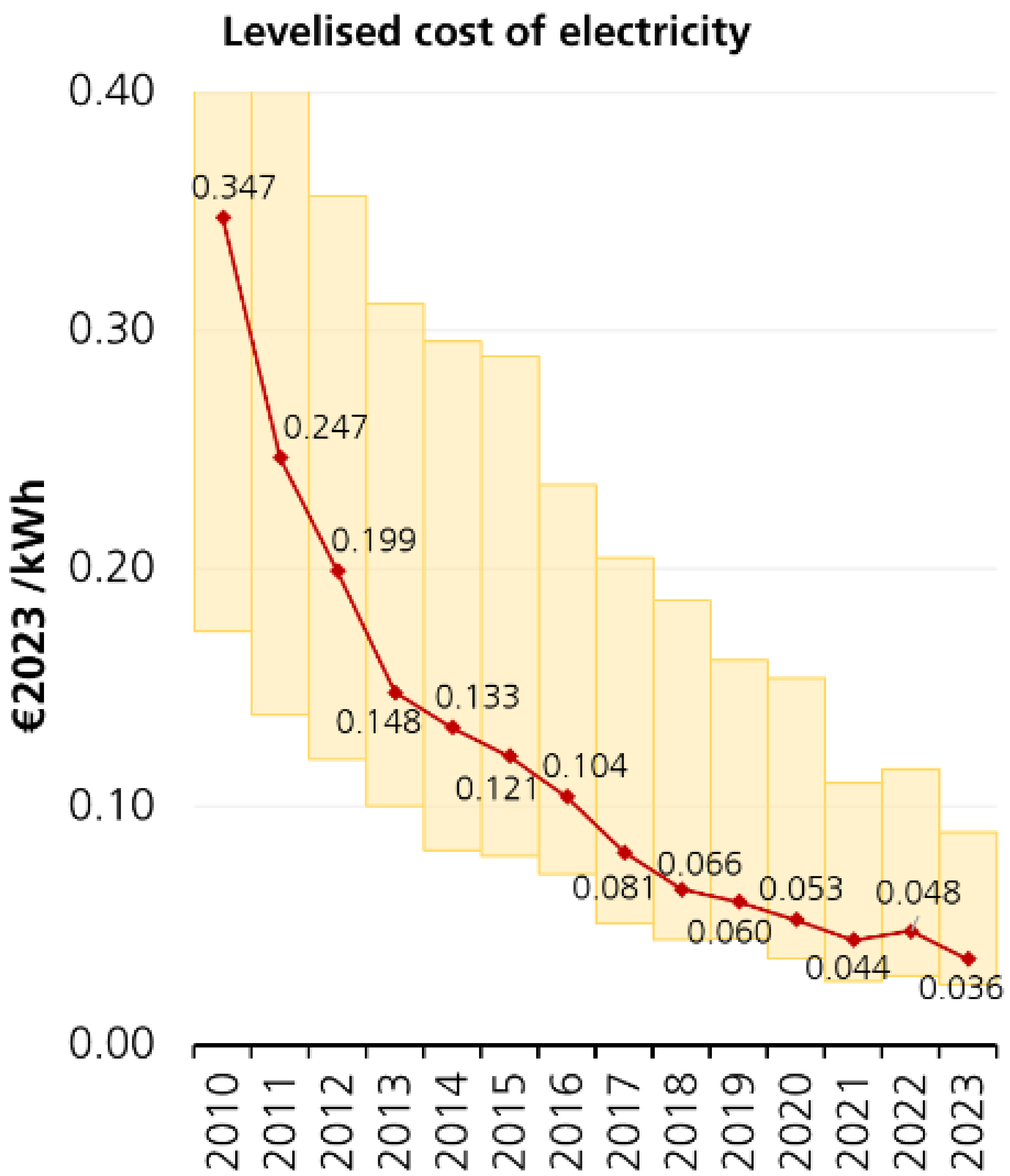
- 1955, 1975, 1995, 2015 …
- **Grid-parity**: electricity price [16 – 60 cent/kWh] > PV LCOE [4 – 14 cent/kWh]
- **Fuel-parity**: LCOE from conventional sources [9 – 58 cent/kWh] > PV LCOE [2.5 – 5 cent/kWh]

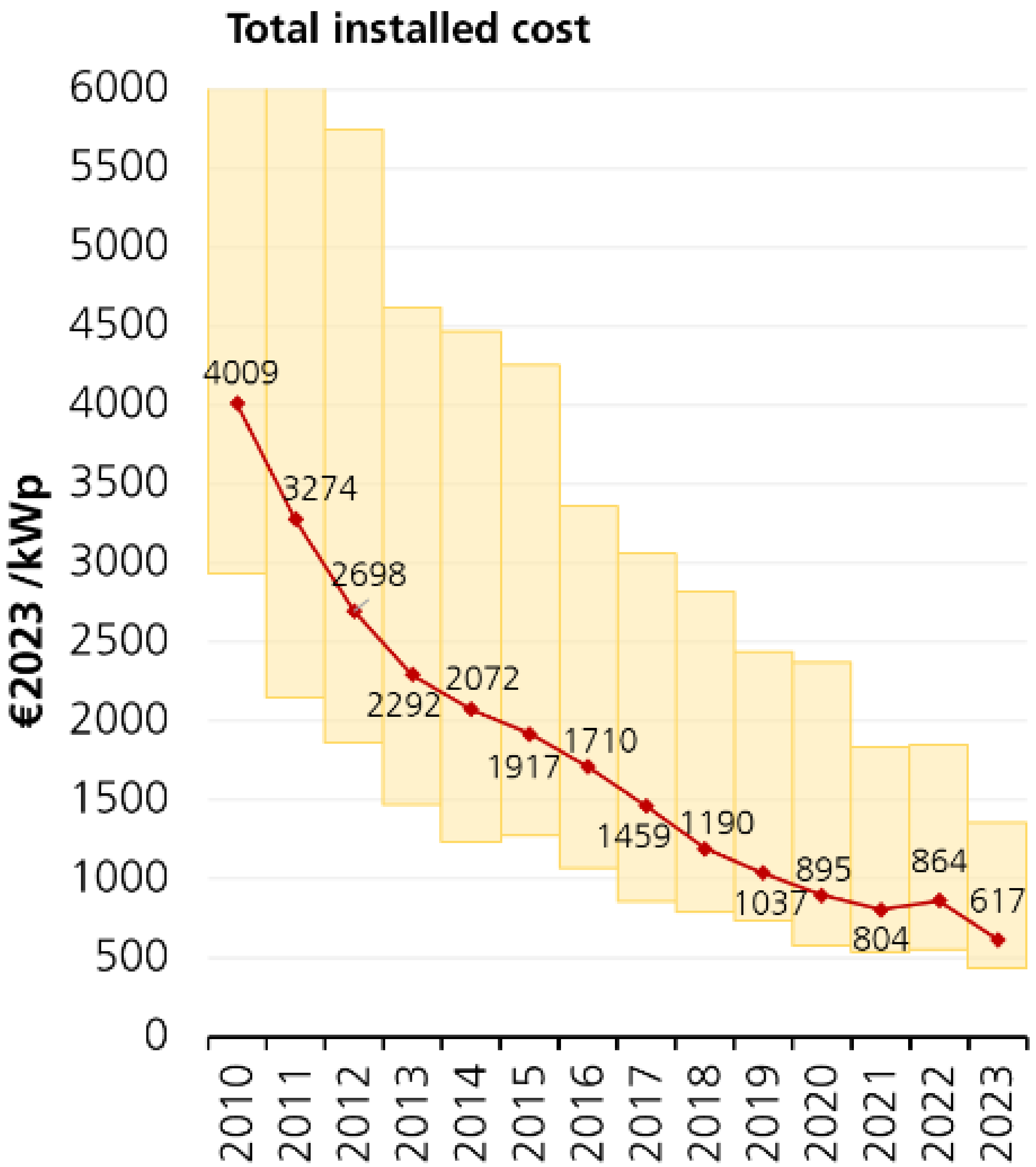
Grid-parity

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





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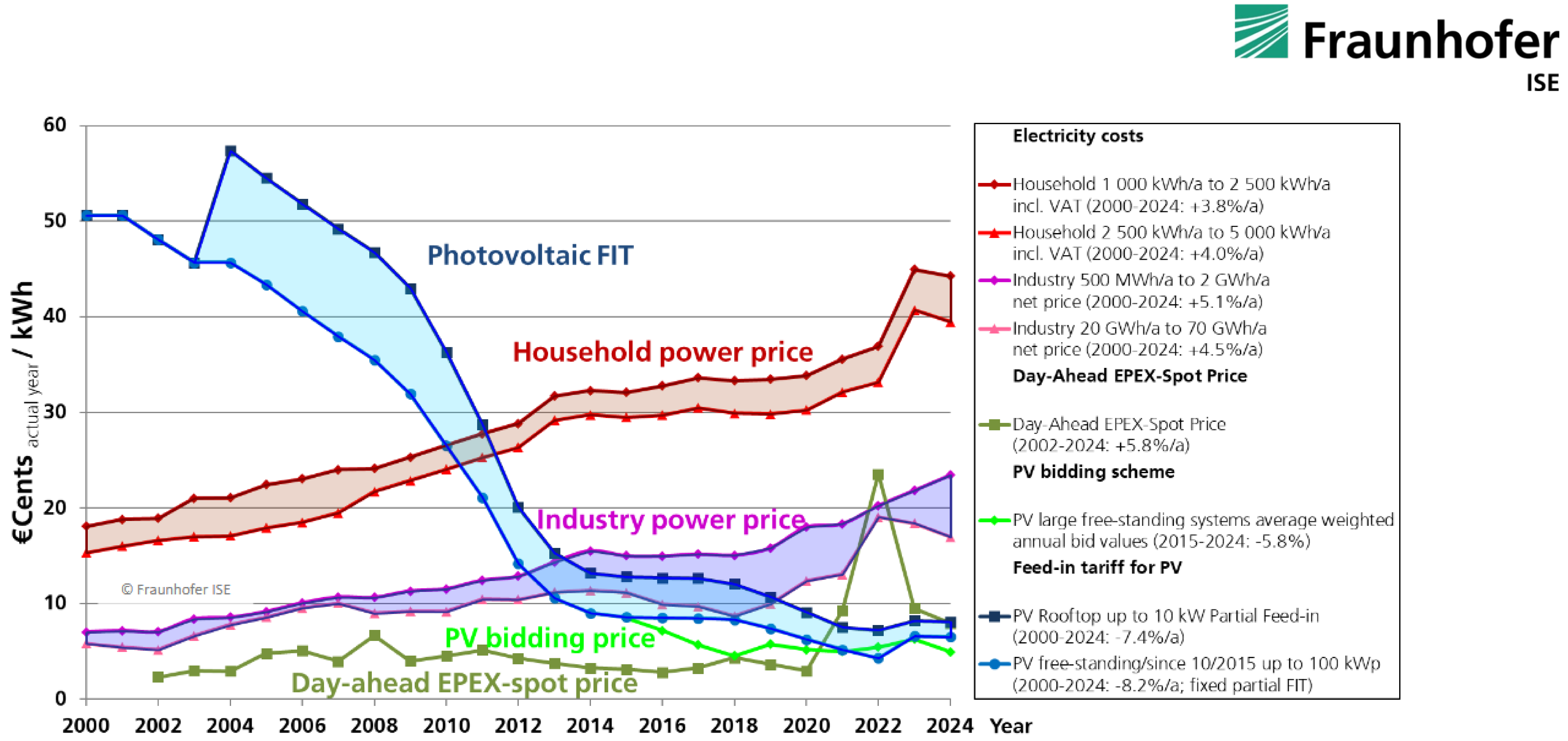
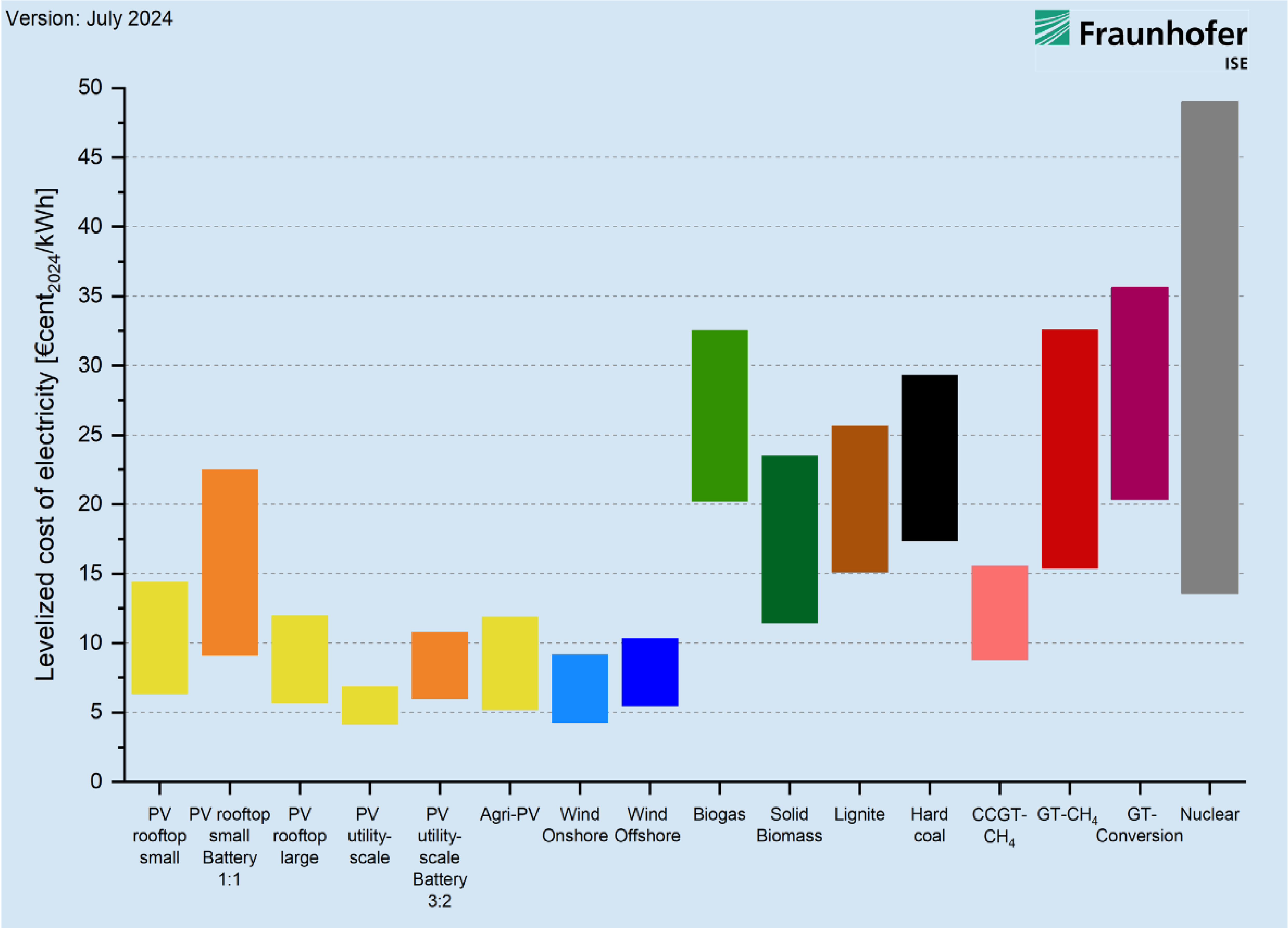
Evolution of LCOE and electricity price



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

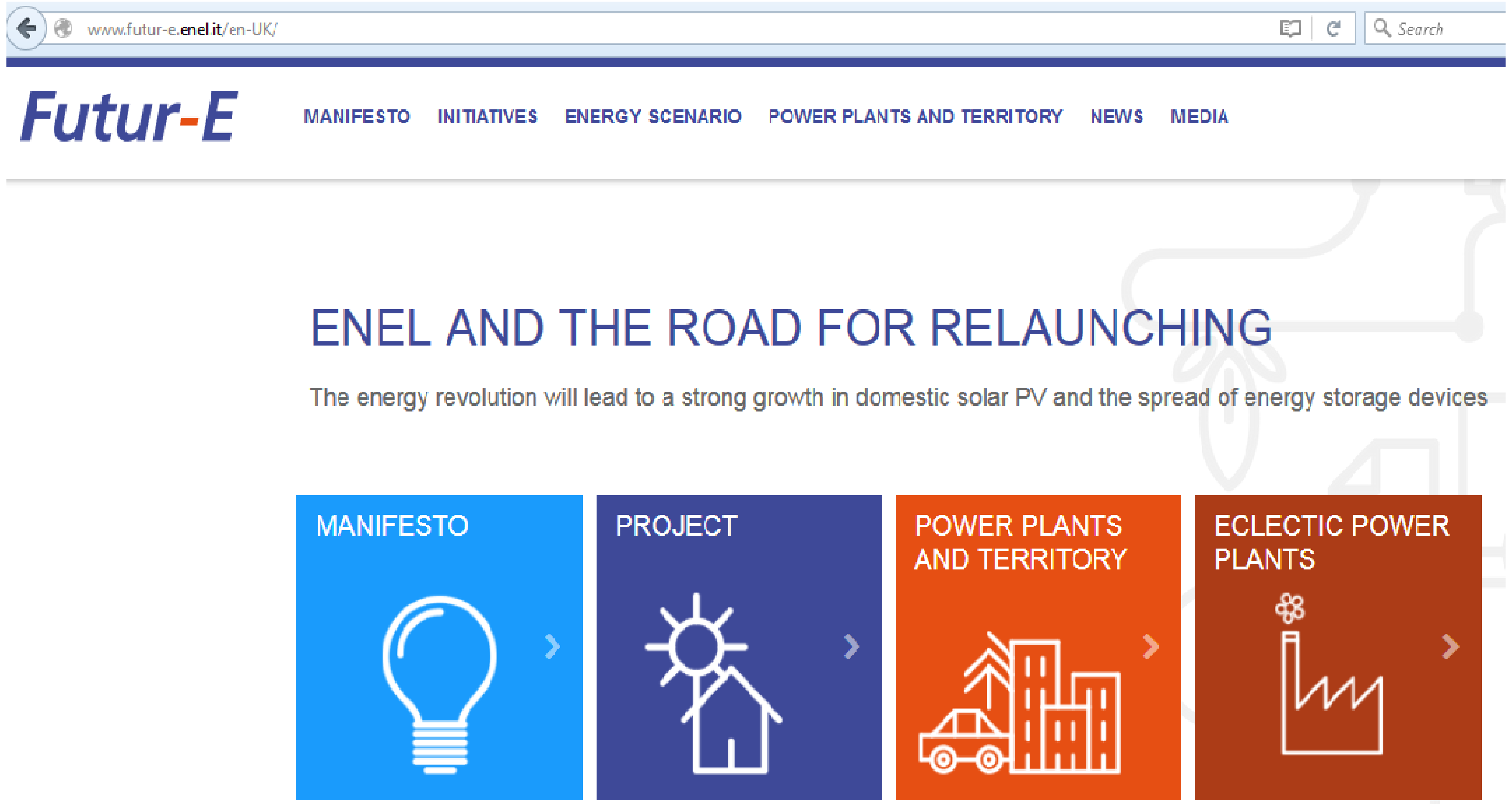


It’s just the beginning: the second clue

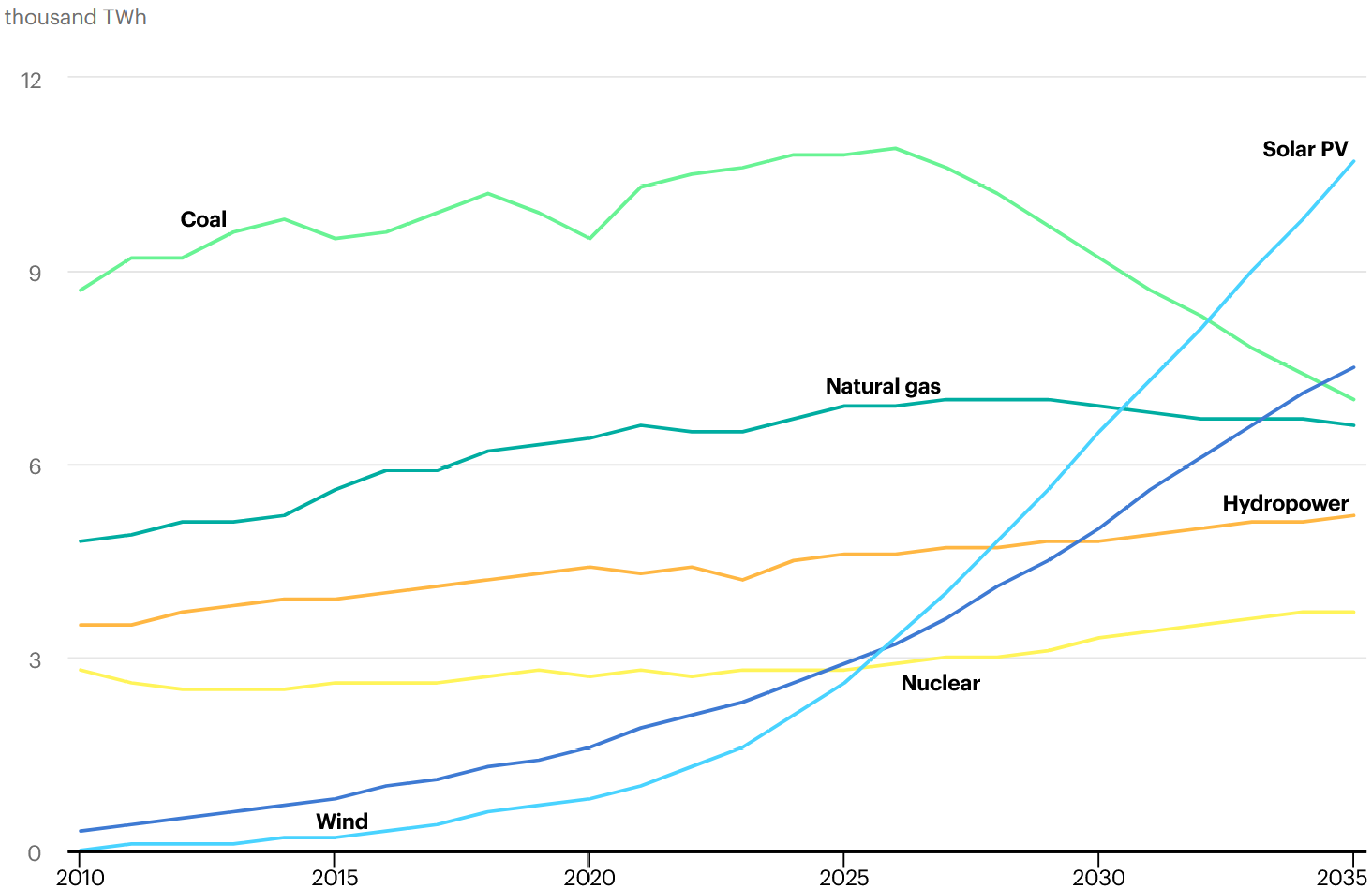
COUNTRY	INSTALLED POWER* [GW]	POPULATION* [MILIONI]	POWER PER CAPITA	GROWTH [%]
GERMANY	90	83.3	1080	22 (24)
ITALY	37	58.9	628	22 (17)
JAPAN	95	123.8	767	6 (8)
EUROPE	345	449.2	768	24 (25)
USA	187	340.1	550	36 (23)
CHINA	887	1419.3	625	46 (55)
INDIA	98	1450.9	120	31 (19)

*2024

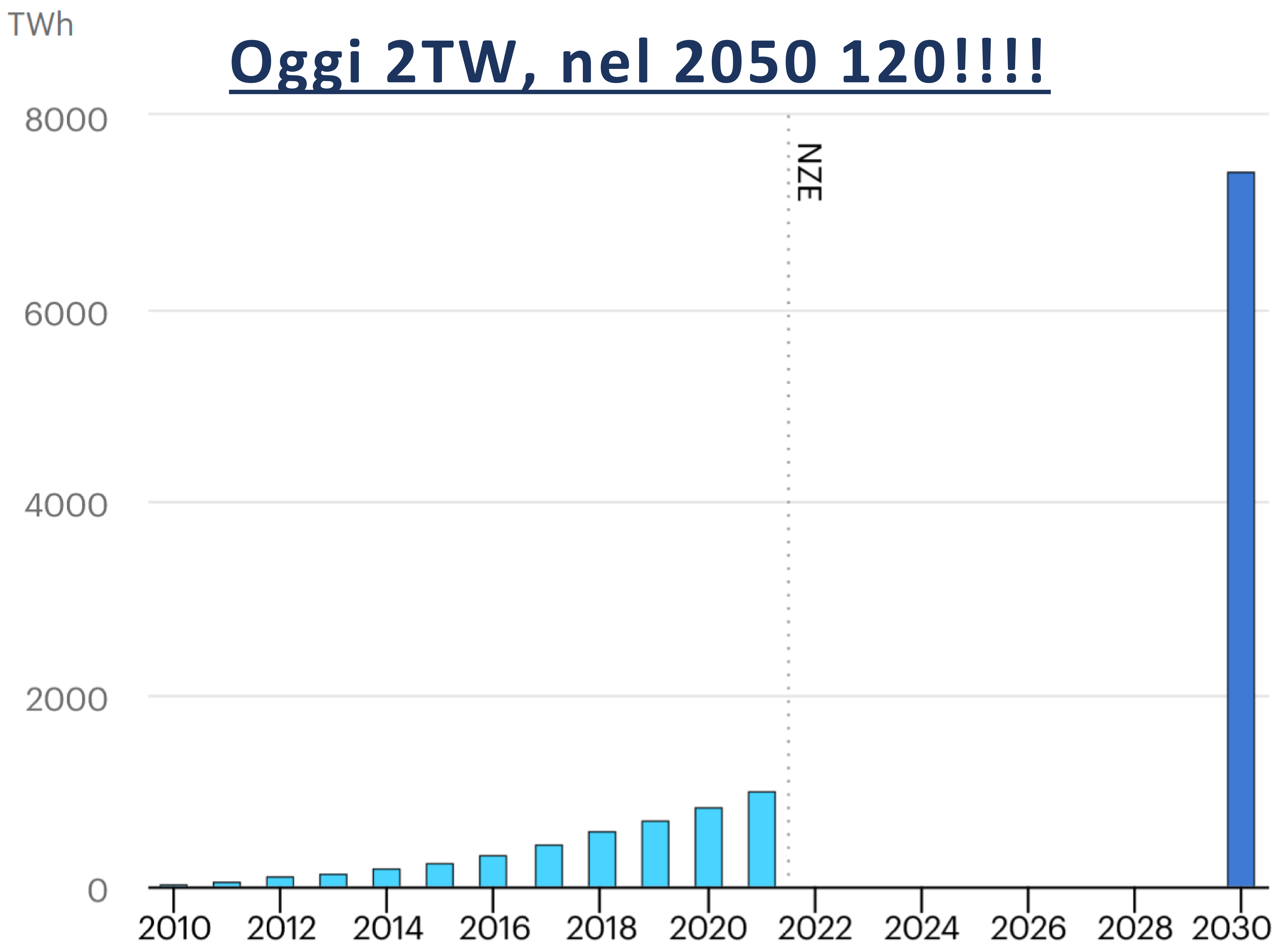
It’s just the beginning: the third clue



Photovoltaics, the first global power source

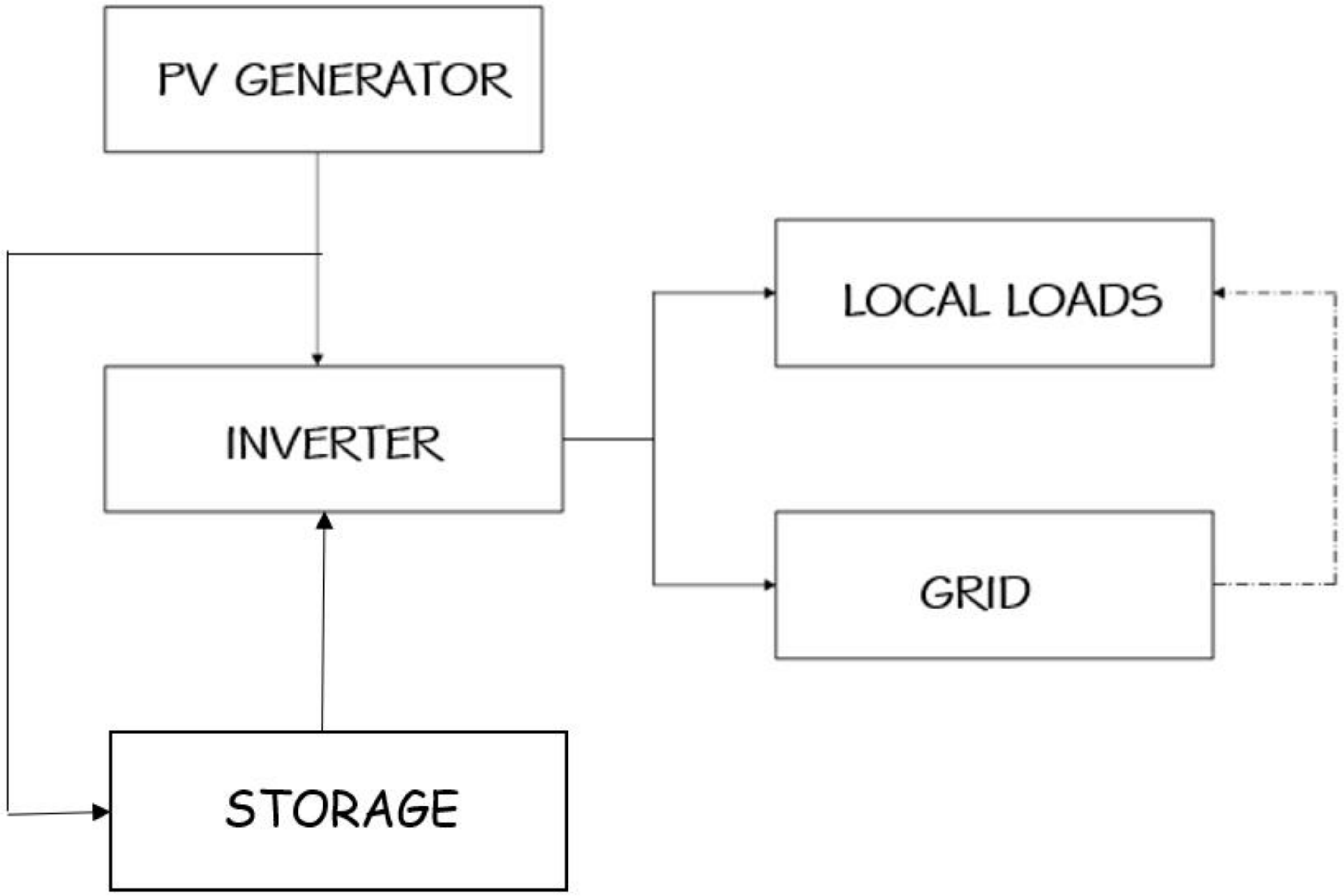


There’s a lot of road to cover



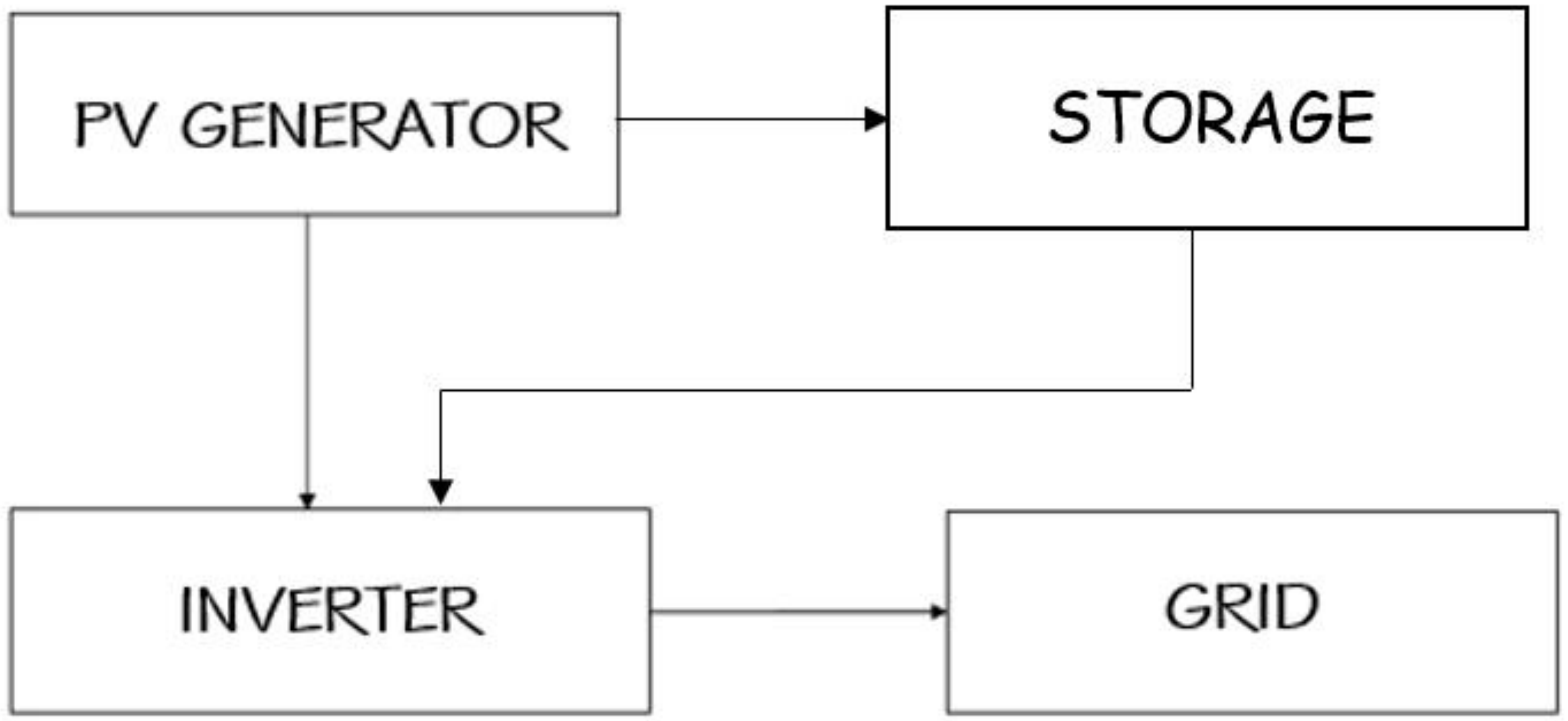
Grid-connected photovoltaic systems

DISTRIBUTED



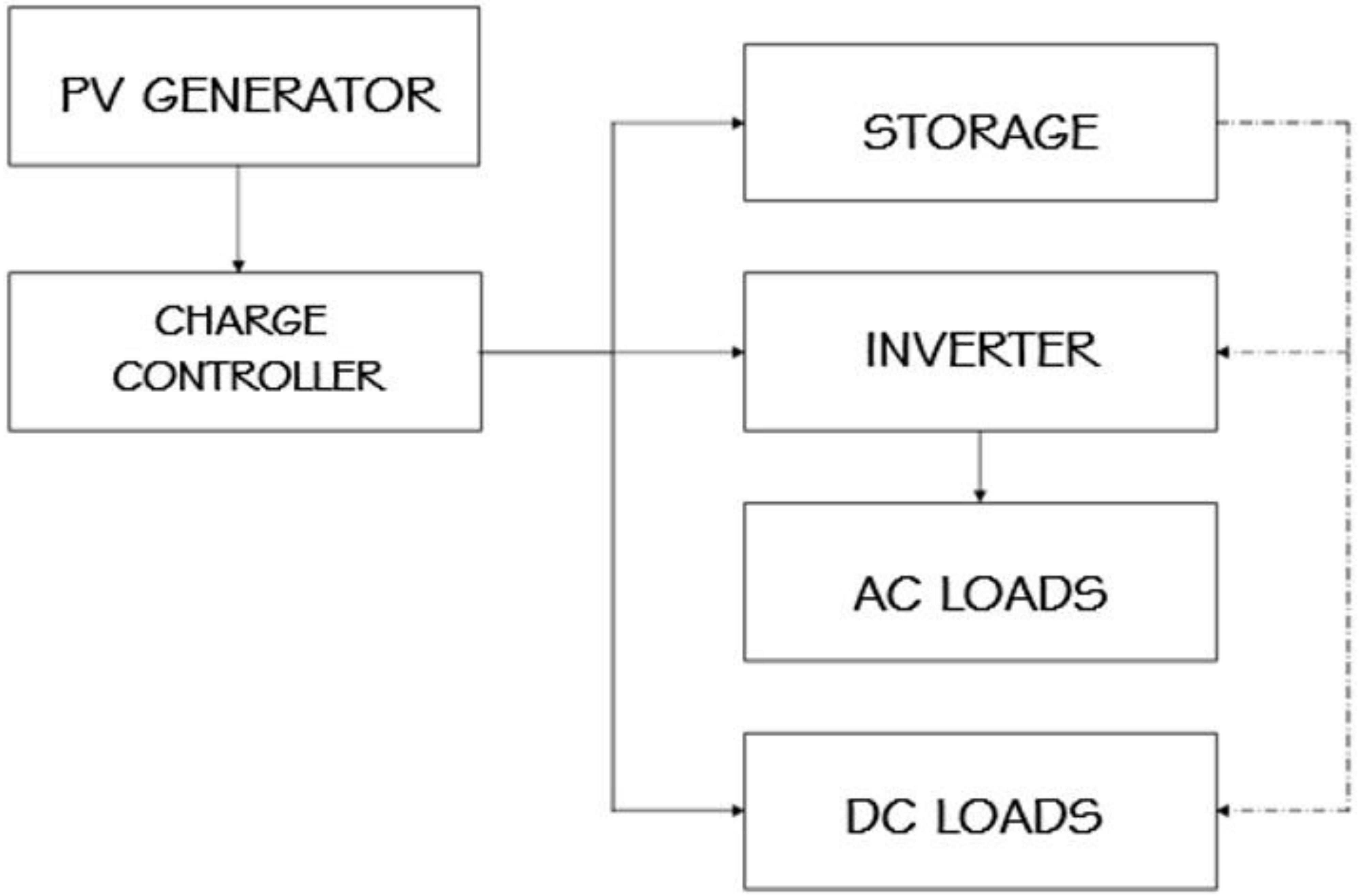
Grid-connected photovoltaic systems

CENTRALIZED



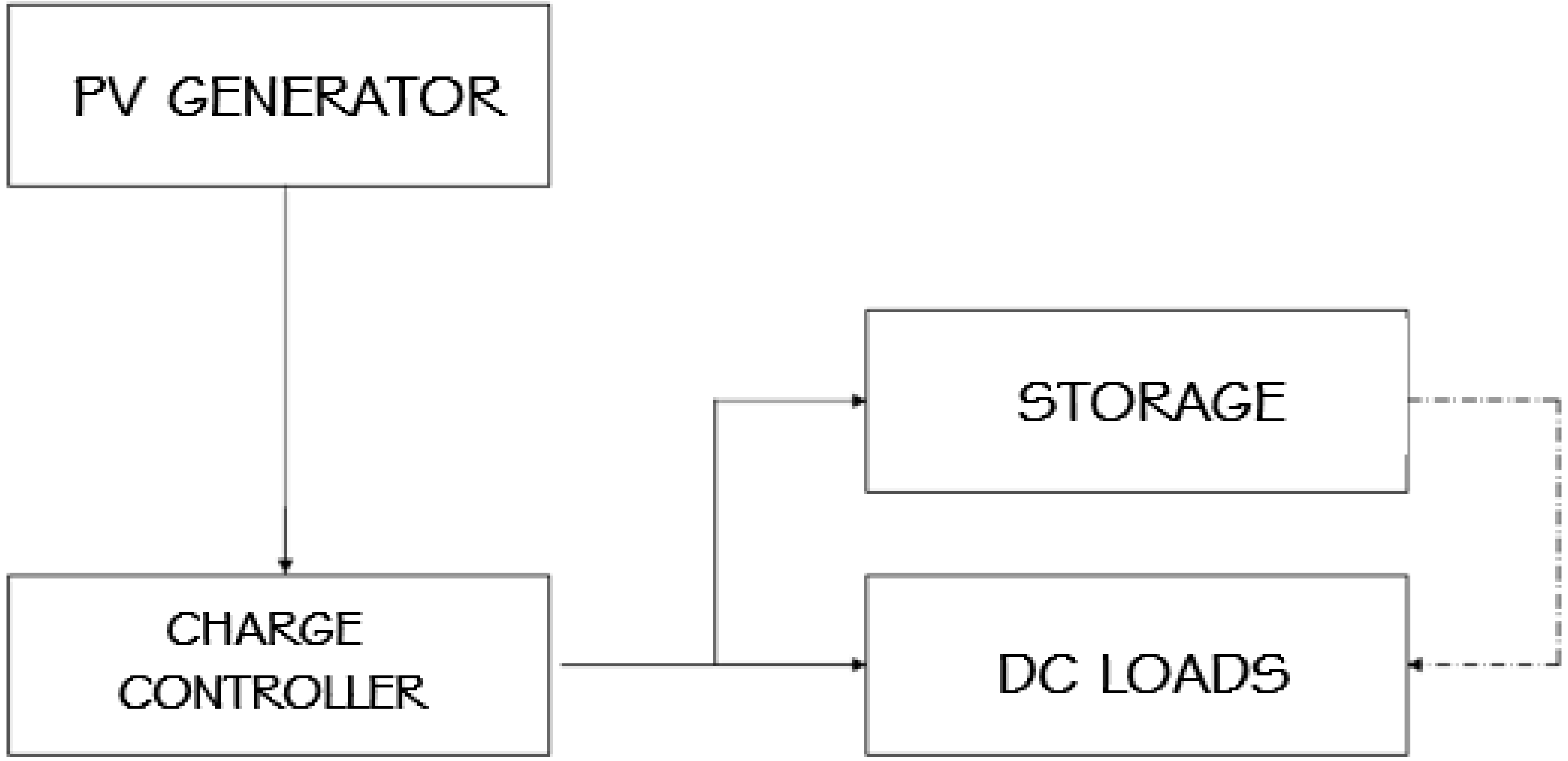
Off-grid photovoltaic systems

RESIDENTIAL

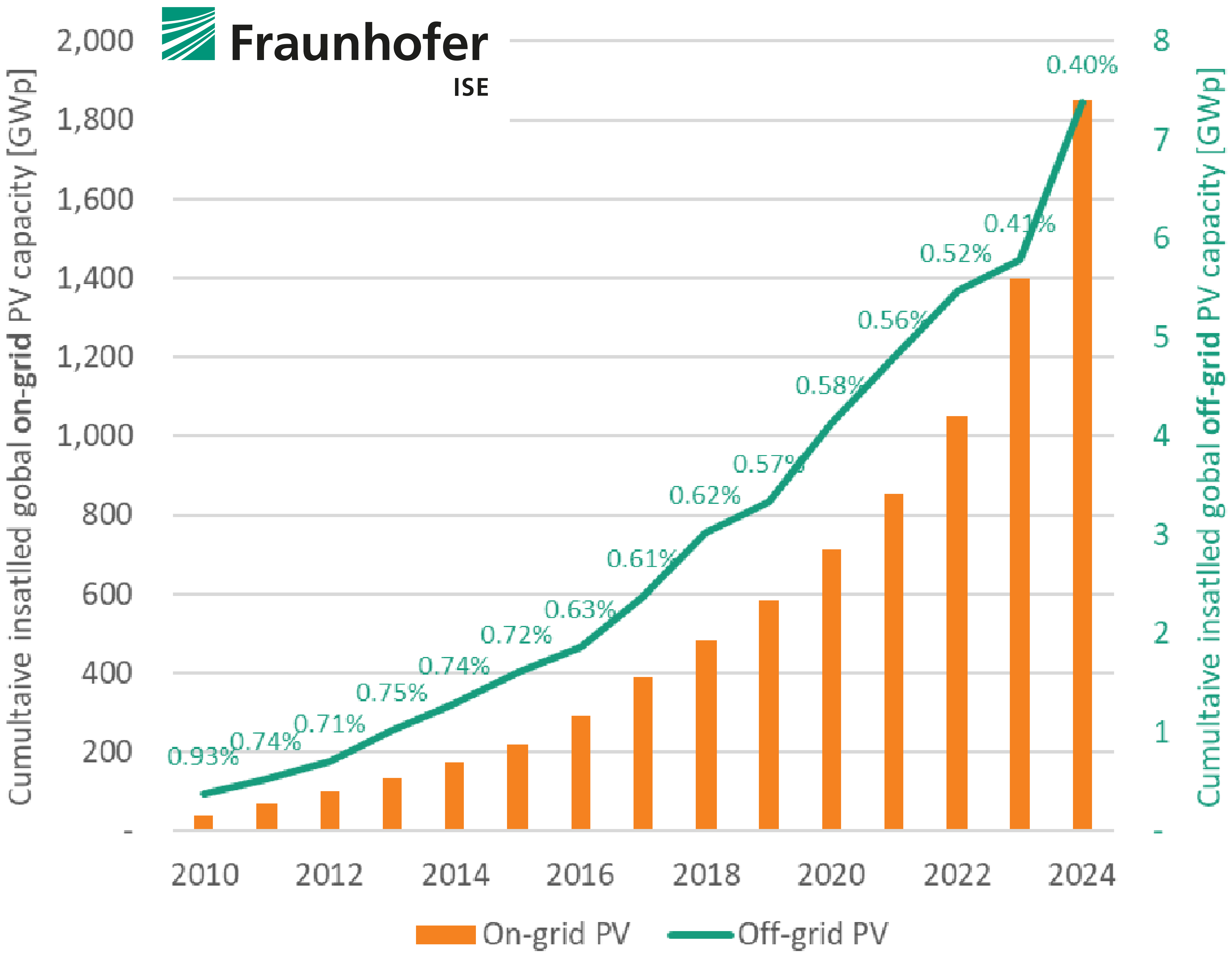


Off-grid photovoltaic systems

INDUSTRIAL



Off-grid photovoltaic systems

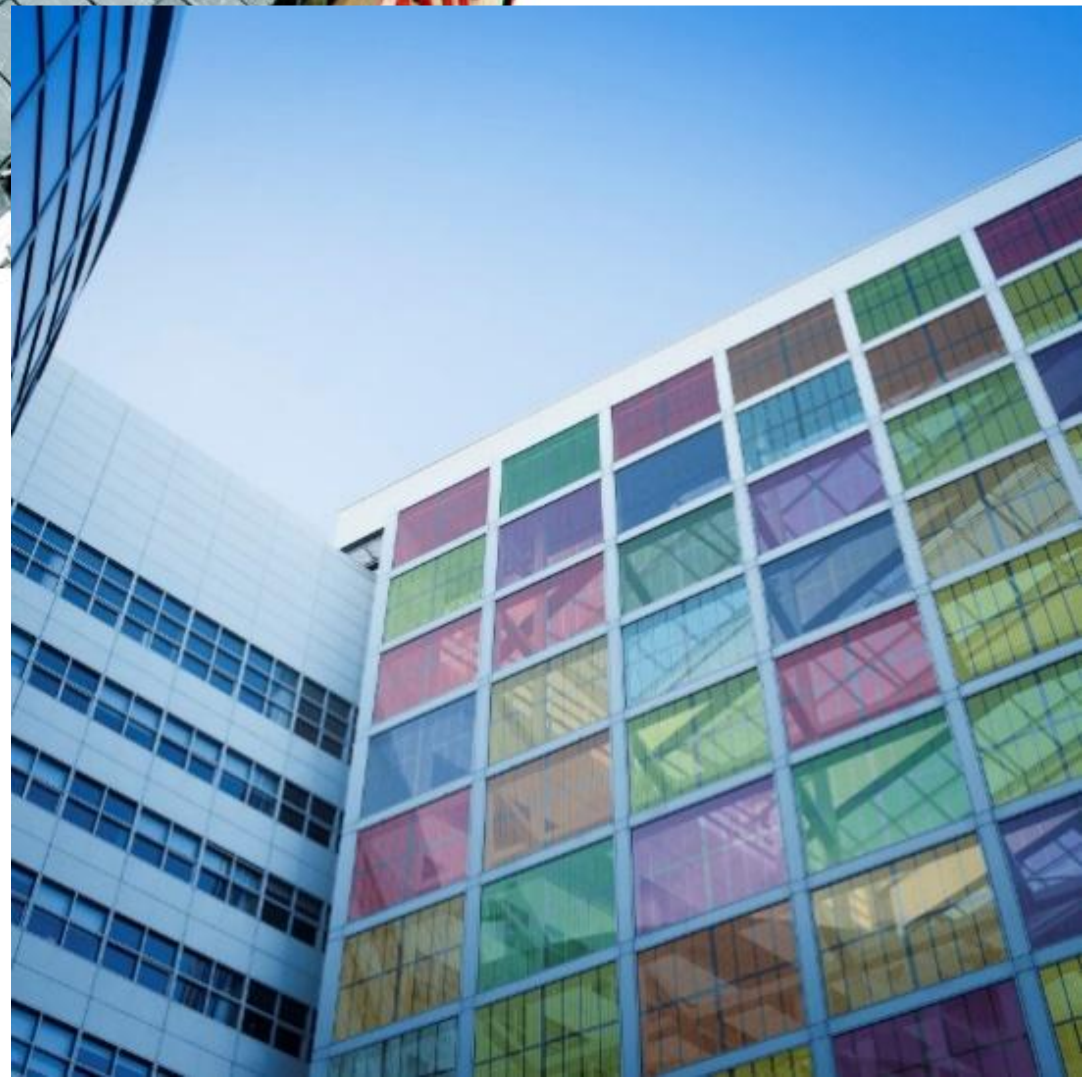


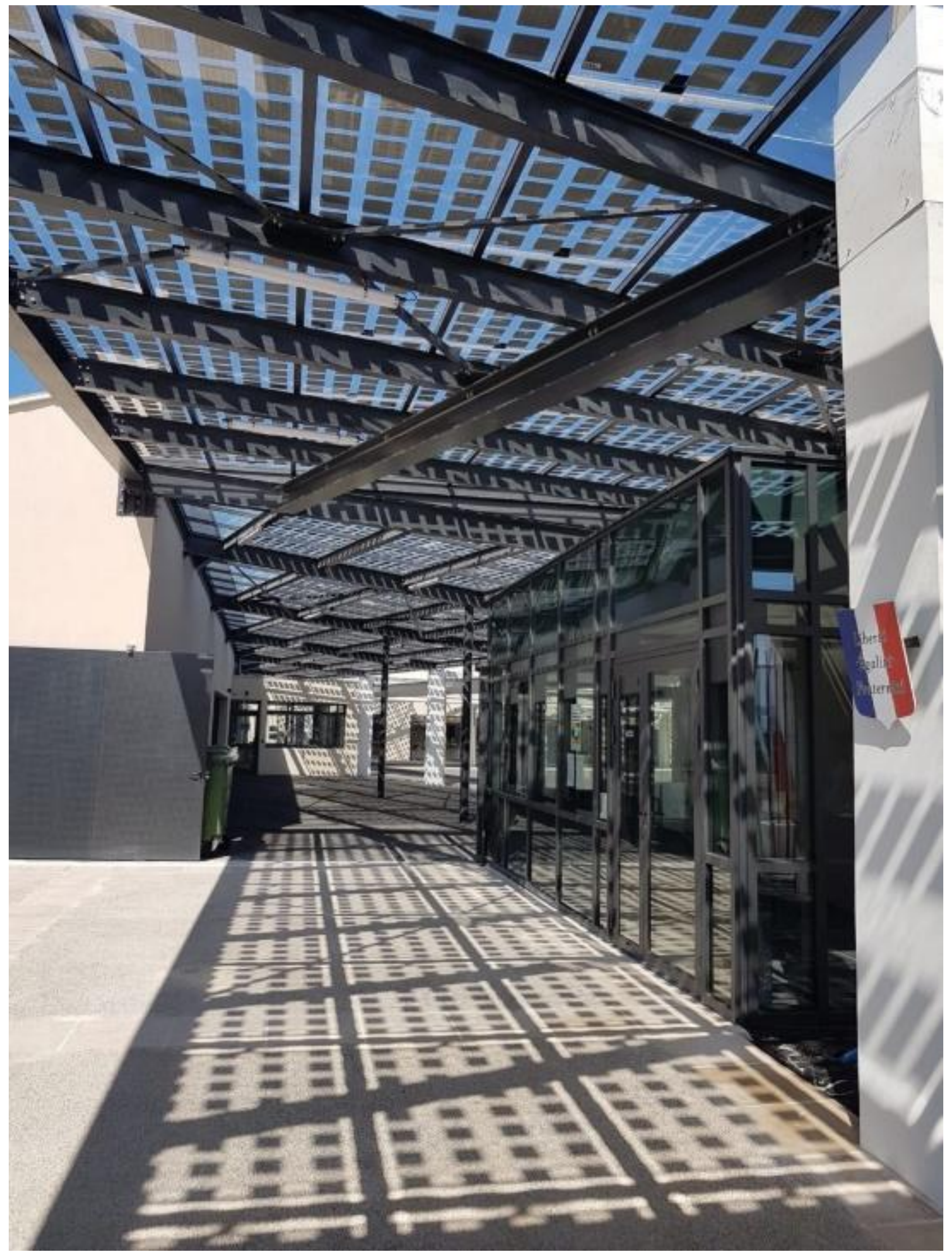
Standard photovoltaics

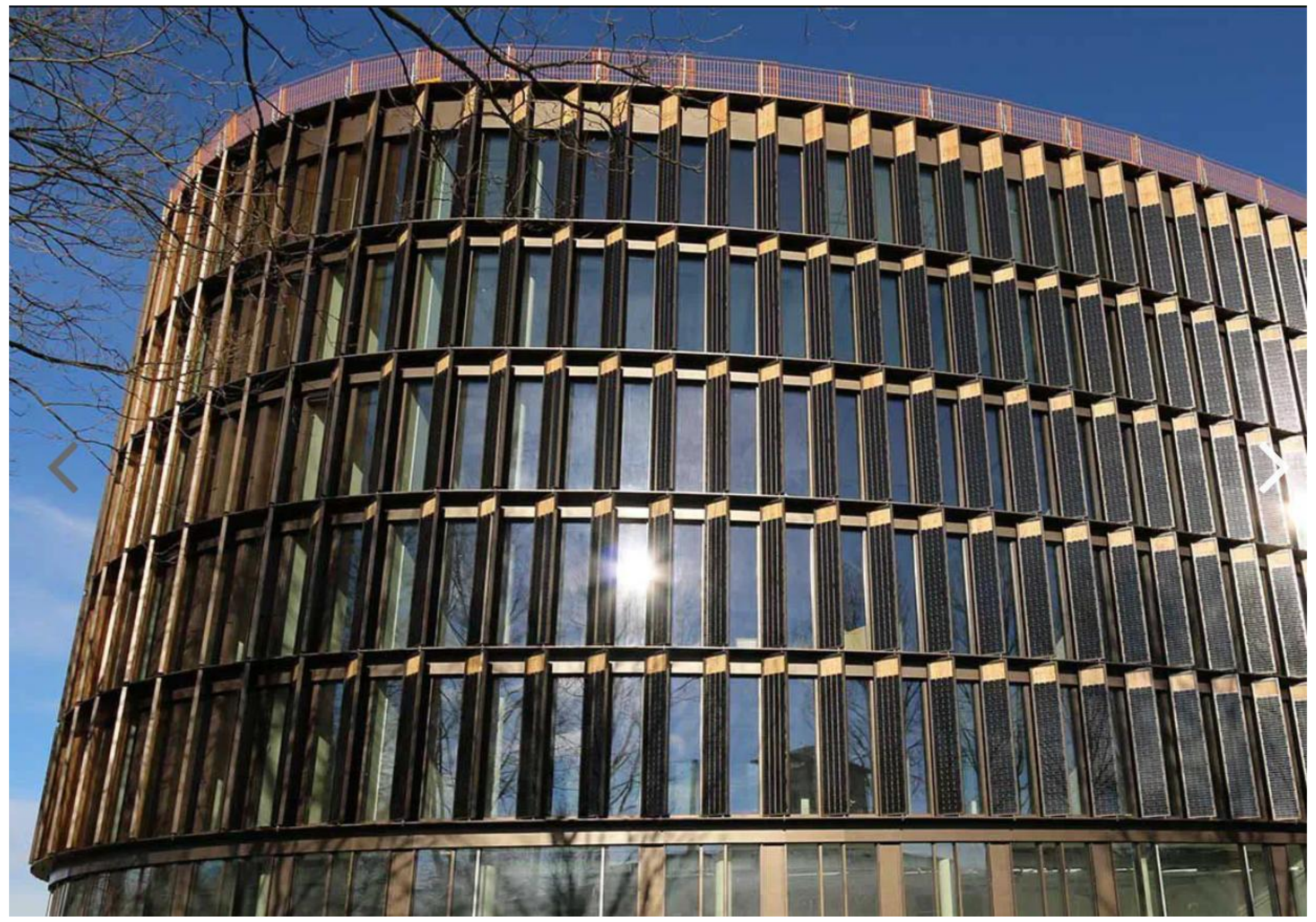
Residential

Commercial/industrial

Building Integrated Photovoltaics (BIPV)

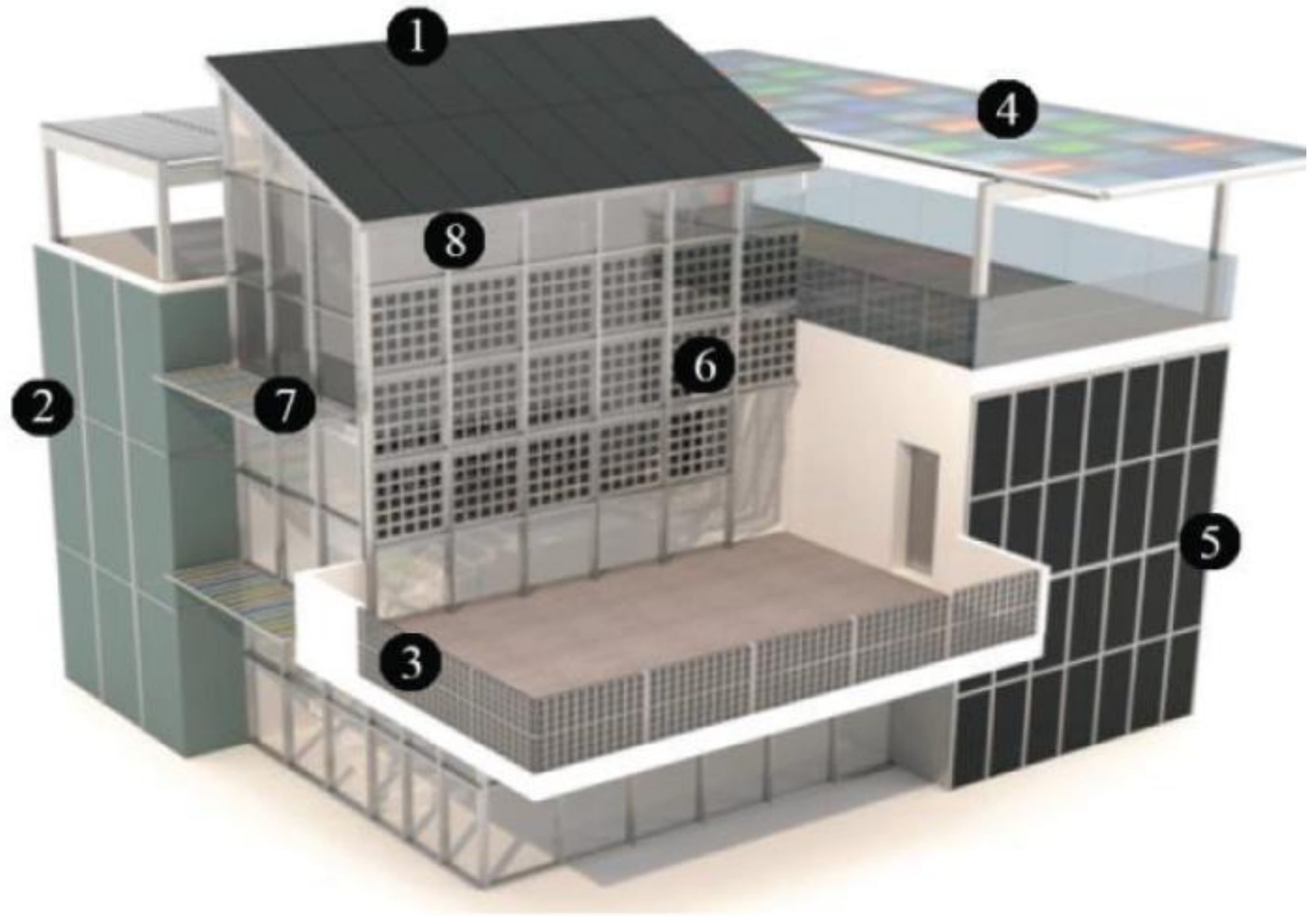






Building Integrated Photovoltaics (BIPV)

BIPV categories		
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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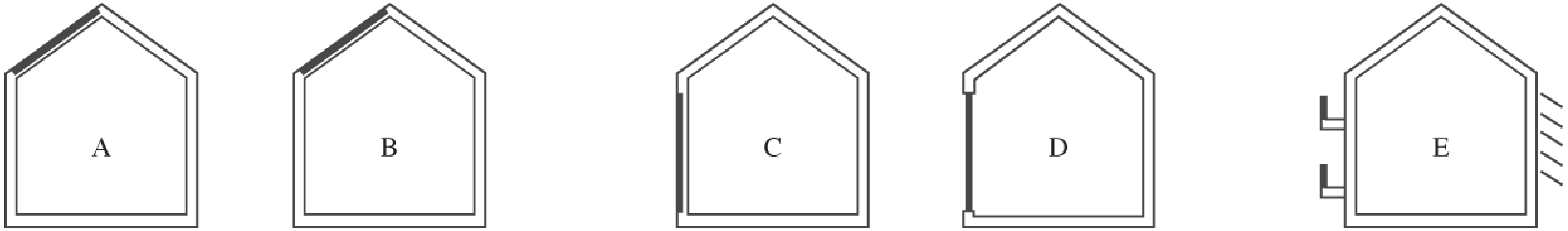


IEC63092 standard

Black Asphalt

Grey Asphalt

Black slate

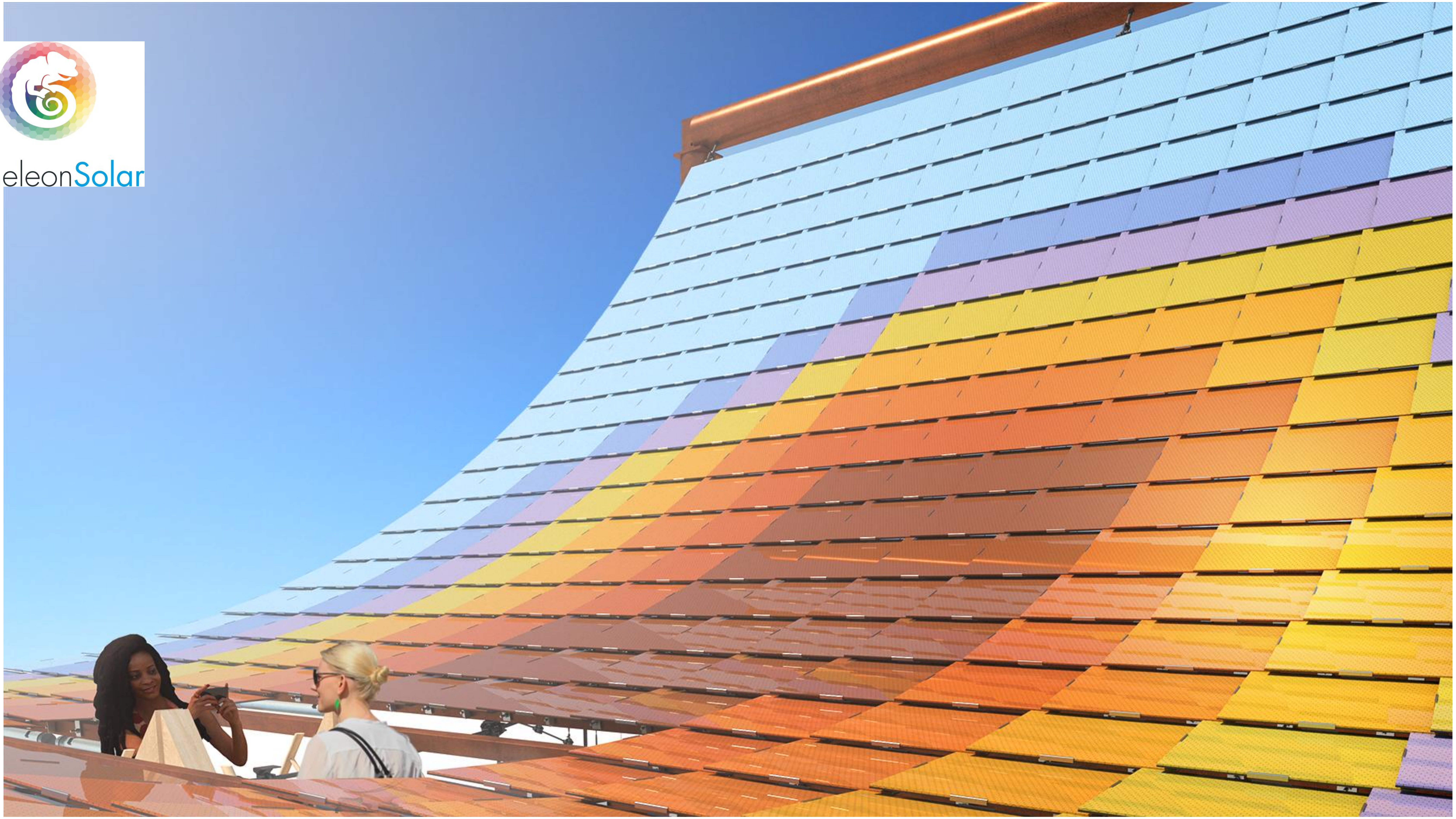
Brown Asphalt

Spanish Clay

MITREX

MITREX™


KameleonSolar

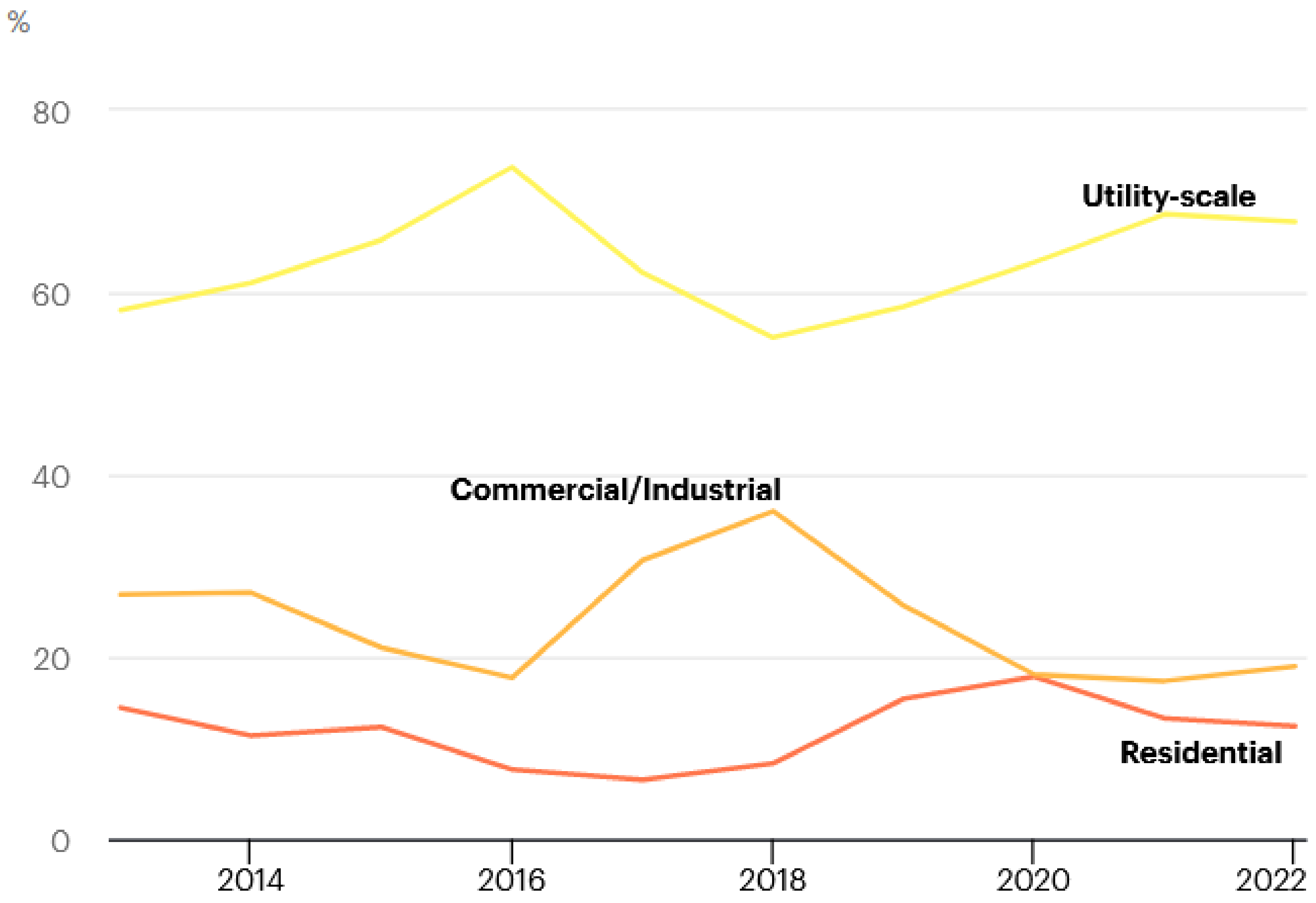


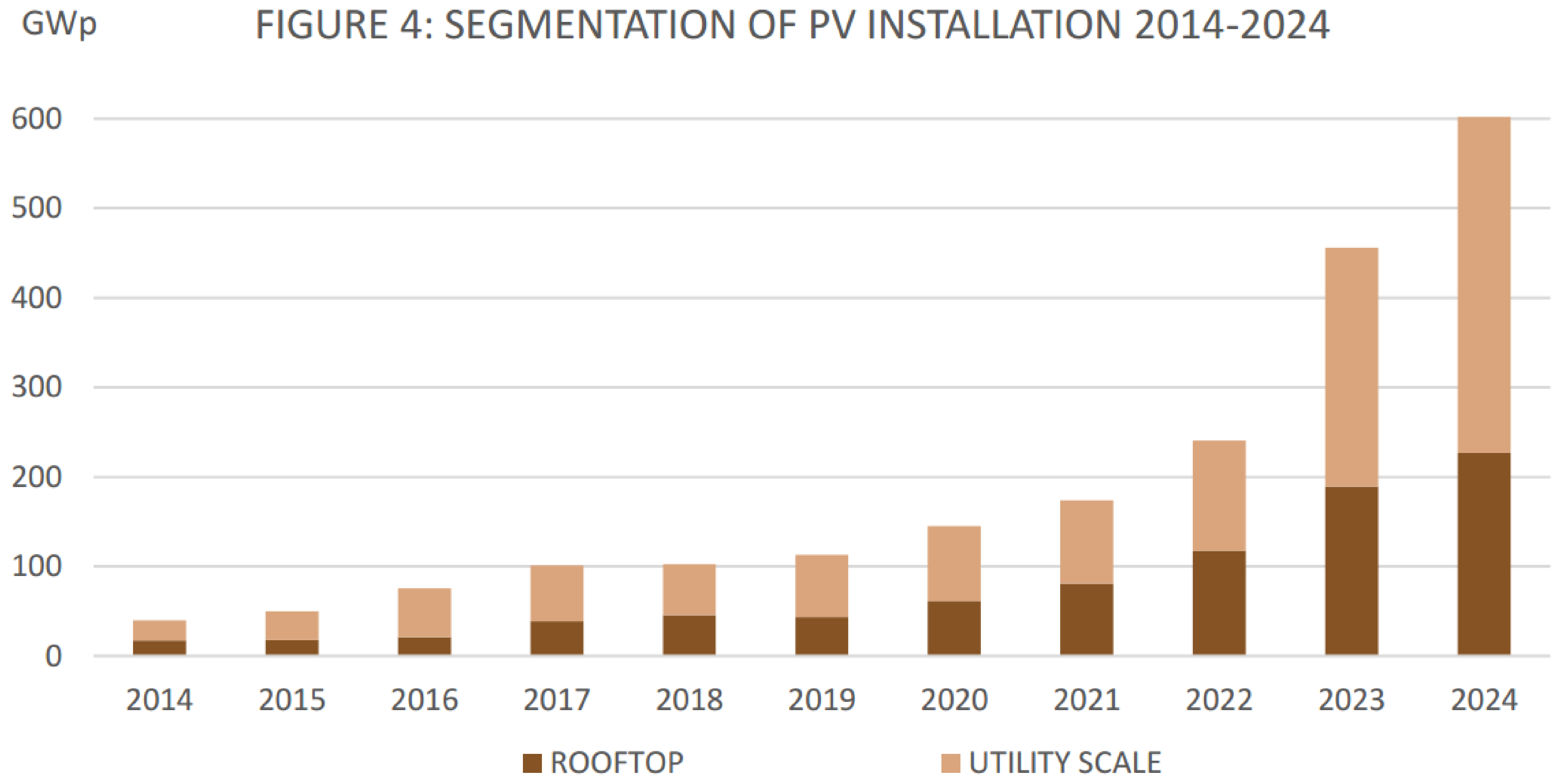

SolaRail™
Electrifying skylines with solar railings


Solar Panel & Roof

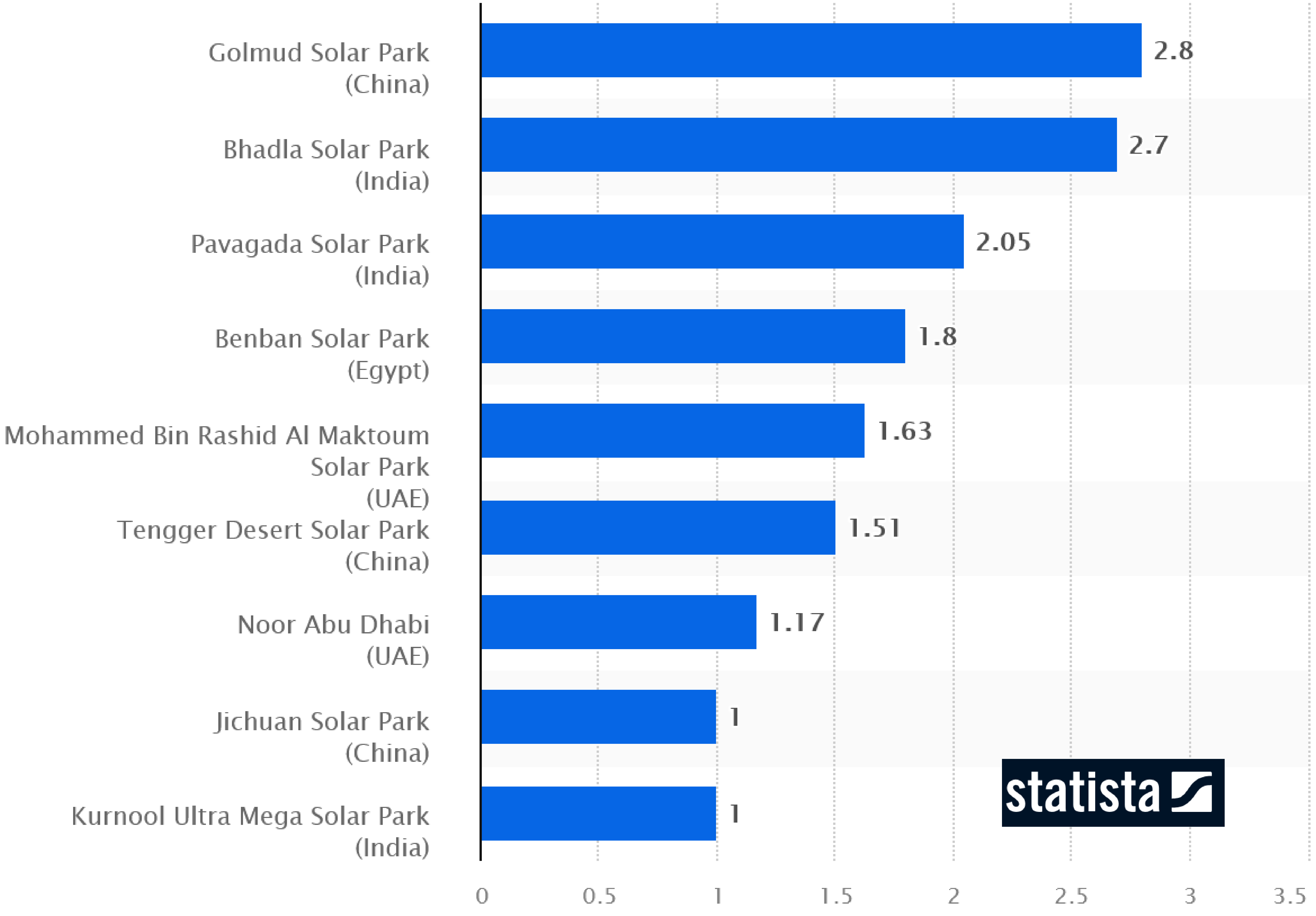
Standard photovoltaics

Utility-scale





Ground-mounted pv systems



- 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

Power [1]	Location	Description [2]	On Grid
20 MW	South Korea, *Busan*	Renault, Samsung facility	2012
13 MW	Belgium, *Kallo*	Loghidden City, Katoen Natie	2010
12.5 MW	Italy, *Padova*	Interporto Padova	2010-2011
12 MW	India, *Amritsar*	RSSB-EES PV Roof System	2015
11.9 MW	France, *Maubeuge*	Renault Solar Project	2012
11.9 MW	France, *Batilly*	Renault Solar Project	2012
11.8 MW	Spain, *Figueruelas*	GM facility Picture courtesy: United Solar Ovonic	2008
11 MW	Spain, *Martorell*	Seat al Sol, SEAT facility	2010-2013
10.6 MW	France, *Flins*	Renault Solar Project	2012
10.5 MW	France, *Sandouville*	Renault Solar Project	2012

Photovoltaic charging stations

Fastned

Photovoltaic carports

ZERO POINT ENERGY

Photovoltaic noise barriers

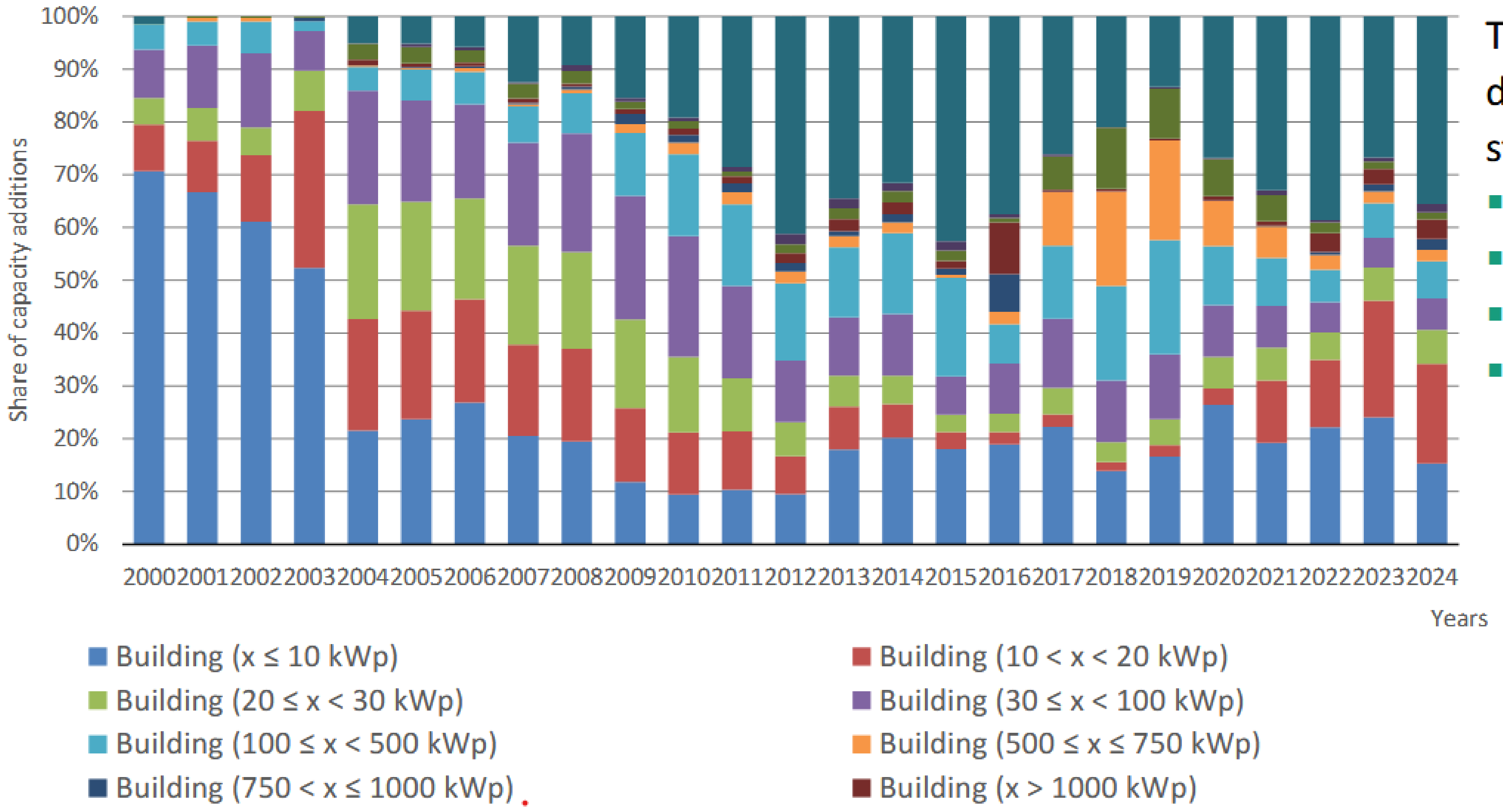
Floating photovoltaics

Agrivoltaics

Fraunhofer
ISE

Shares of PV additions by application in Germany

Fraunhofer



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

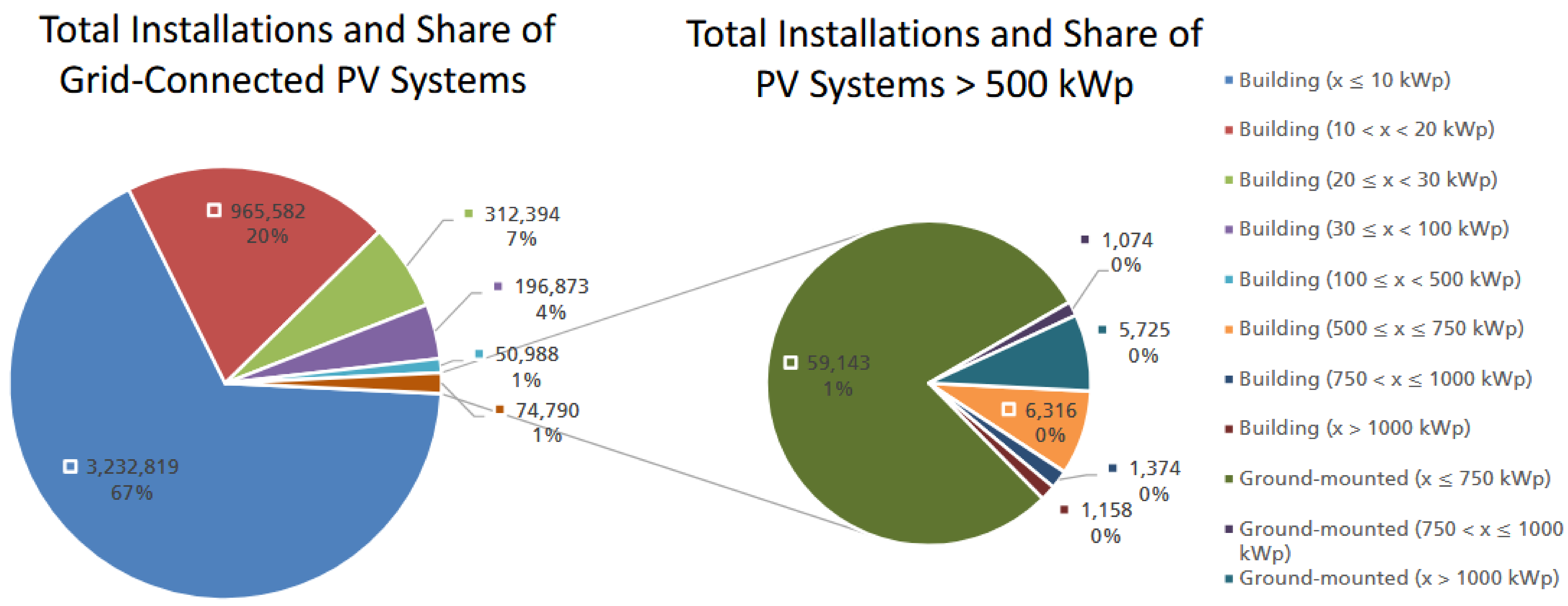
- regulations
- market incentives (like EEG)
- tender procedures
- bankability (trust of investors)

Note:

“Building” includes roofs, facades and plug-in systems.

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

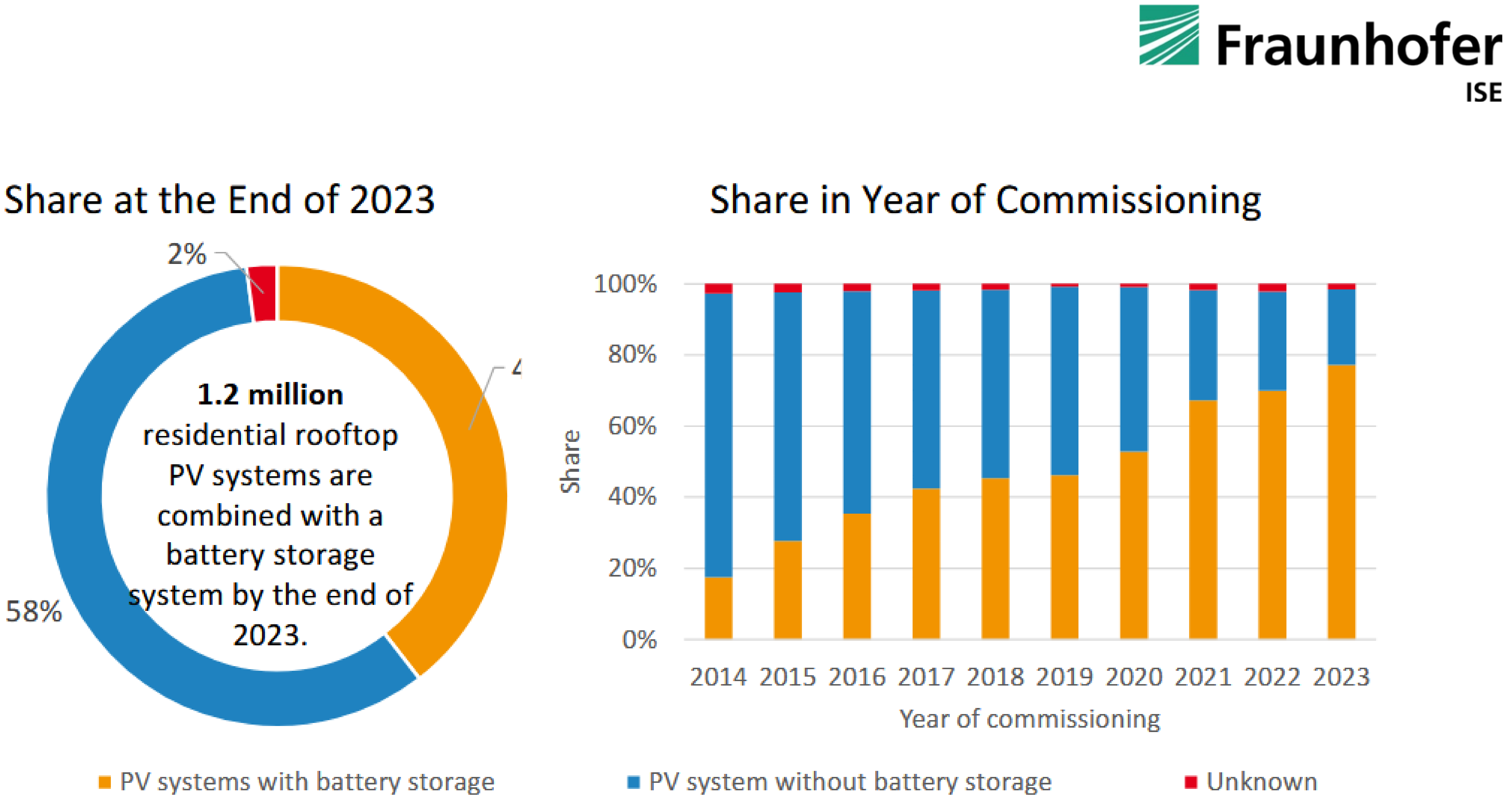
Shares of PV additions by application in Germany



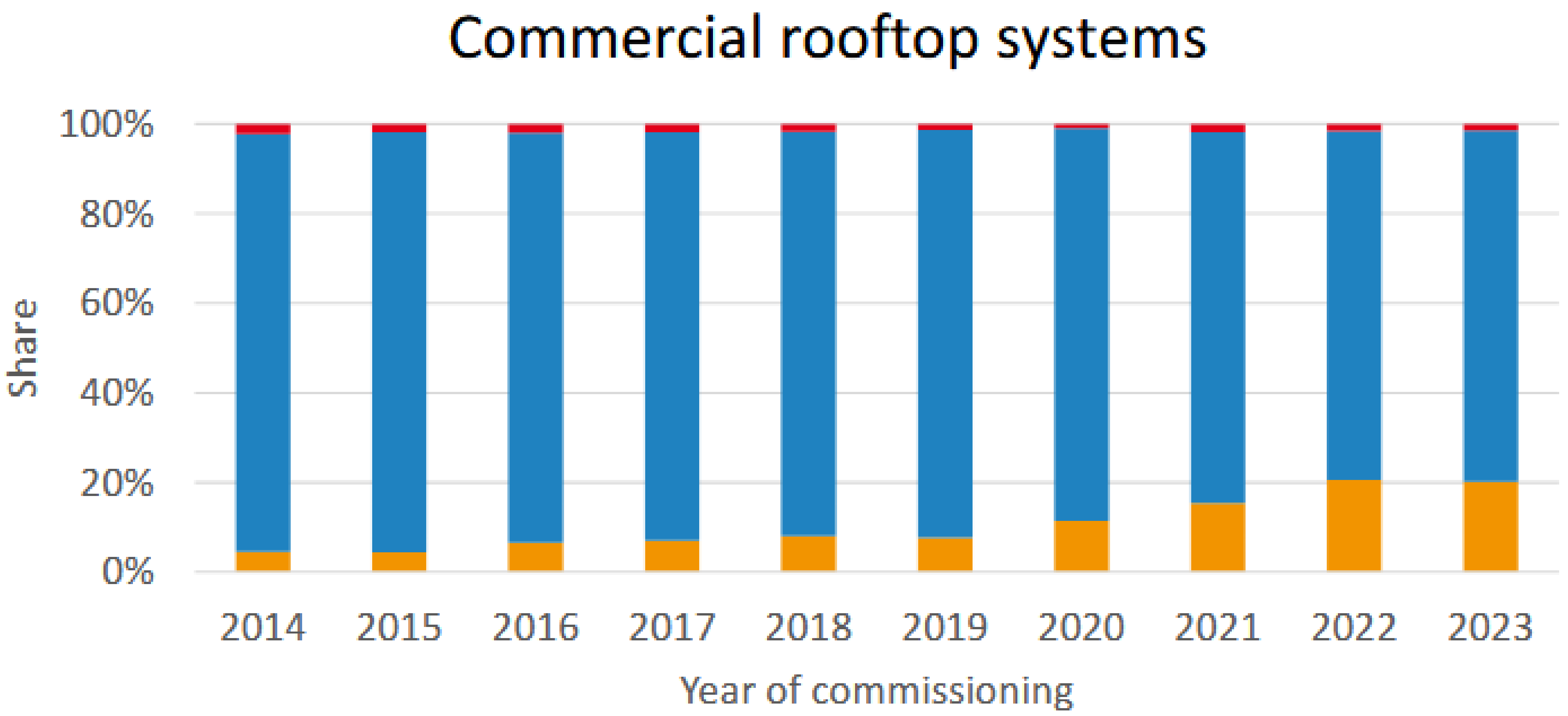
At the end of 2024, about 4.8 million grid-connected PV systems were installed in Germany.

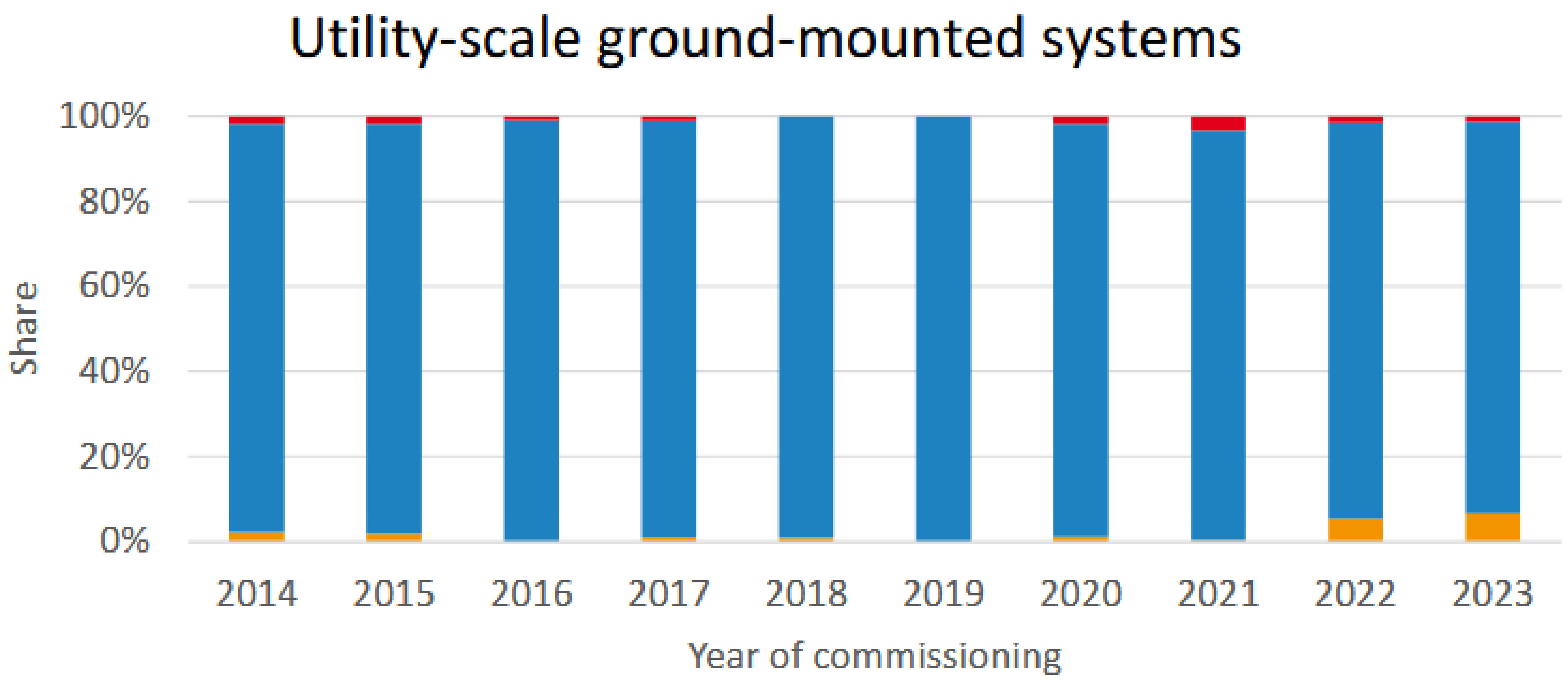
Note:
In 2024, around 800,000 plug-in systems (up to 800 W feed-in power from so-called balcony PV systems), were registered in Germany.
Due to underreporting, the actual number is estimated to be around 3 million installed systems. [1]

Shares of residential PV with and without storage in Germany



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





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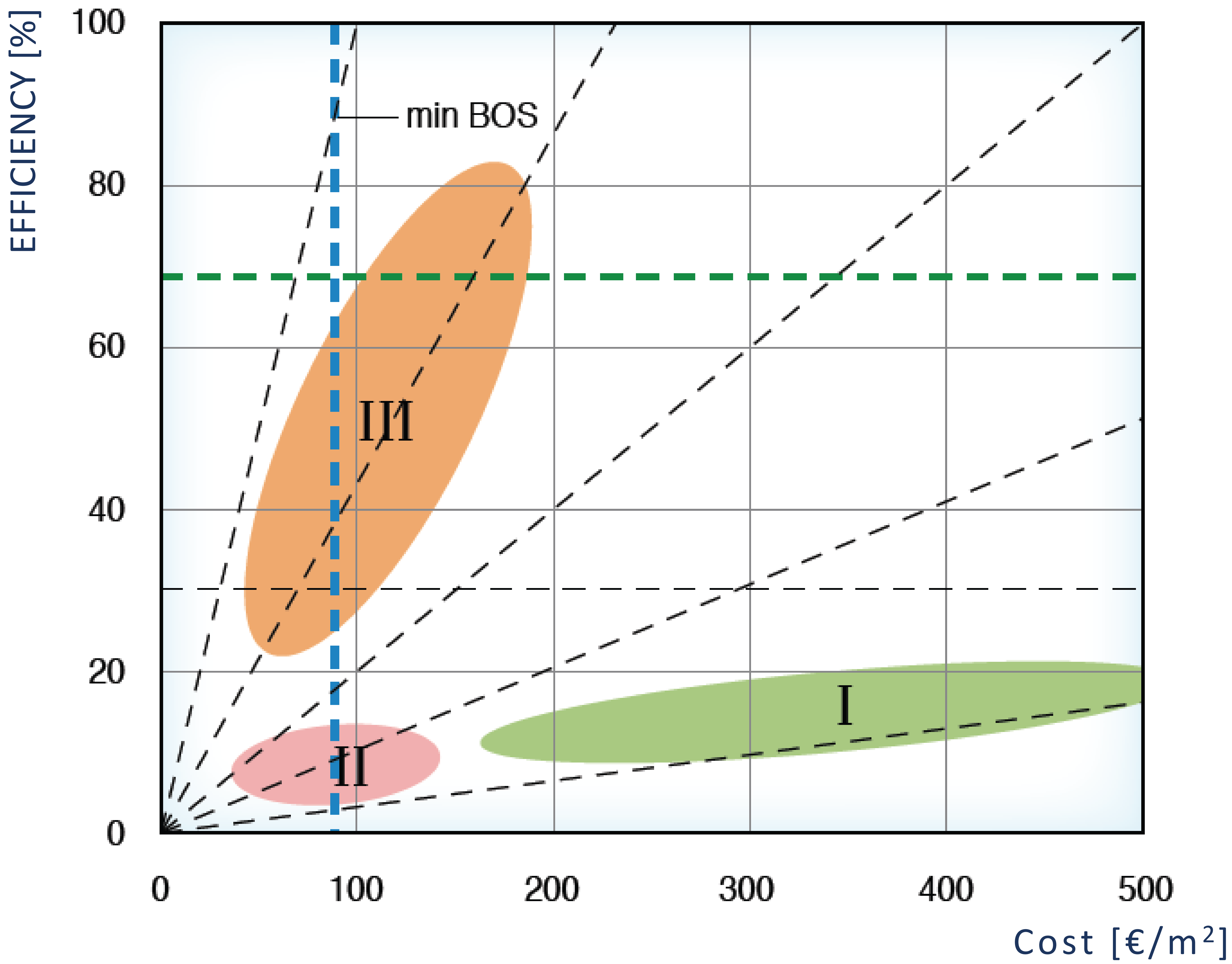
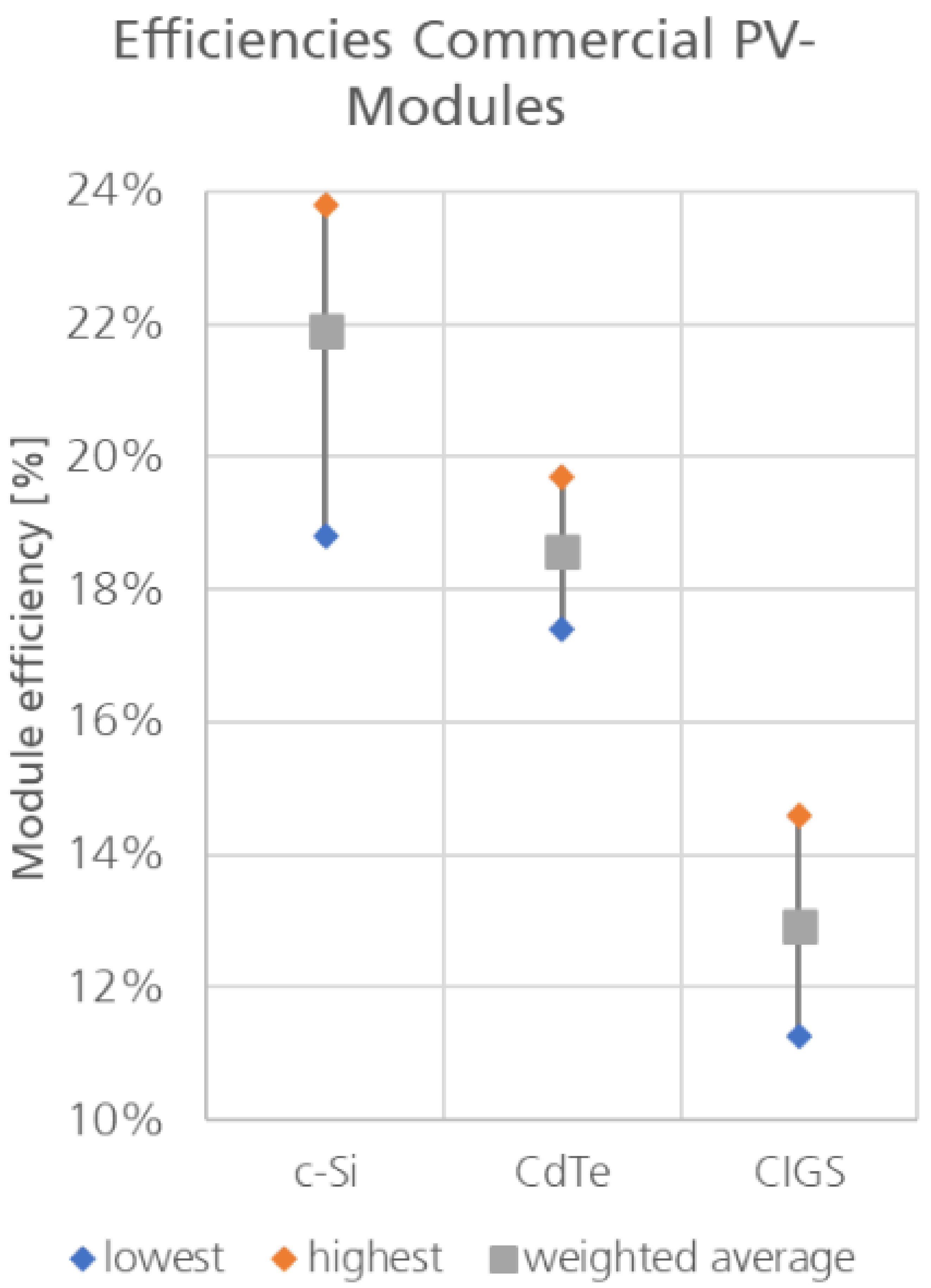
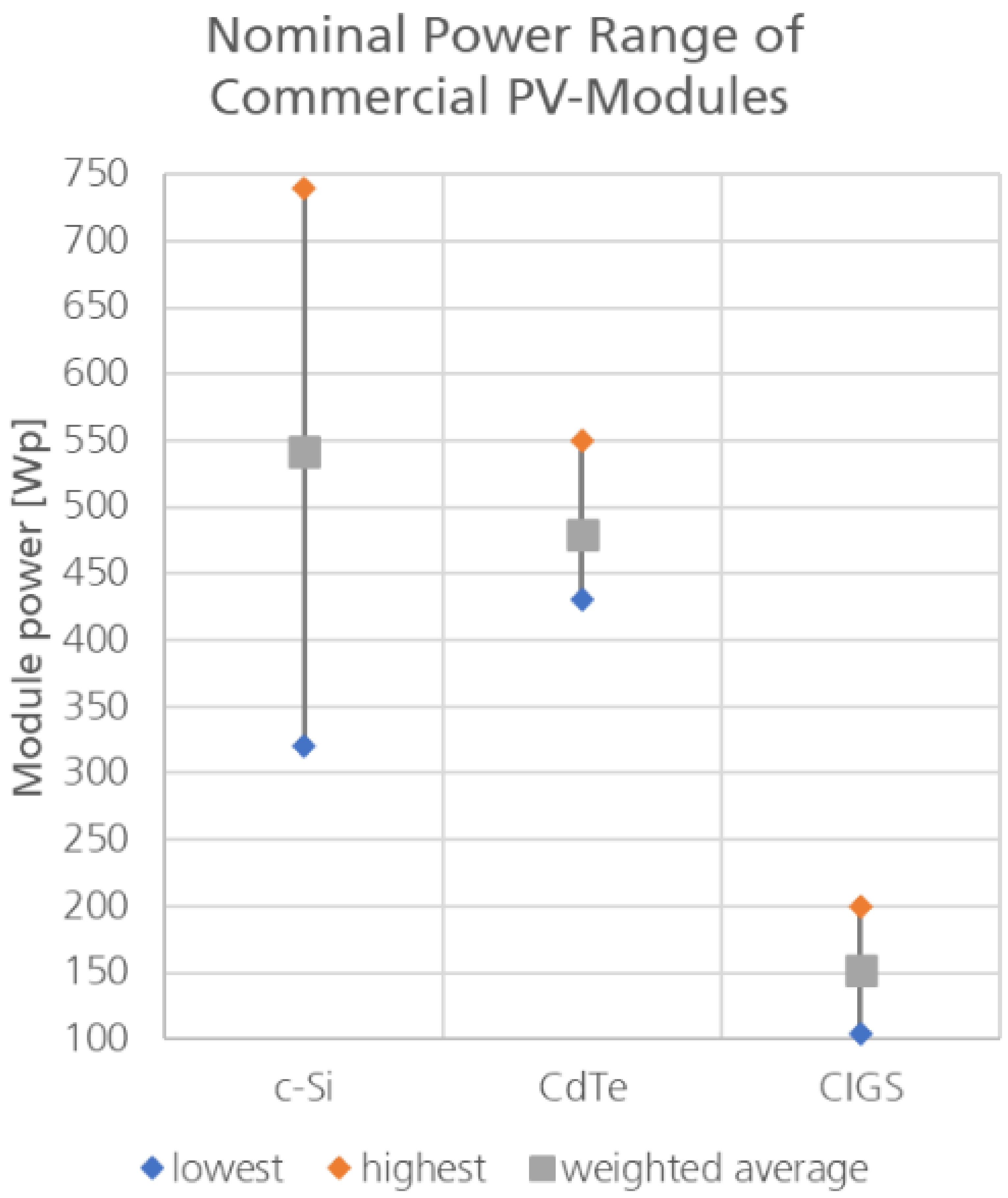
Generations of photovoltaic modules



Efficiencies and power of commercial PV modules





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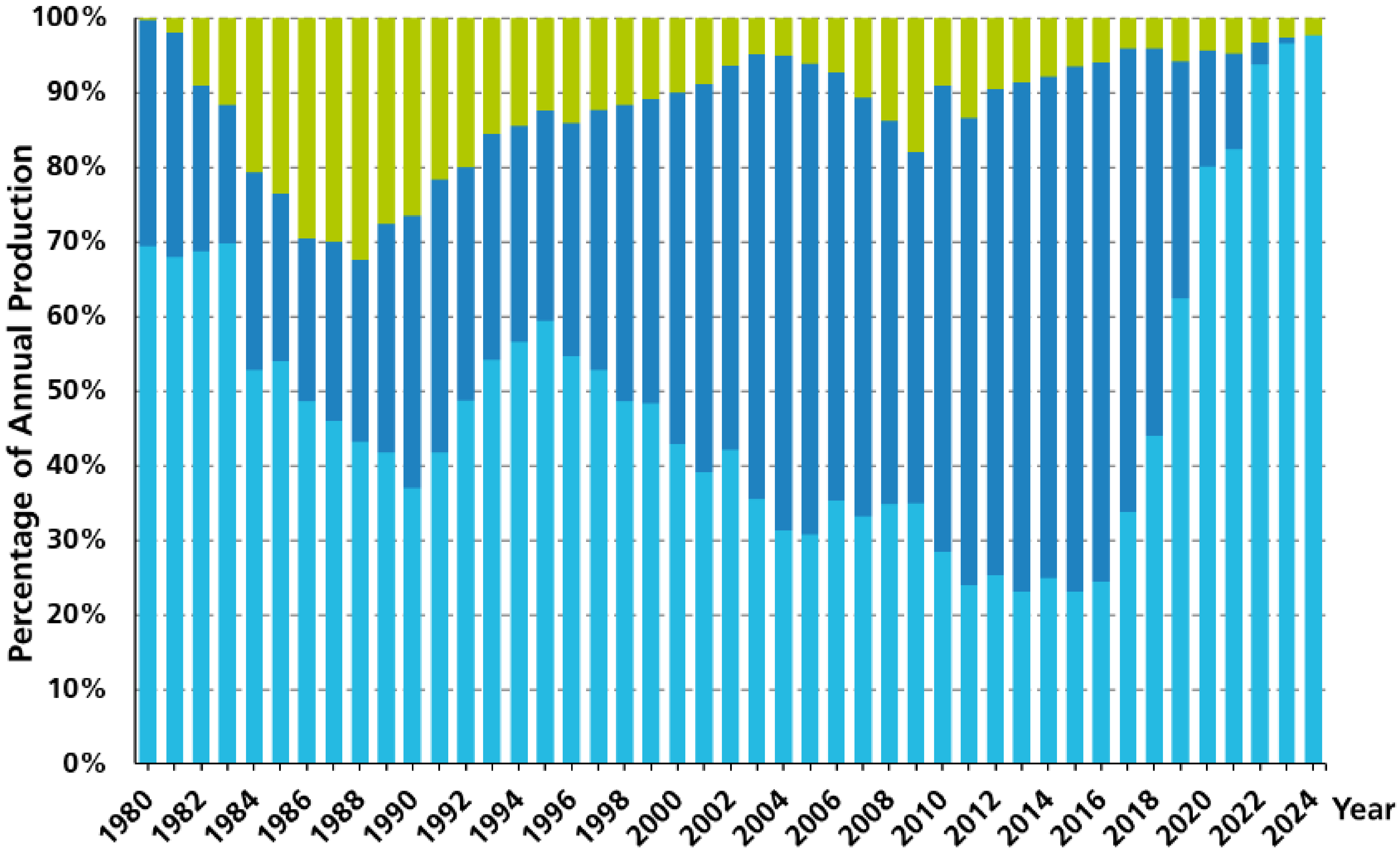
Global PV production by technology



Production 2024 (GWp)

Thin film*	16	
Multi-Si	0	
Mono-Si	687	
Total	703	(ITRPV)

*only First Solar and Avancis were considered

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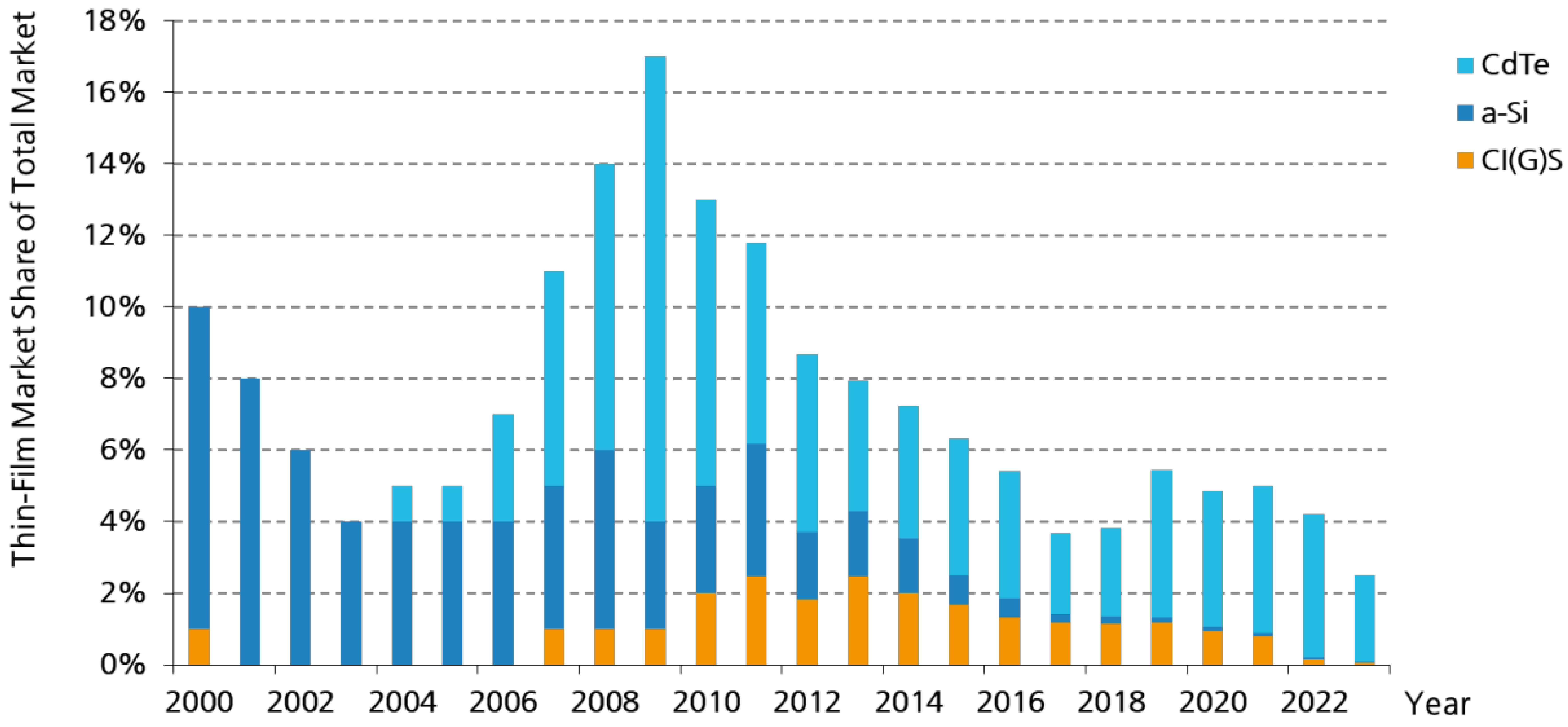
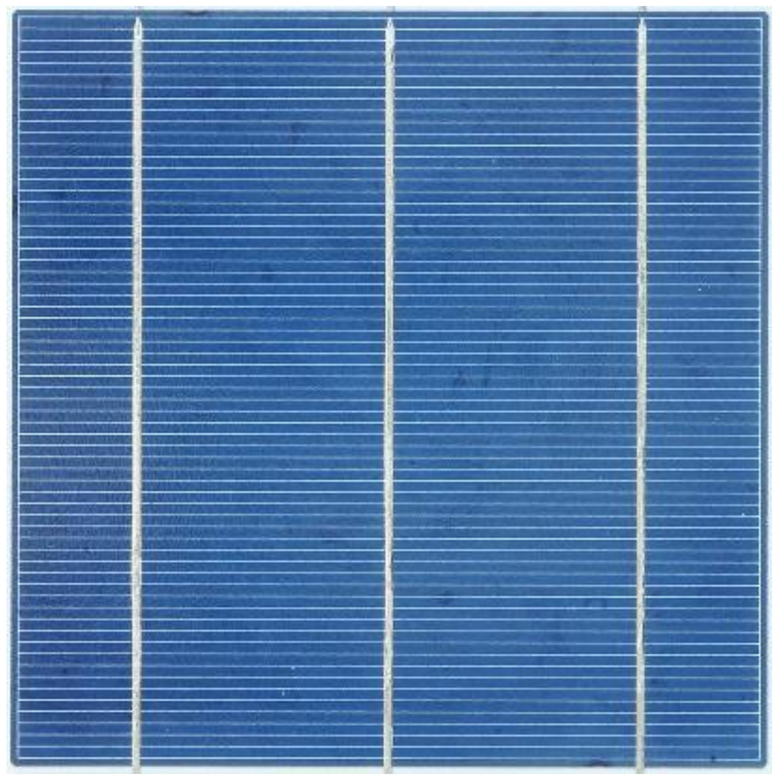
Thin film photovoltaic modules

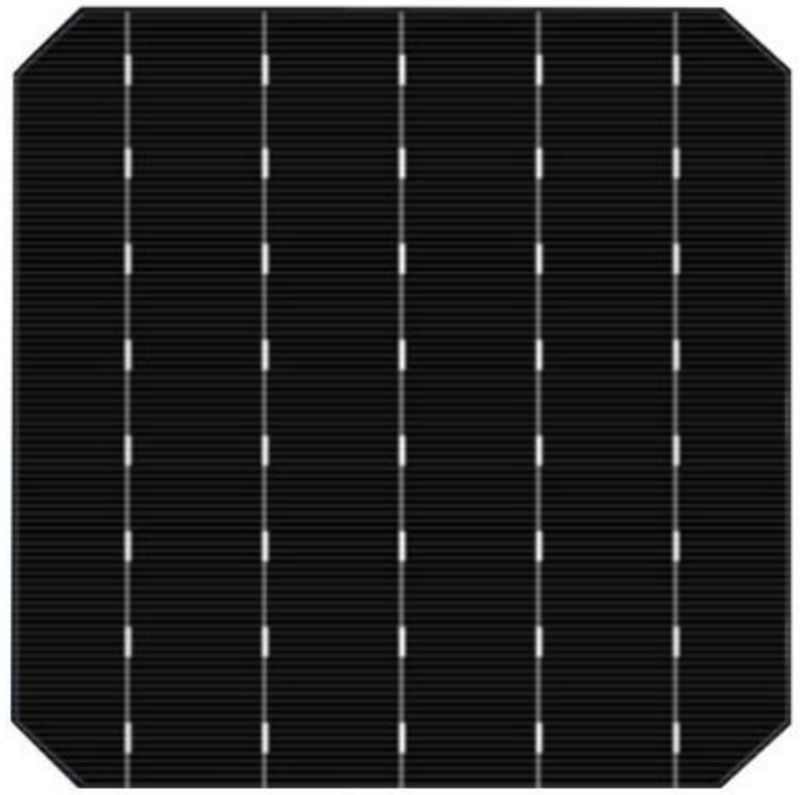


Thin-Film technology contributed in year 2023 with about 2.5% to the total PV-market.

First generation

Poly - Si

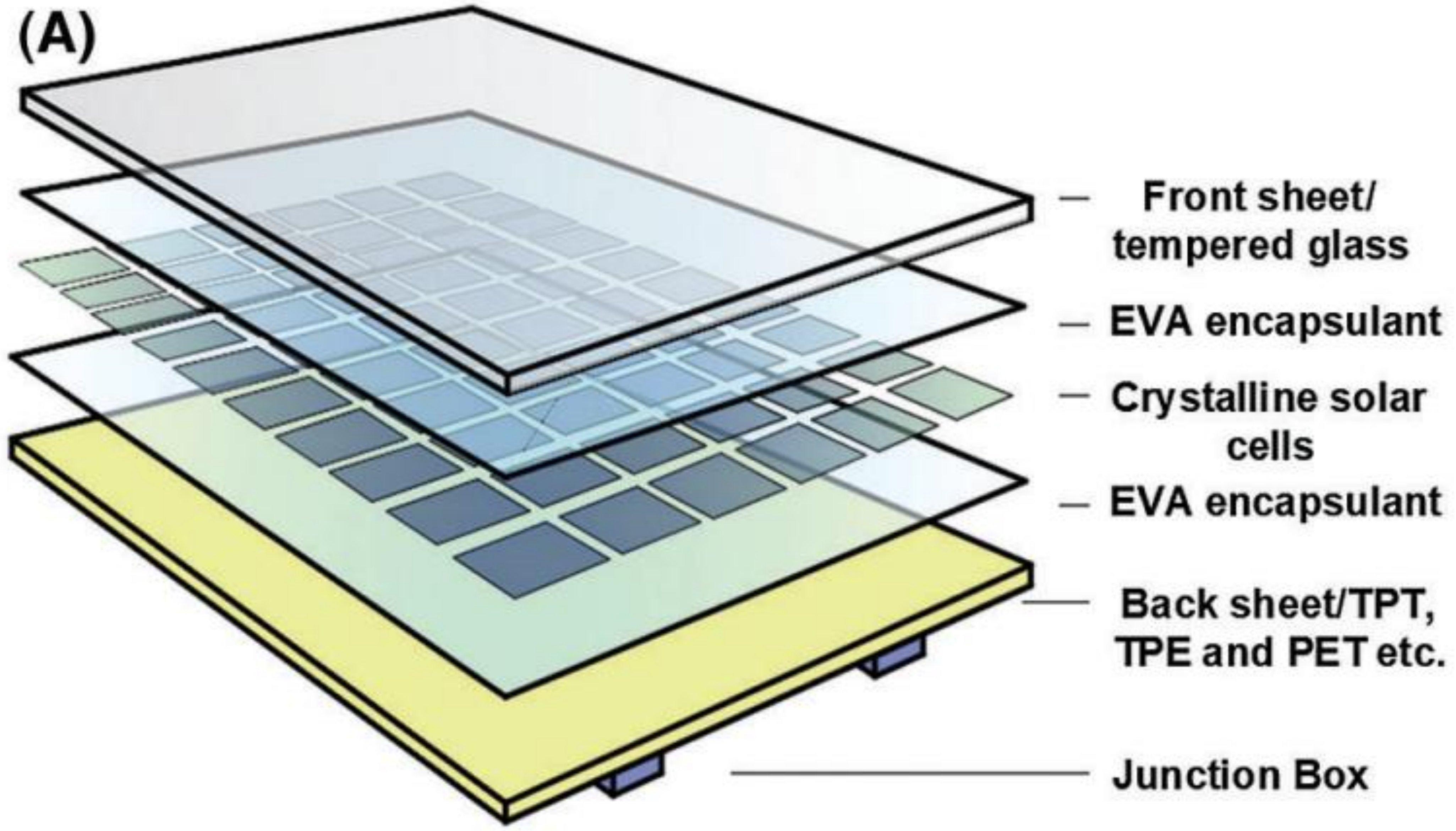


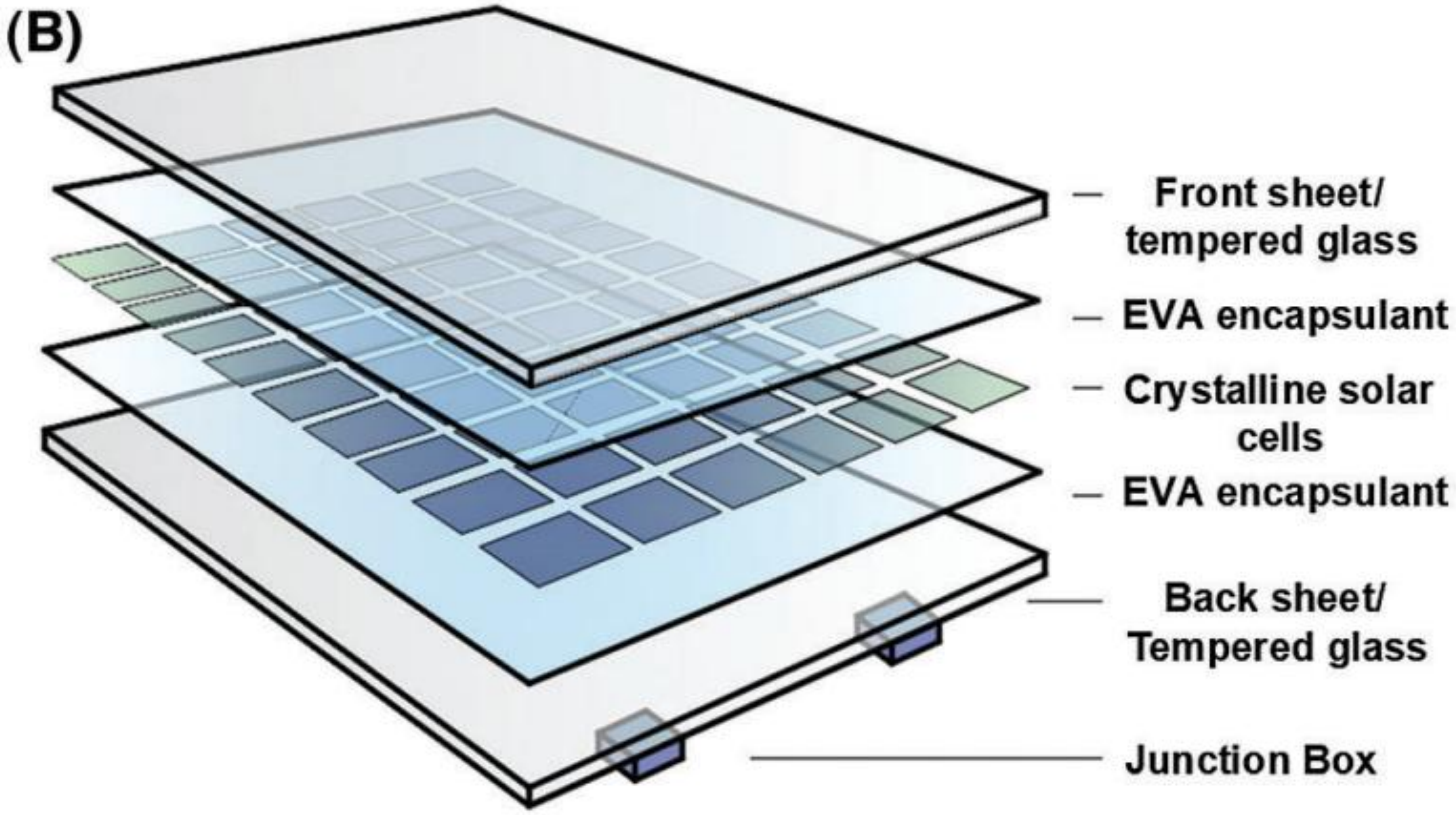


Mono - Si

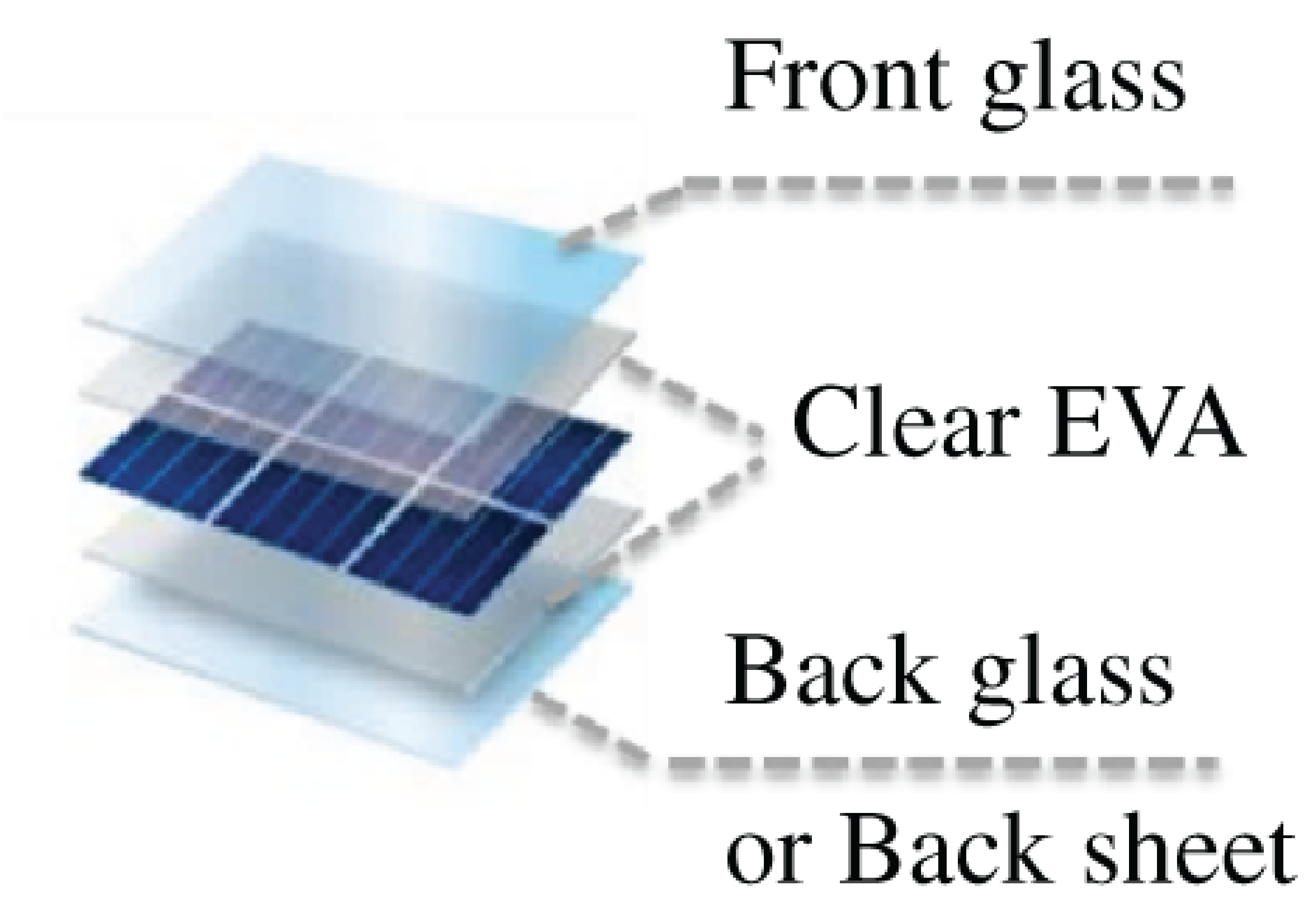
Single-glass photovoltaic modules

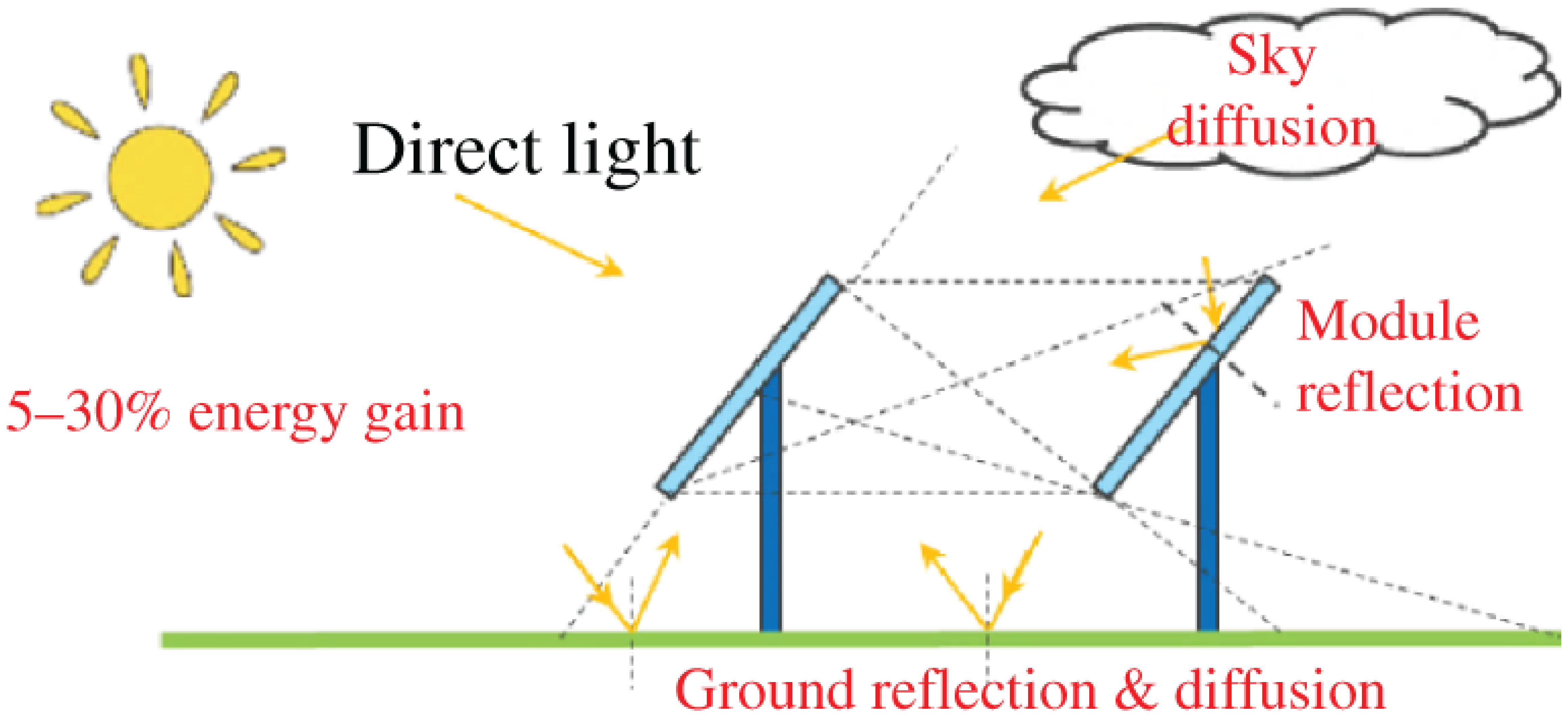
Double-glazed photovoltaic modules





Bifacial modules





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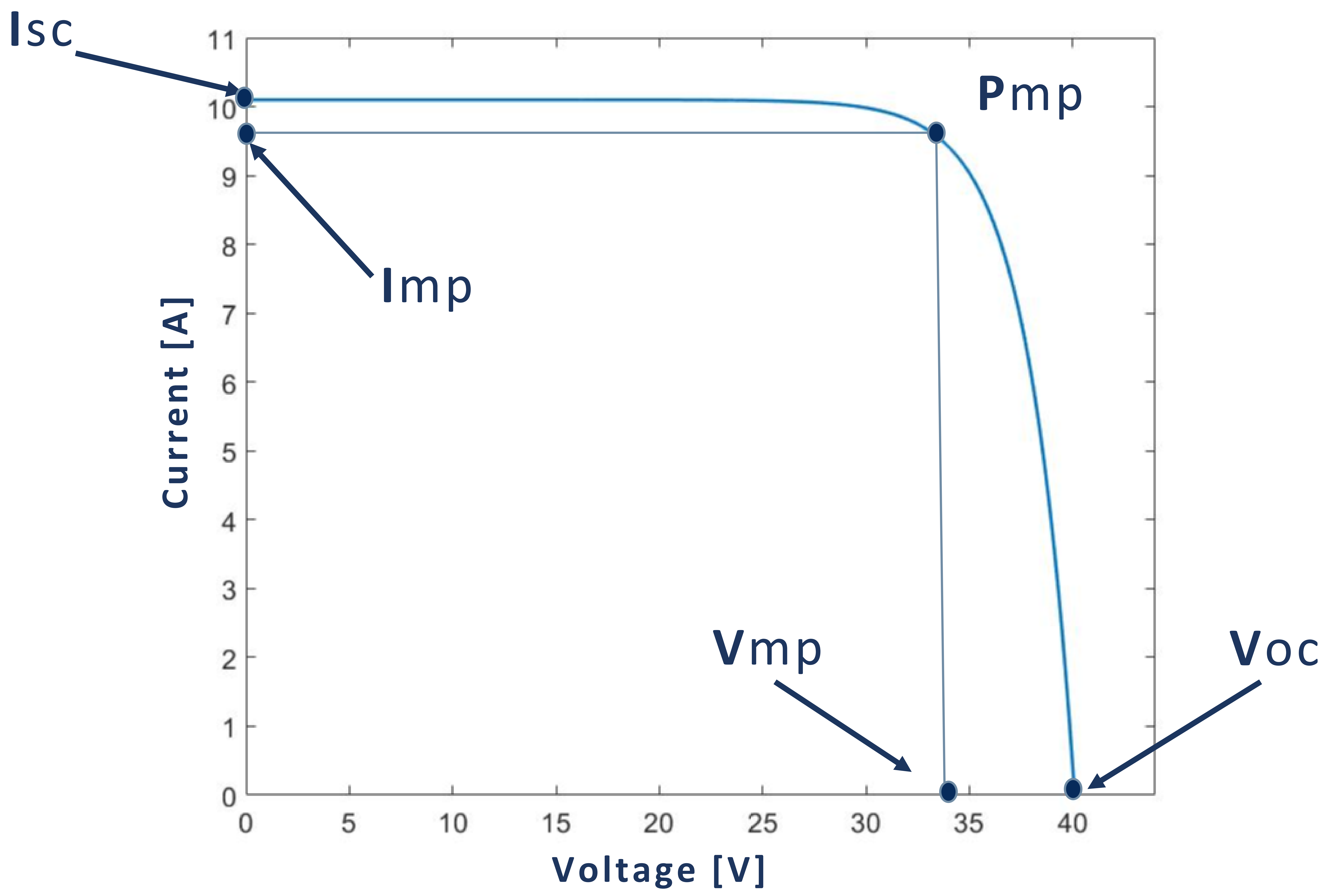
Electrical parameters – Current/voltage curve



Electrical parameters

STANDARD TEST CONDITIONS (STC)

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

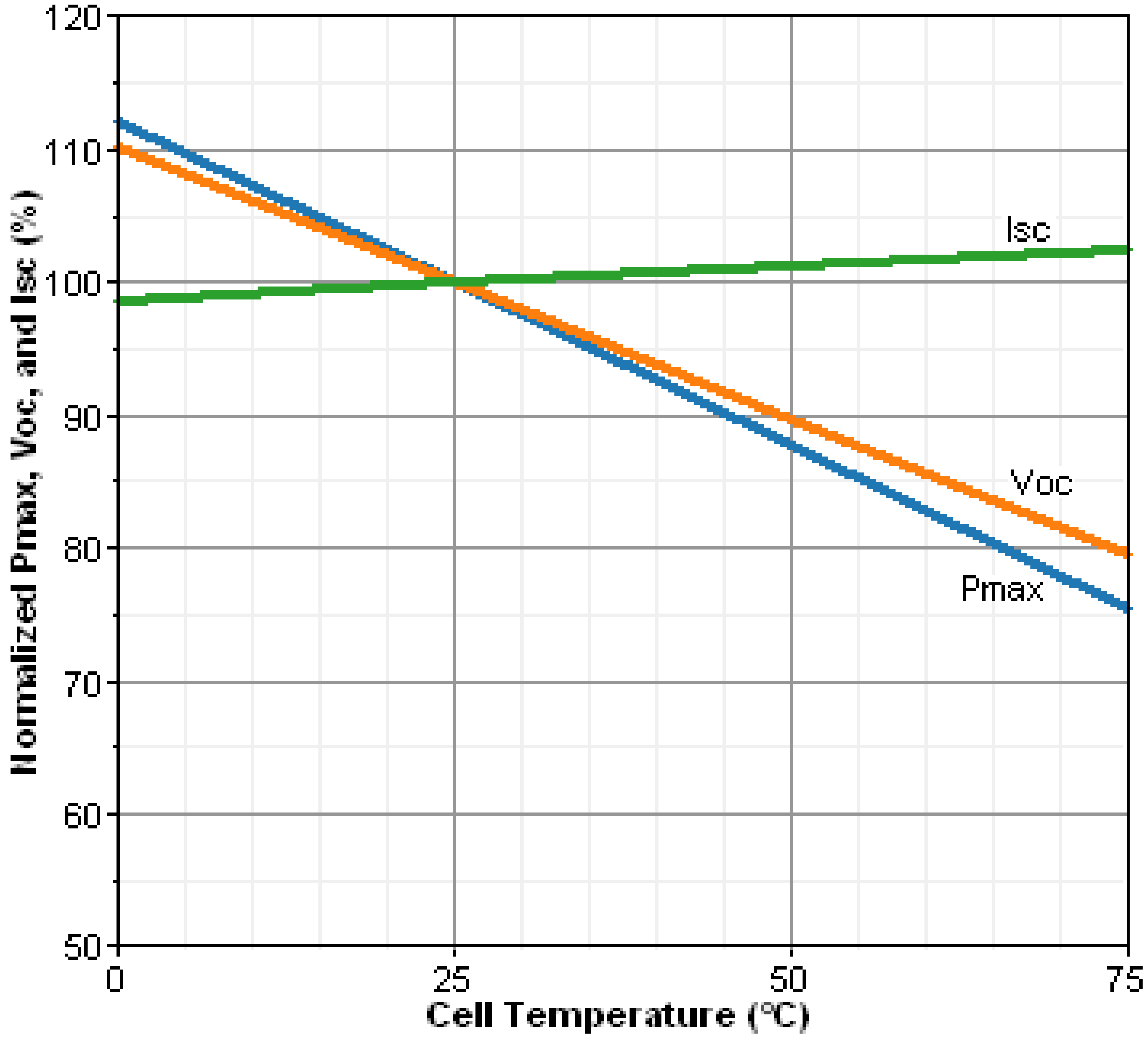
PV MODULE Q.CELLS – Q.PEAK DUO-G5 320	
Nominal Power - P_{mp} [Wp]	320 + [0-5]
Short circuit current - I_{sc} [A]	10,1
Open circuit voltage – V_{oc} [V]	40,1
Current at MPP – I_{mp} [A]	9,6
Voltage at MPP – V_{mp} [V]	33,3
Temperature coefficient of I_{sc} – Z [%/K]	+0.04%/K
Temperature coefficient of 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

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

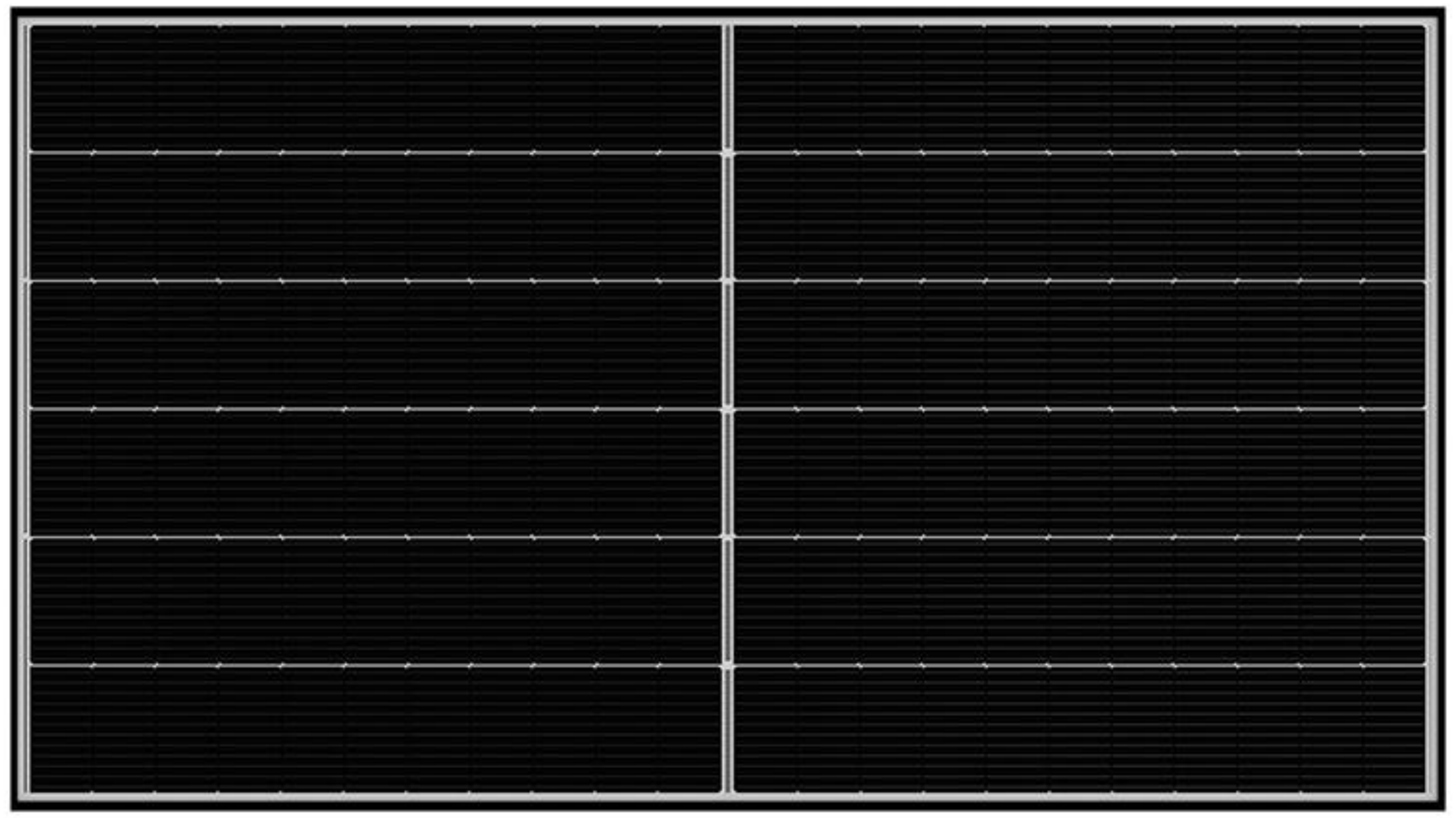
$$A_{1kWp} = \frac{1}{\eta_{STC}}$$

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

A first generation photovoltaic module

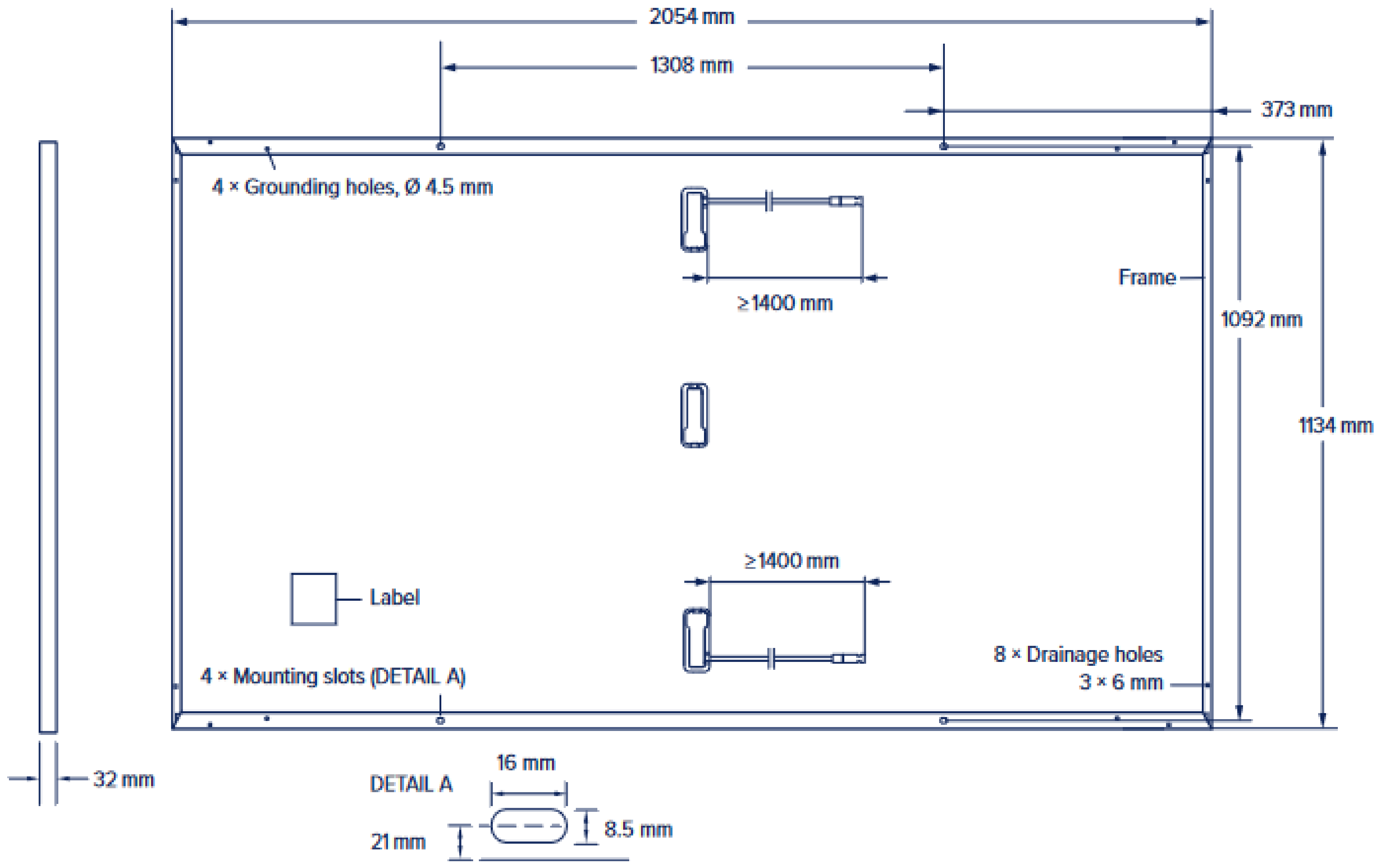
Q.PEAK DUO ML-G11

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

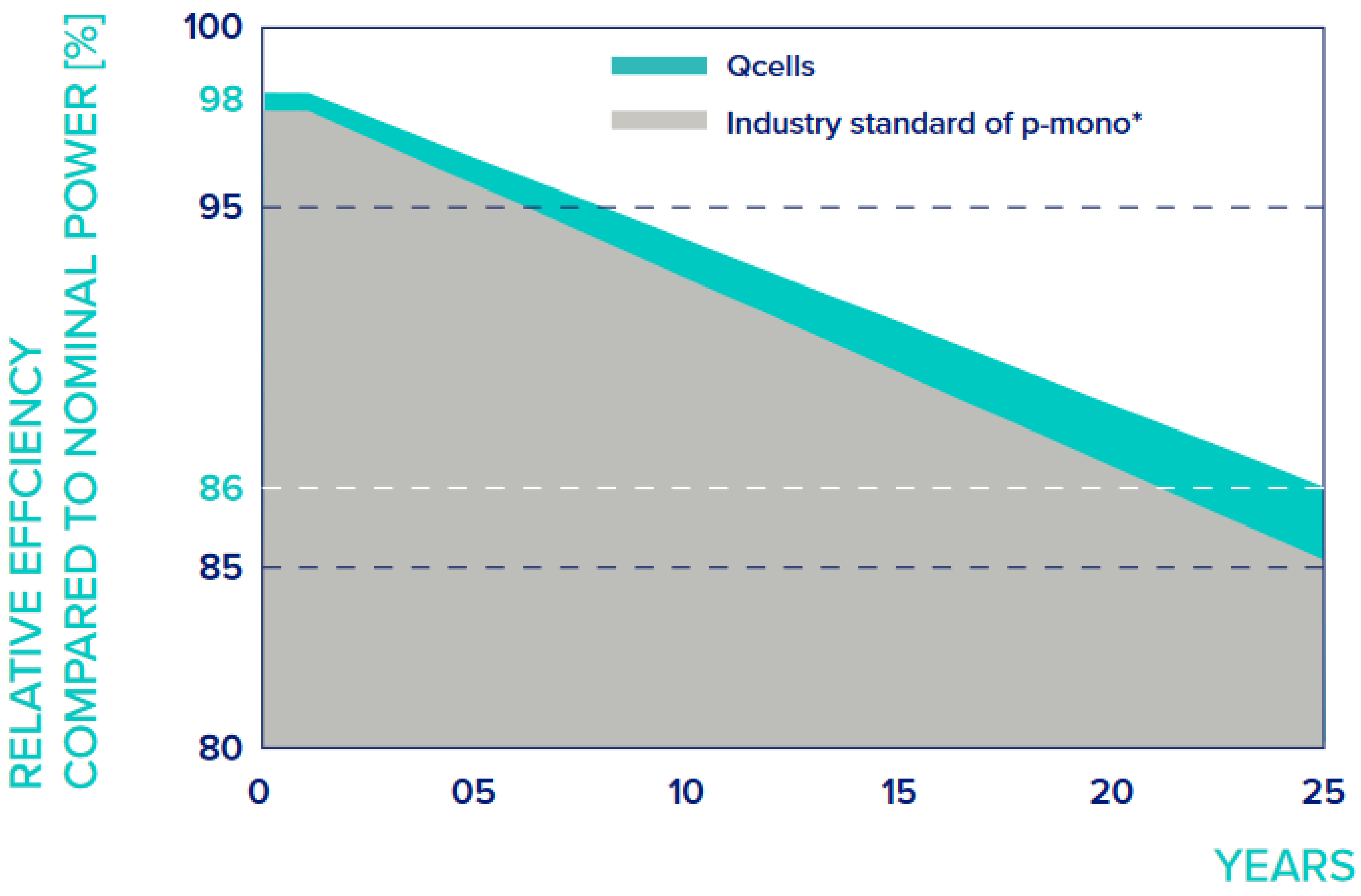
TEMPERATURE COEFFICIENTS							
Temperature Coefficient of I_{SC}	α	[%/K]	+0.04	Temperature Coefficient of V_{OC}	β	[%/K]	−0.27
Temperature Coefficient of P_{MPP}	γ	[%/K]	−0.34	Nominal Module Operating Temperature	NMOT	[°C]	43±3

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

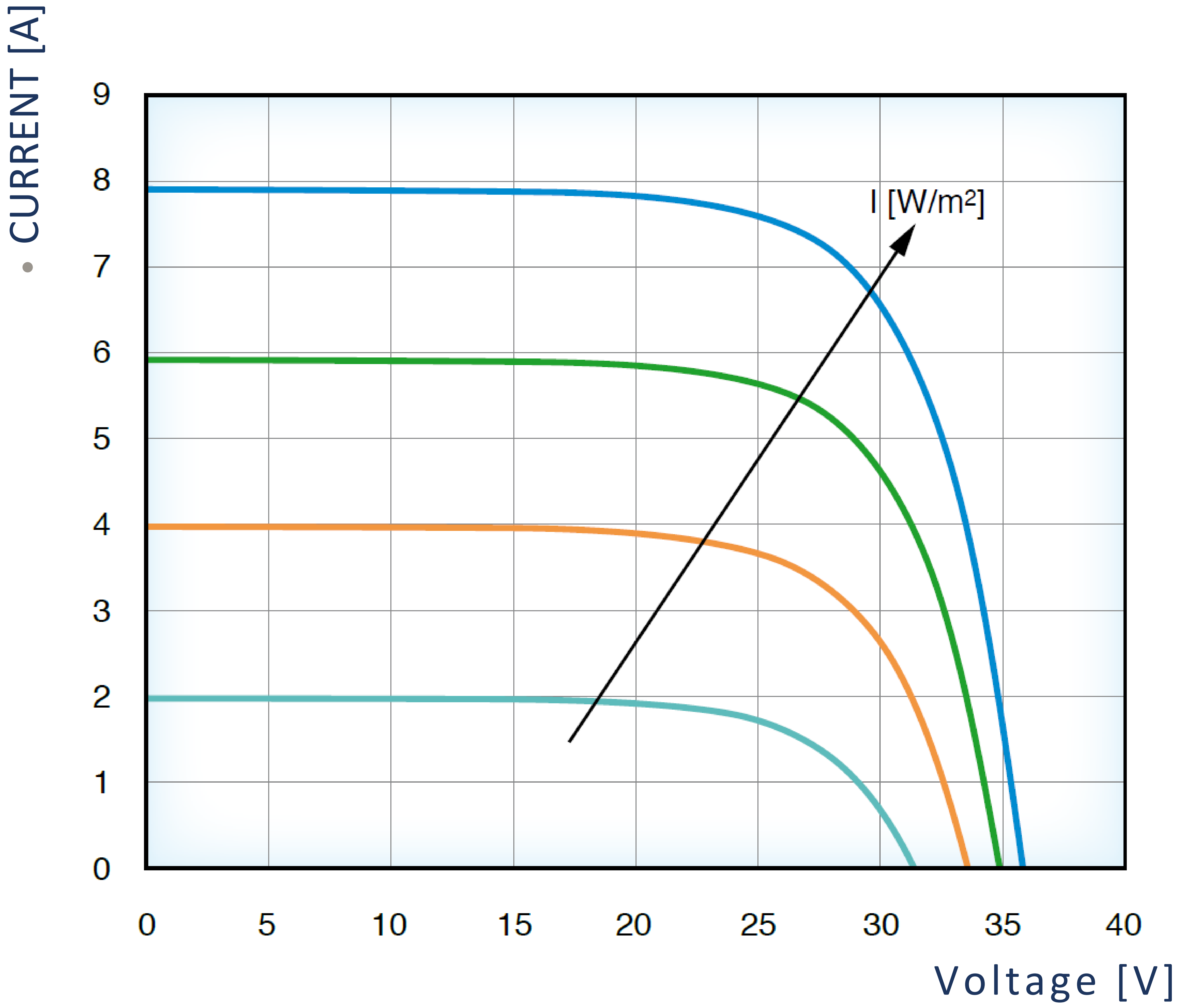
Qcells PERFORMANCE WARRANTY

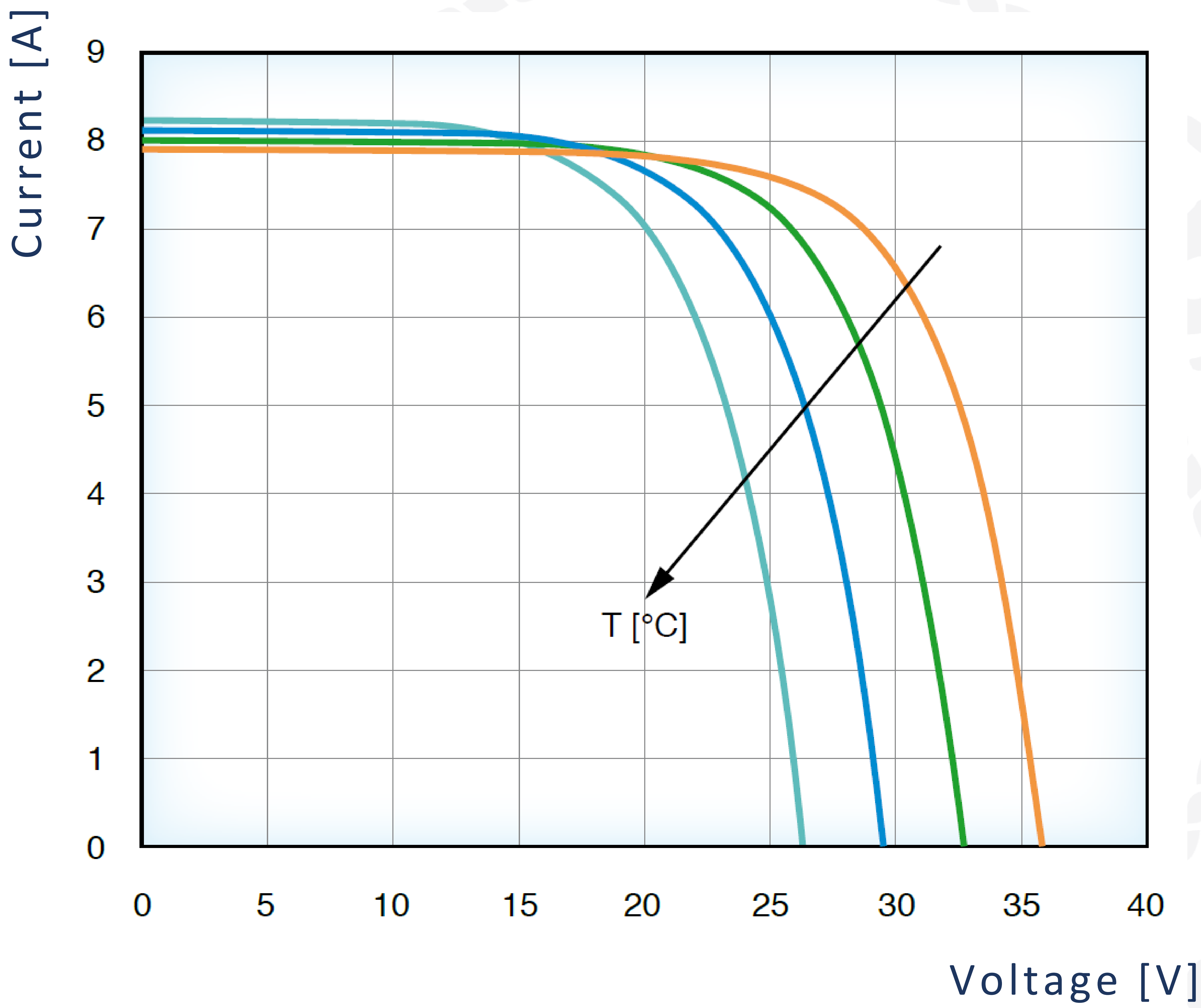


At least 98 % of nominal power during first year. Thereafter max. 0.5 % degradation per year. At least 93.5 % of nominal power up to 10 years. At least 86 % of nominal power up to 25 years.

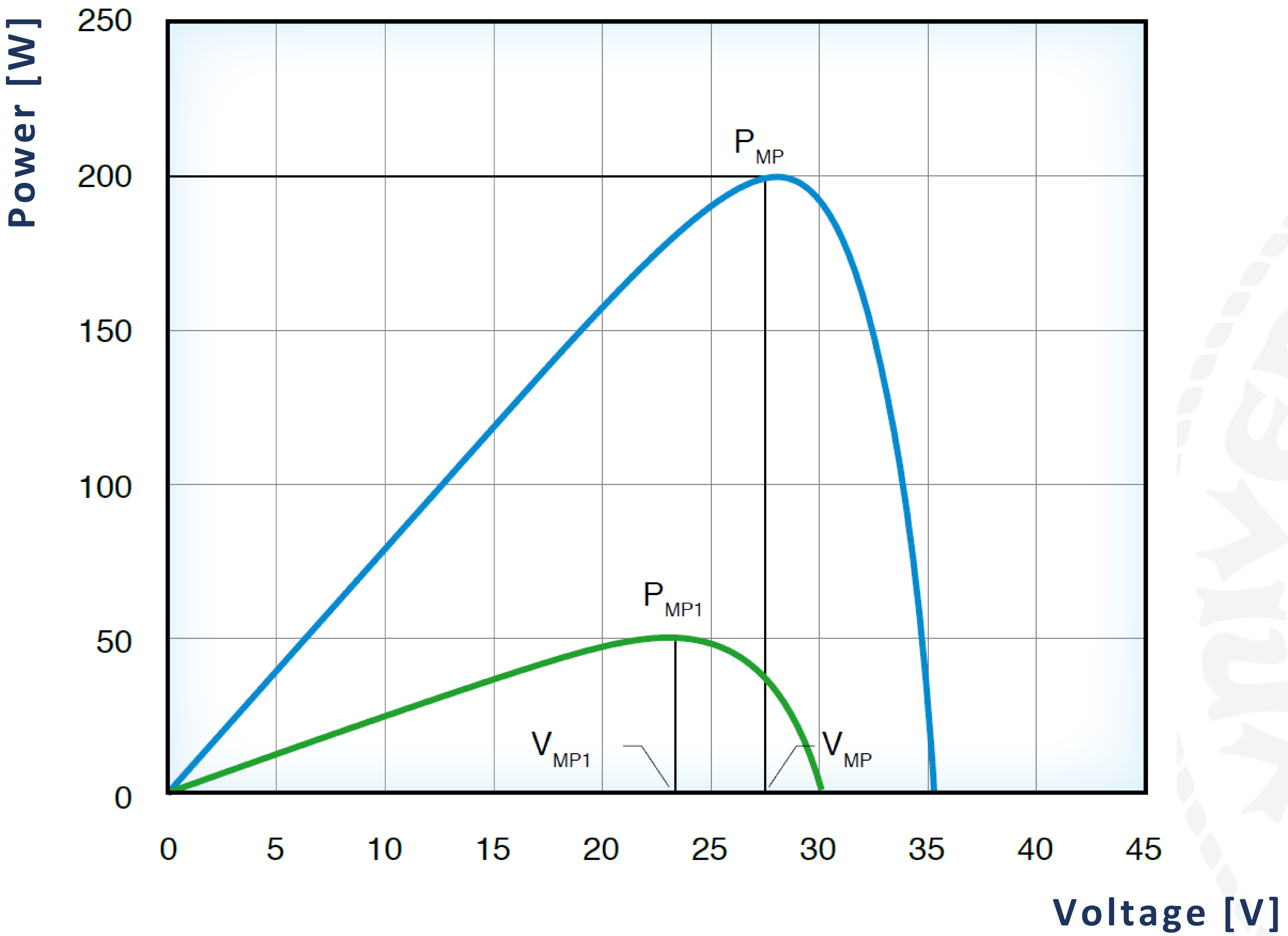
All data within measurement tolerances. Full warranties in accordance with the warranty terms of the Qcells sales organisation of your respective country.

Solar irradiance and cell temperatures dependences





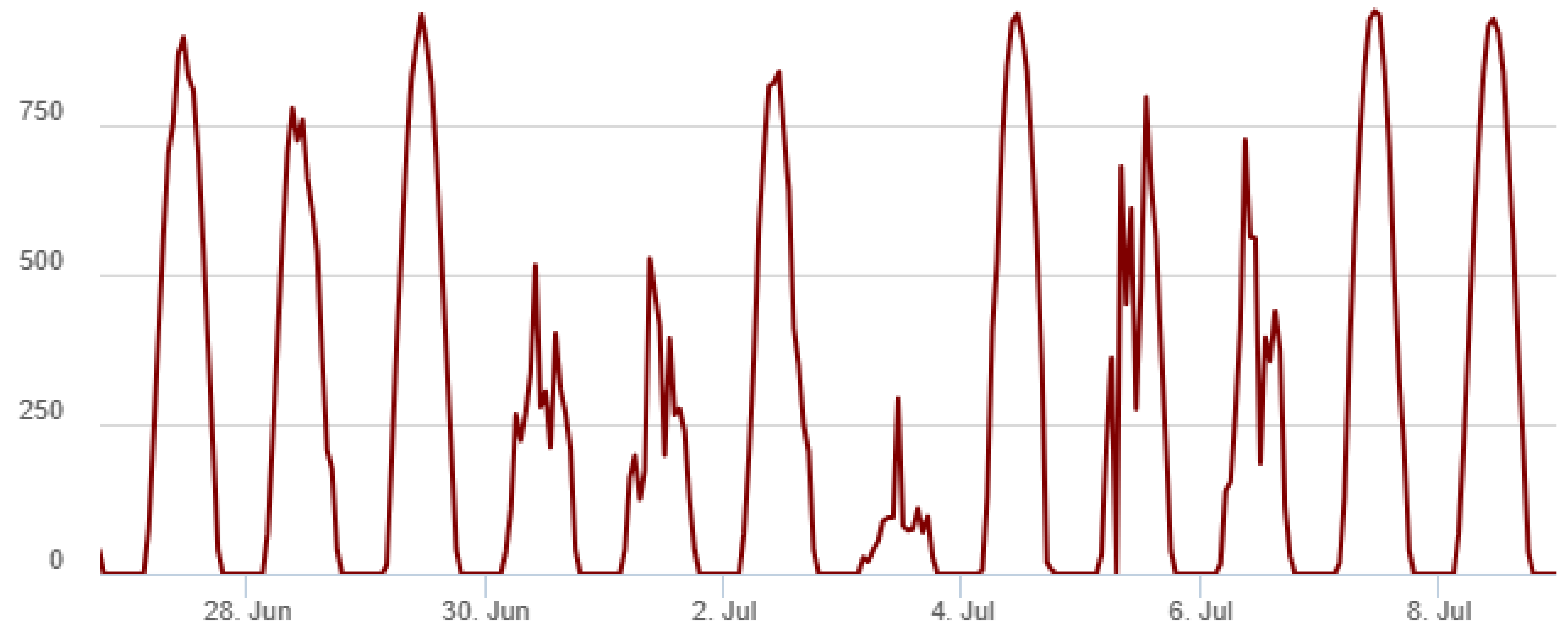
Power/voltage characteristic



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/m²] – Solar Irradiance (Plane Of Array)
- A [m²] – Area of the module
- P [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 $\left[\frac{V}{°C}\right] = \frac{\text{W } [\%/°C]}{100} \cdot V_{oc}$

Photovoltaic devices modelling: simple models 2

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

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

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

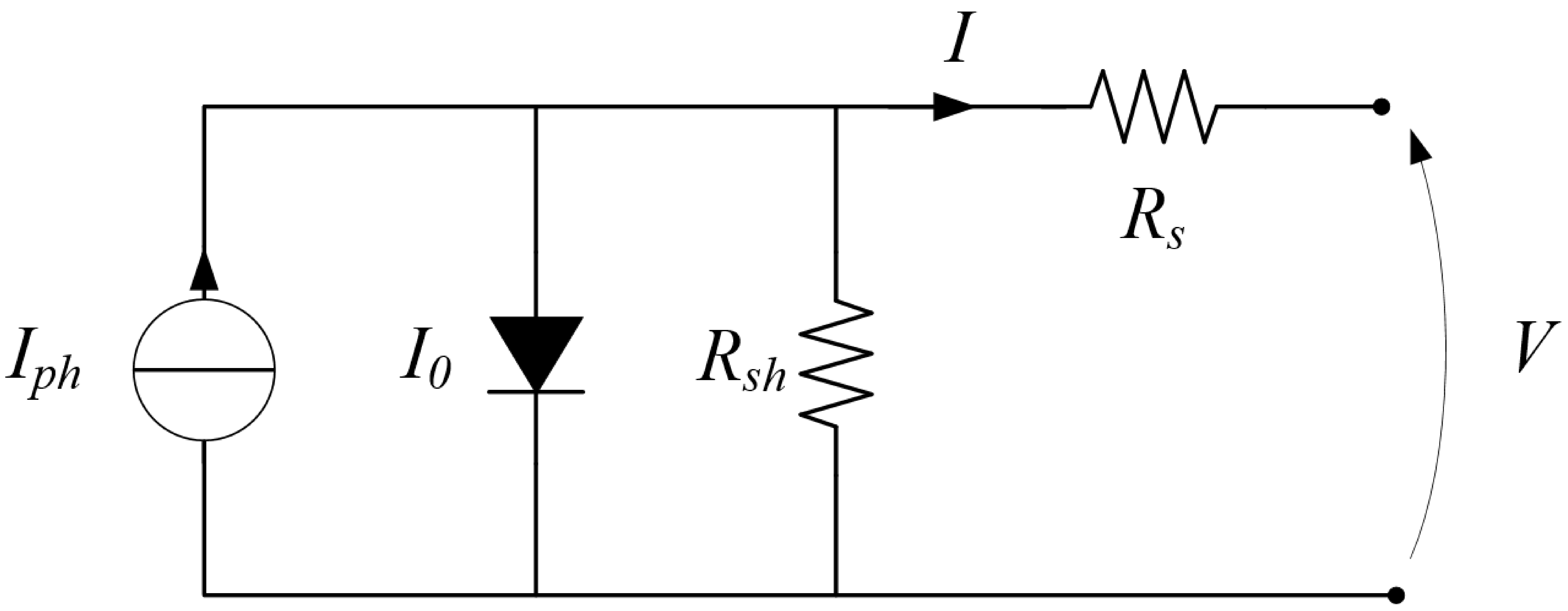
Photovoltaic devices modelling: simple models 2

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

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

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

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

SOLAR ENERGY
The Official Journal of the International Solar Energy Society

Modelling photovoltaic devices: the empirical model

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

MODULE PARAMETERS AT STC

V_{OC}	[V]
I_{SC}	[A]
V_{mp}	[V]
I_{mp}	[A]
W	[%/°C]
Z	[%/°C]

MODULE PARAMETERS

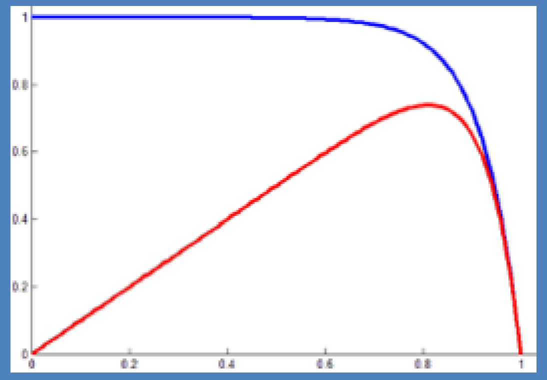
m [ ], w [1/°C], z [1/°C]

CLIMATE CONDITIONS

I_L [p.u.], T [°C]

ARBITRARY CLIMATE CONDITIONS

v_{OC}	[p.u.]
i_{SC}	[p.u.]
v_{mp}	[p.u.]
i_{mp}	[p.u.]



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)

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

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

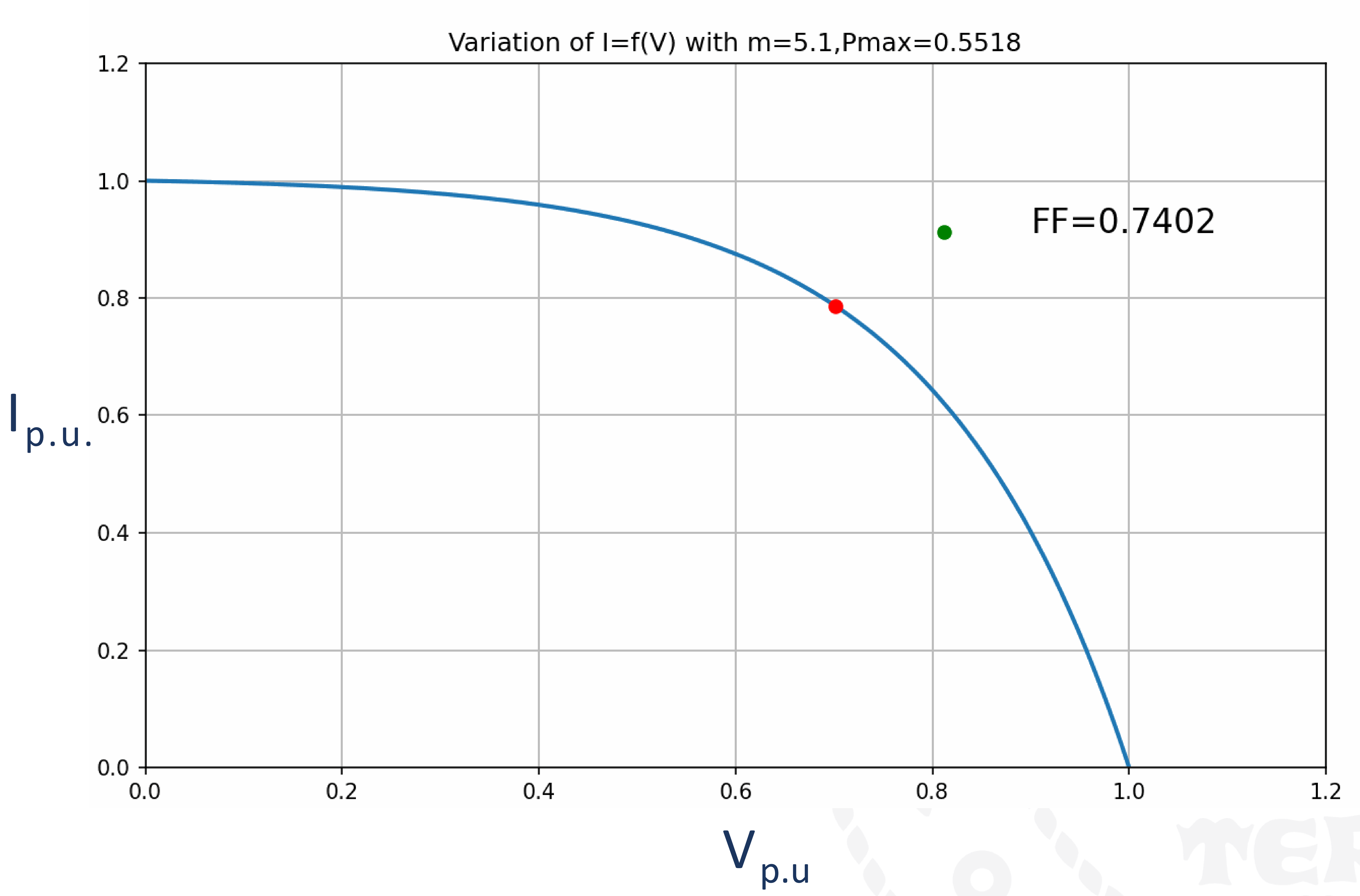
m = 12.0 $\Rightarrow I = 1 - \frac{e^{12V} - 1}{e^{12} - 1} \Rightarrow$ P_{max} =0.7274

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

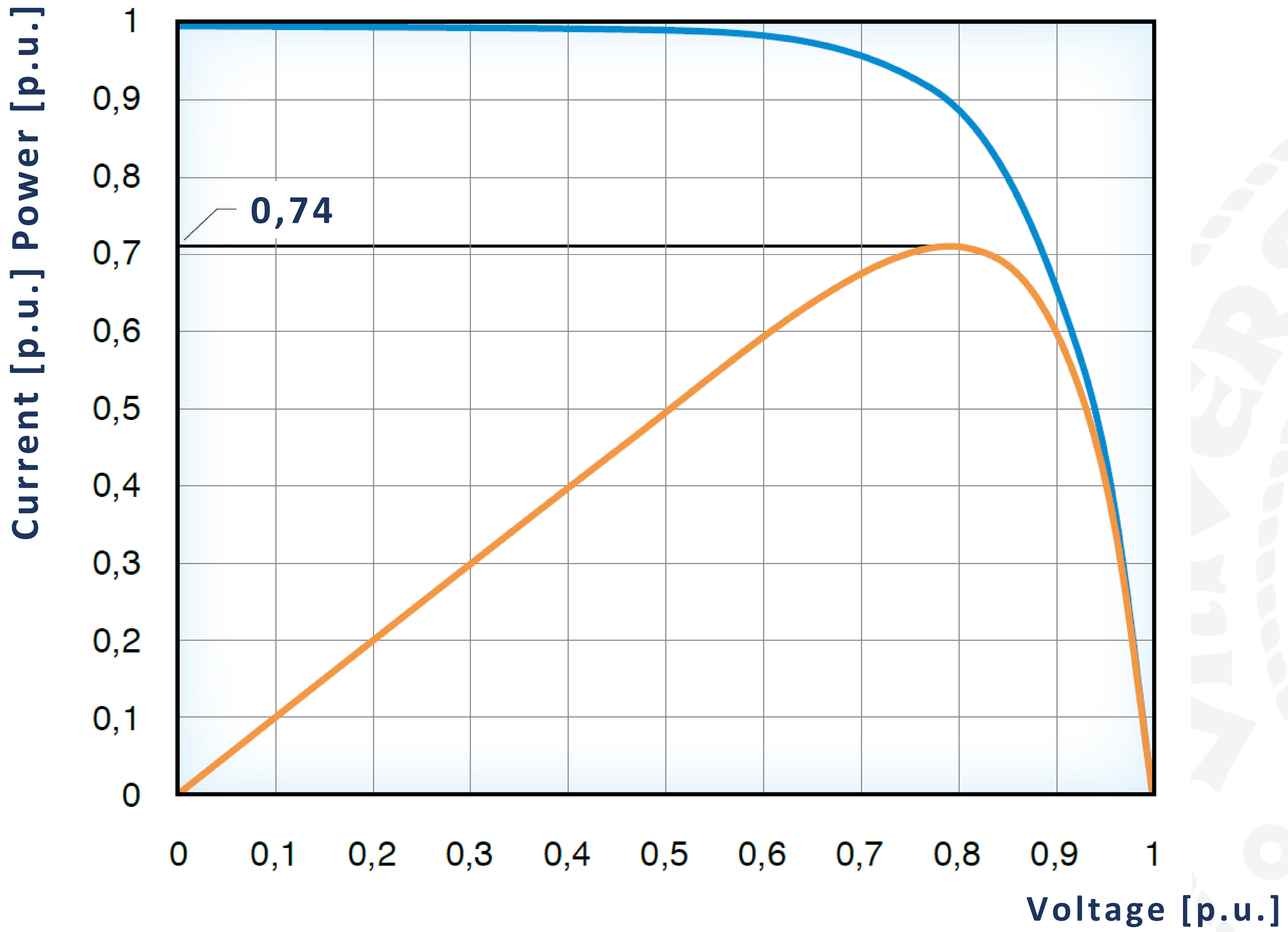
m = 12.9 $\Rightarrow I = 1 - \frac{e^{12.9V} - 1}{e^{12.9} - 1} \Rightarrow$ P_{max} =0.7402

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

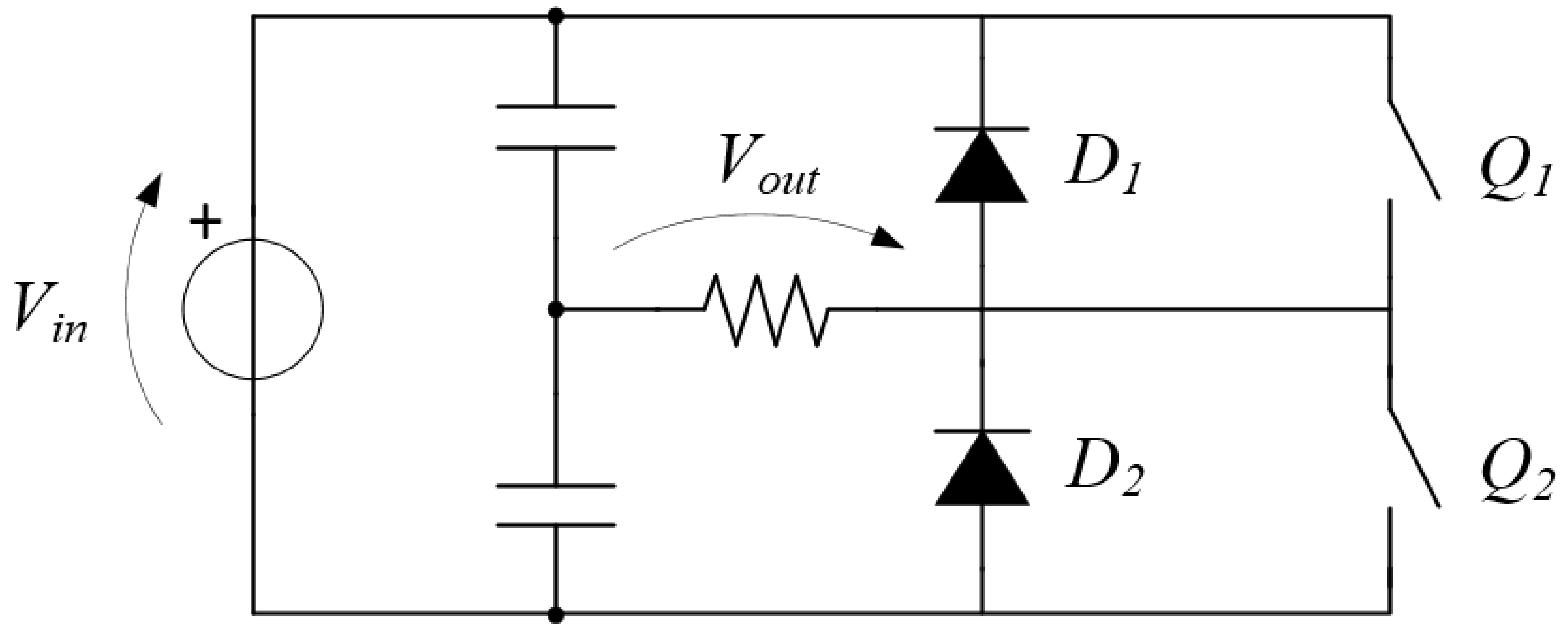
Alessandro Massi Pavan[1,2], Adel Mellit[3,4*], Davide De Pieri[5] and Vanni Lughi[1]

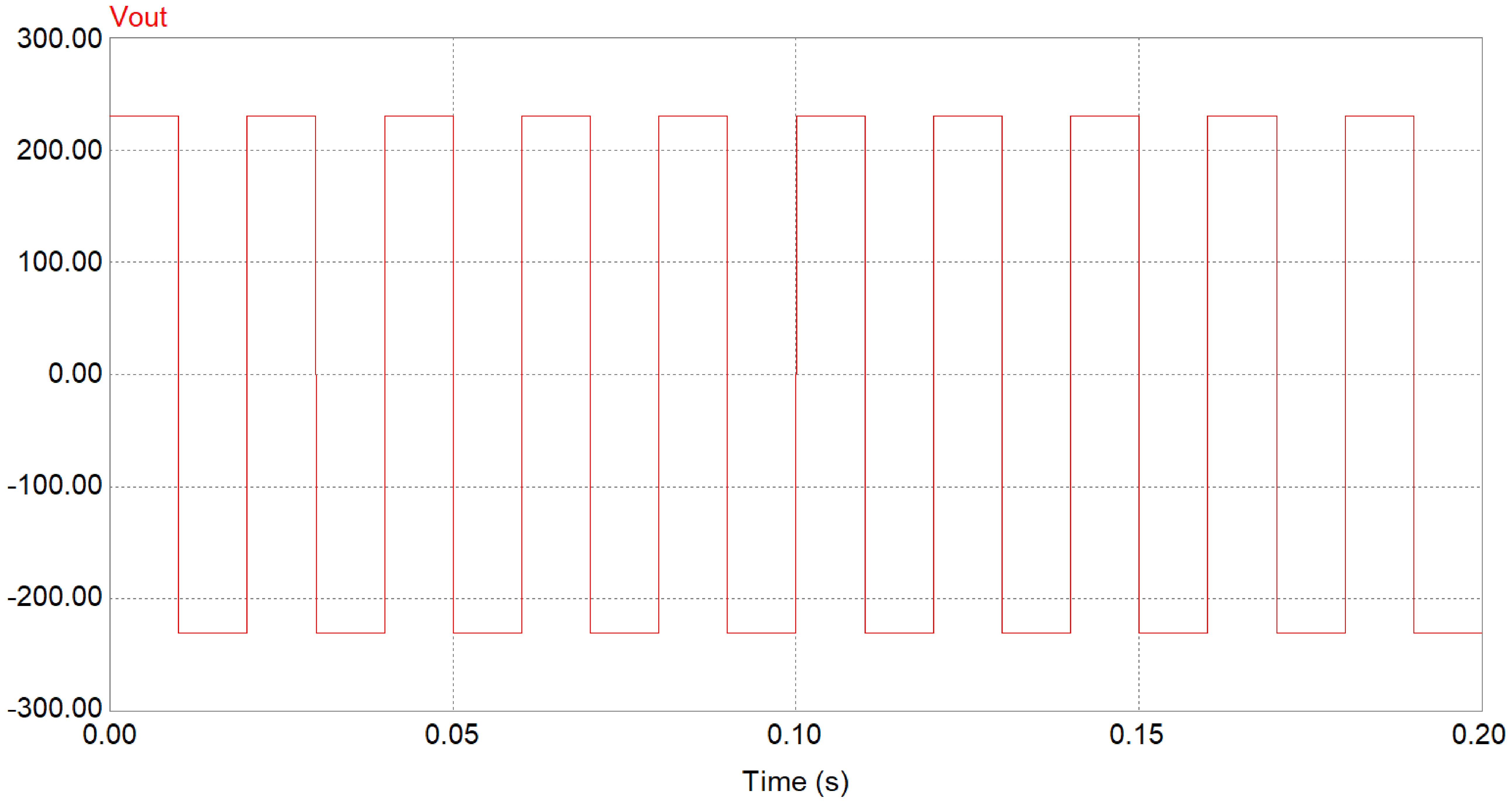
Progress in PHOTOVOLTAICS

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

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

Square-wave half bridge inverter

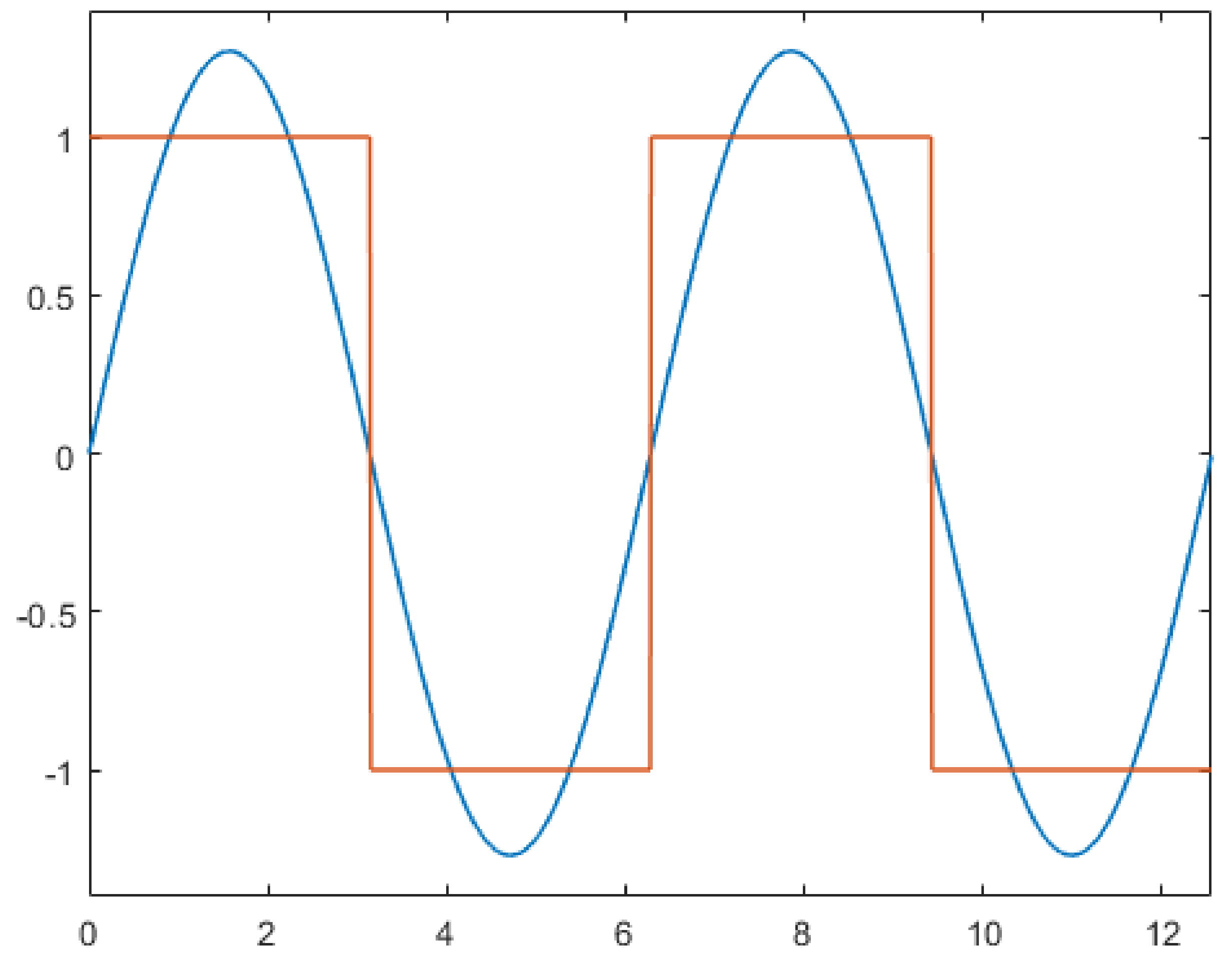


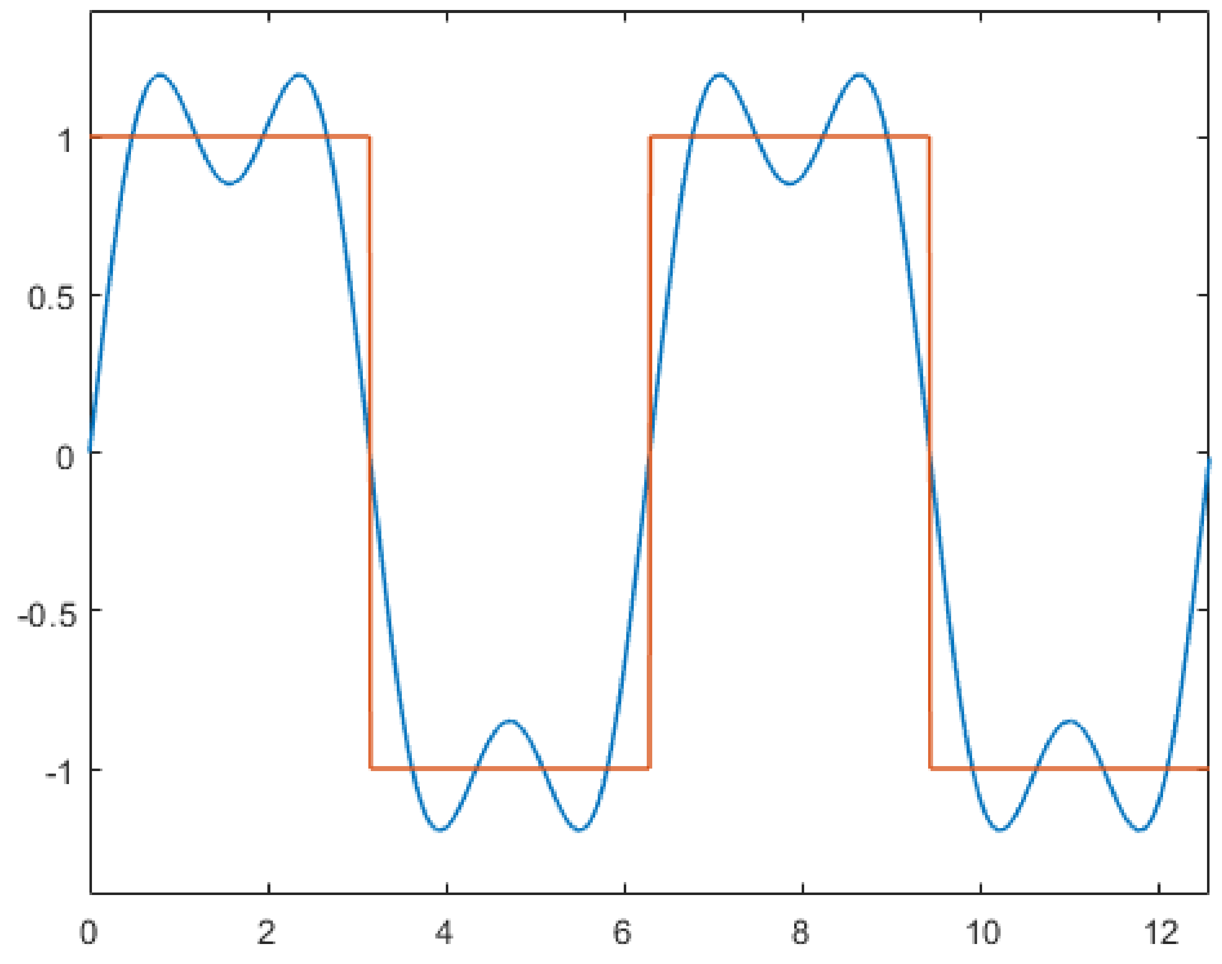


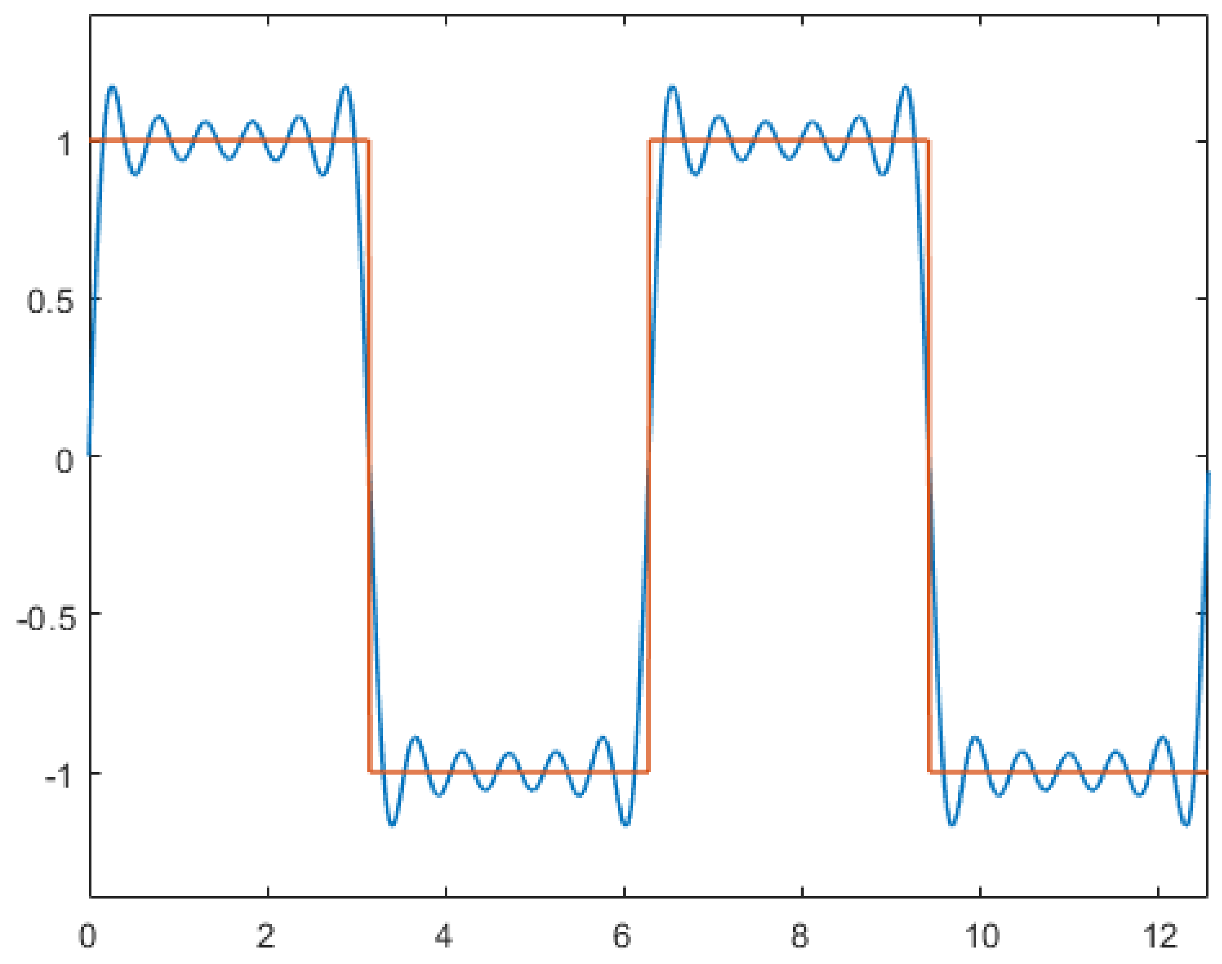
$$V_{out,eff} = \frac{V_{in}}{2}$$

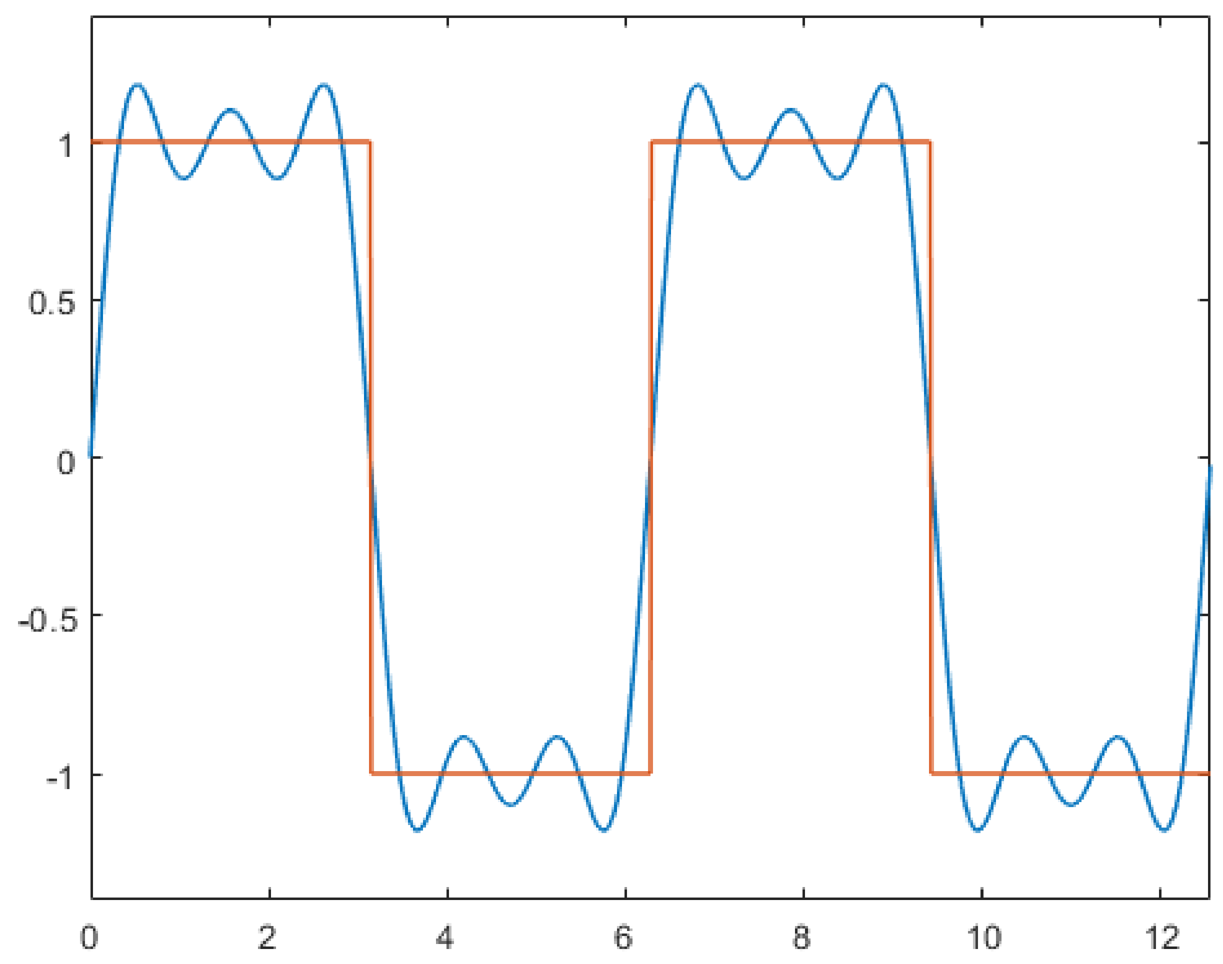
$$V_{out}(t) = \sum_{n=1,3,5,\dots}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$$

Harmonic analysis using Fourier series

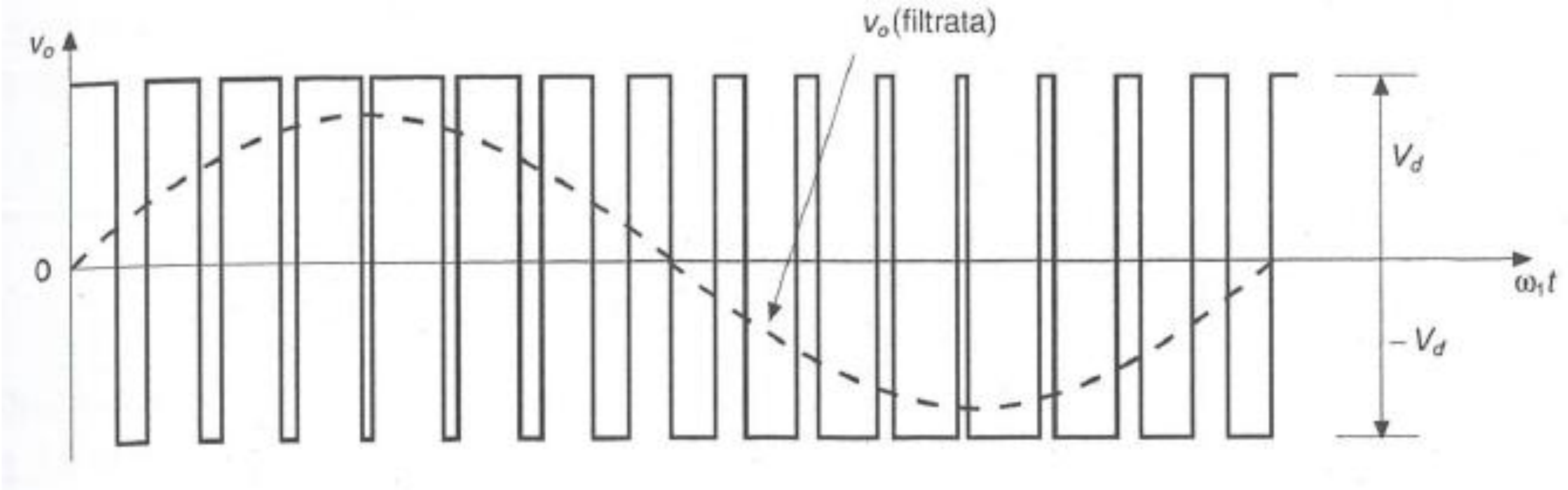


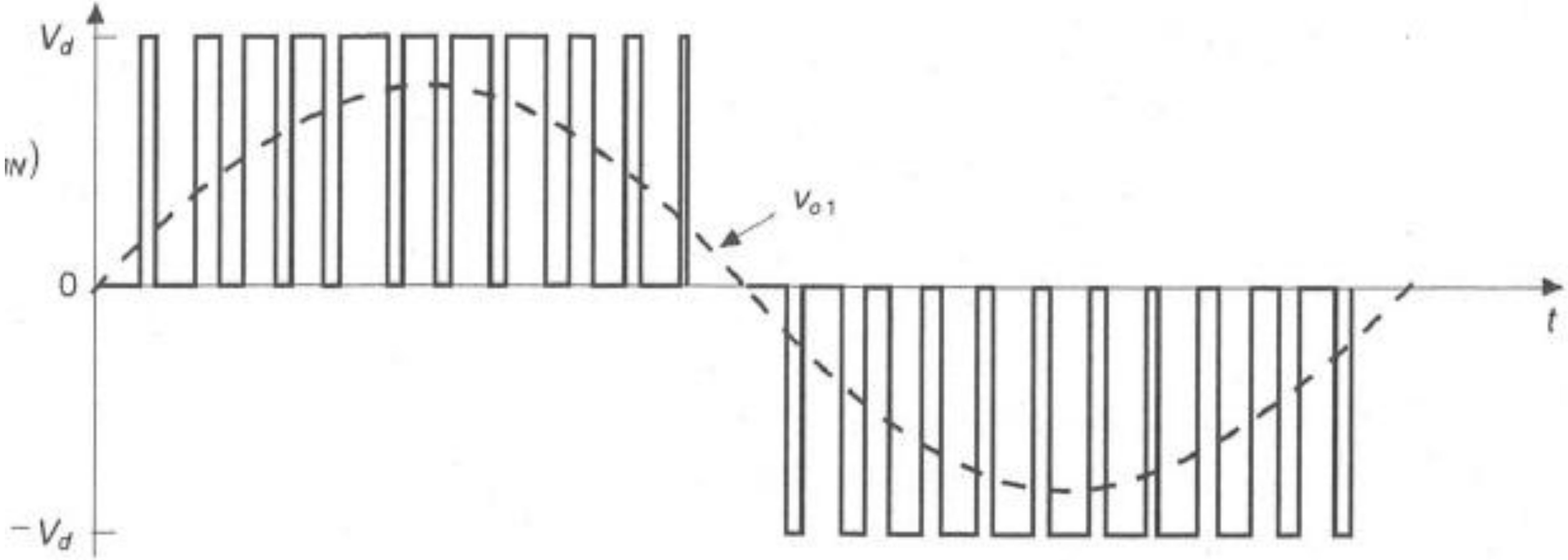






PWM (Pulse With Modulation) Inverter





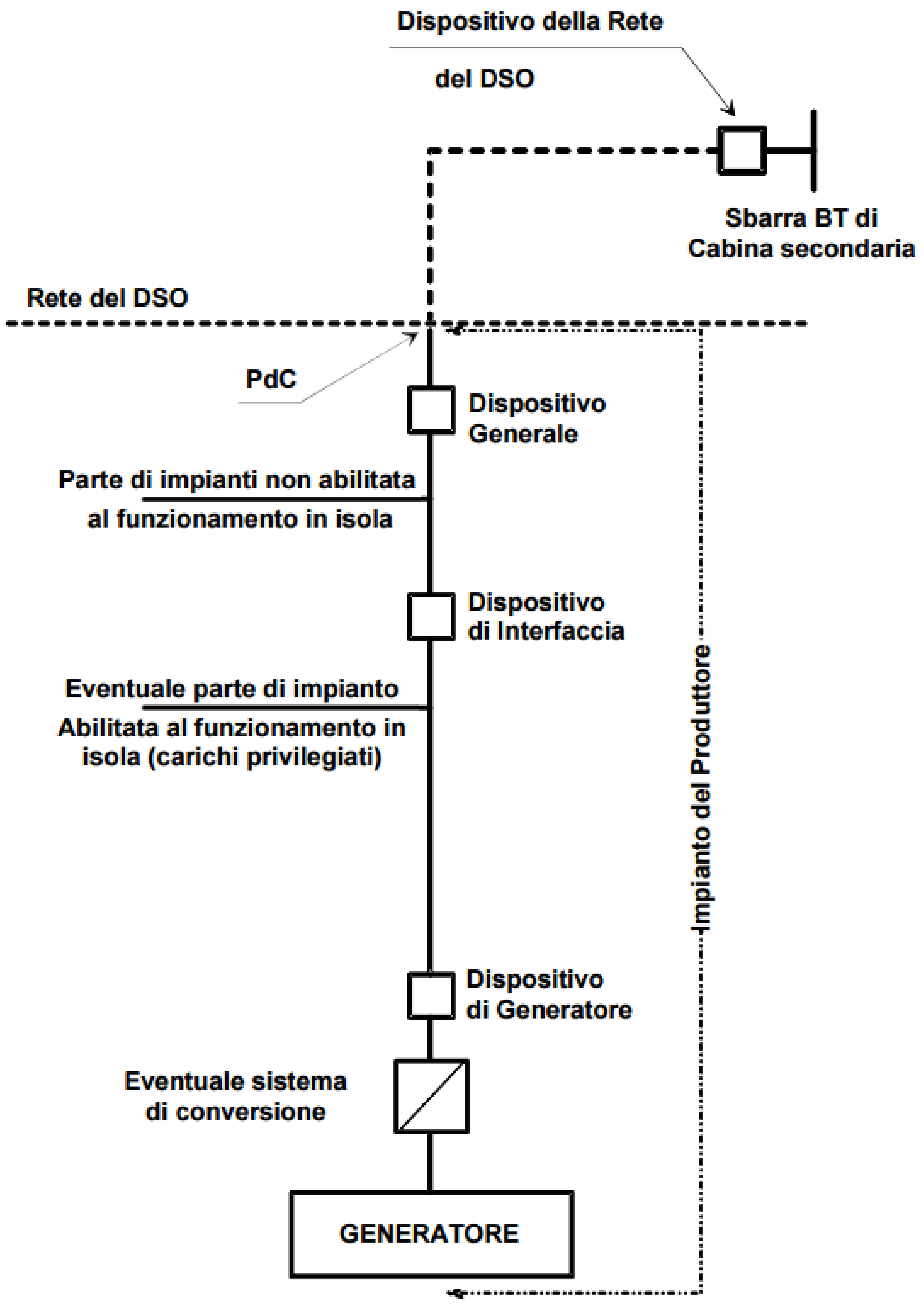
Inverter for grid-connected applications

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

Interface protection system (switch)

The interface protection system (SPI) must ensure:

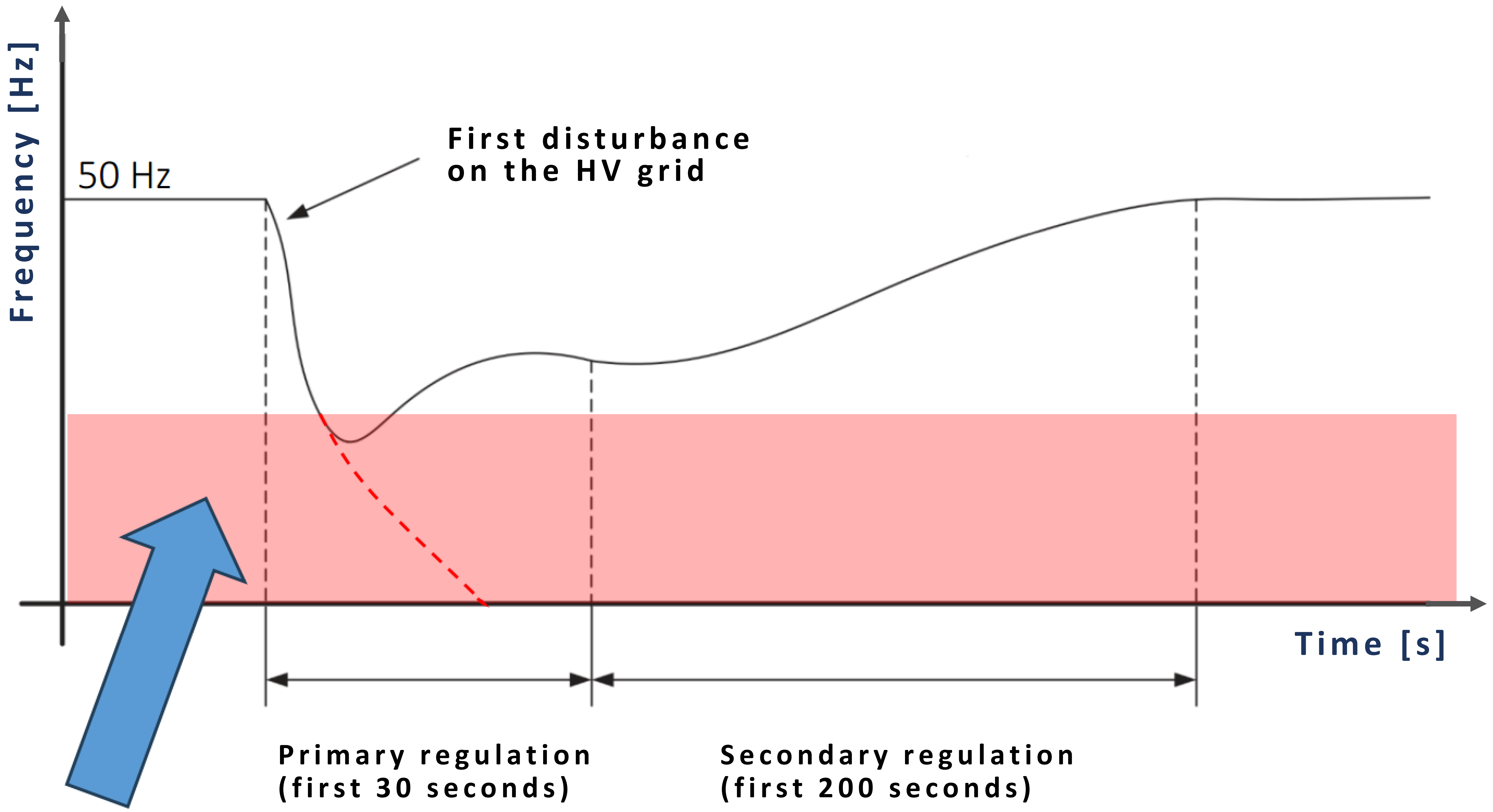
- a reliable connection between the generator and the grid during normal grid operation, even in the presence of disturbances originating from the high-voltage system;
- the fast and reliable disconnection of the generator in case of a fault occurring on the distribution network (to prevent unintentional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

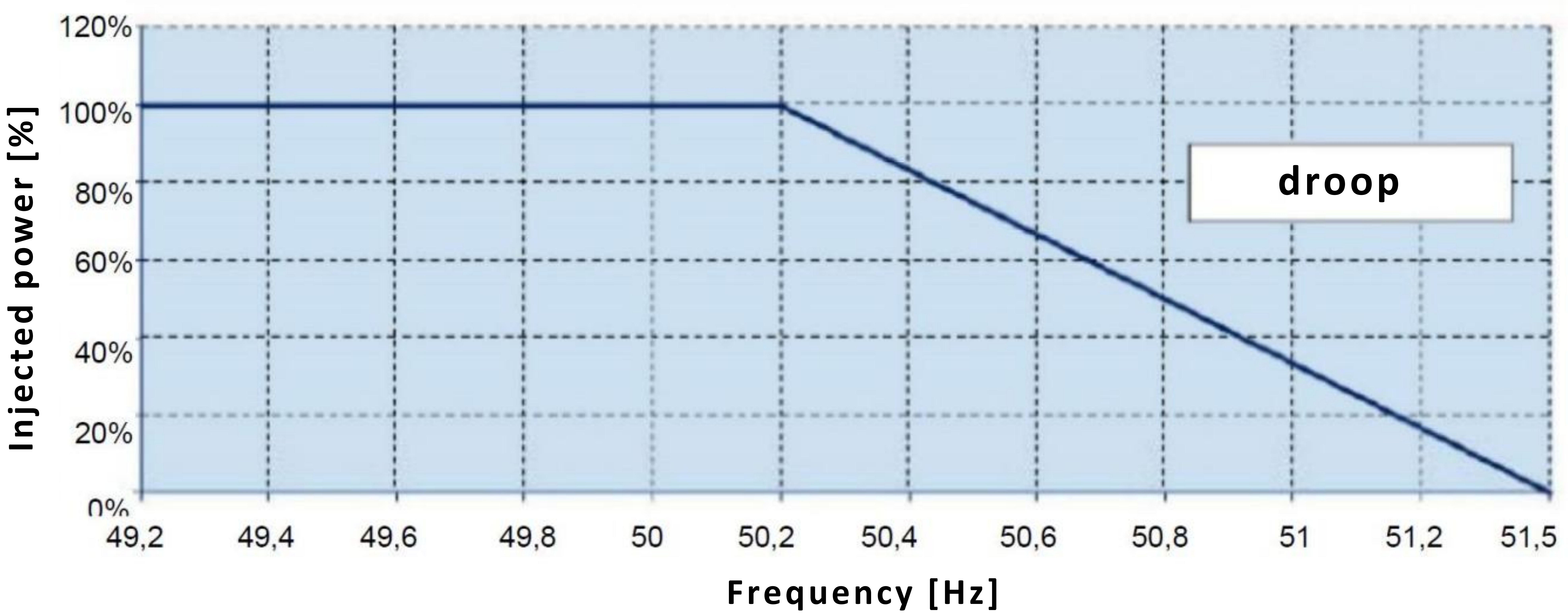
Stability of the power network



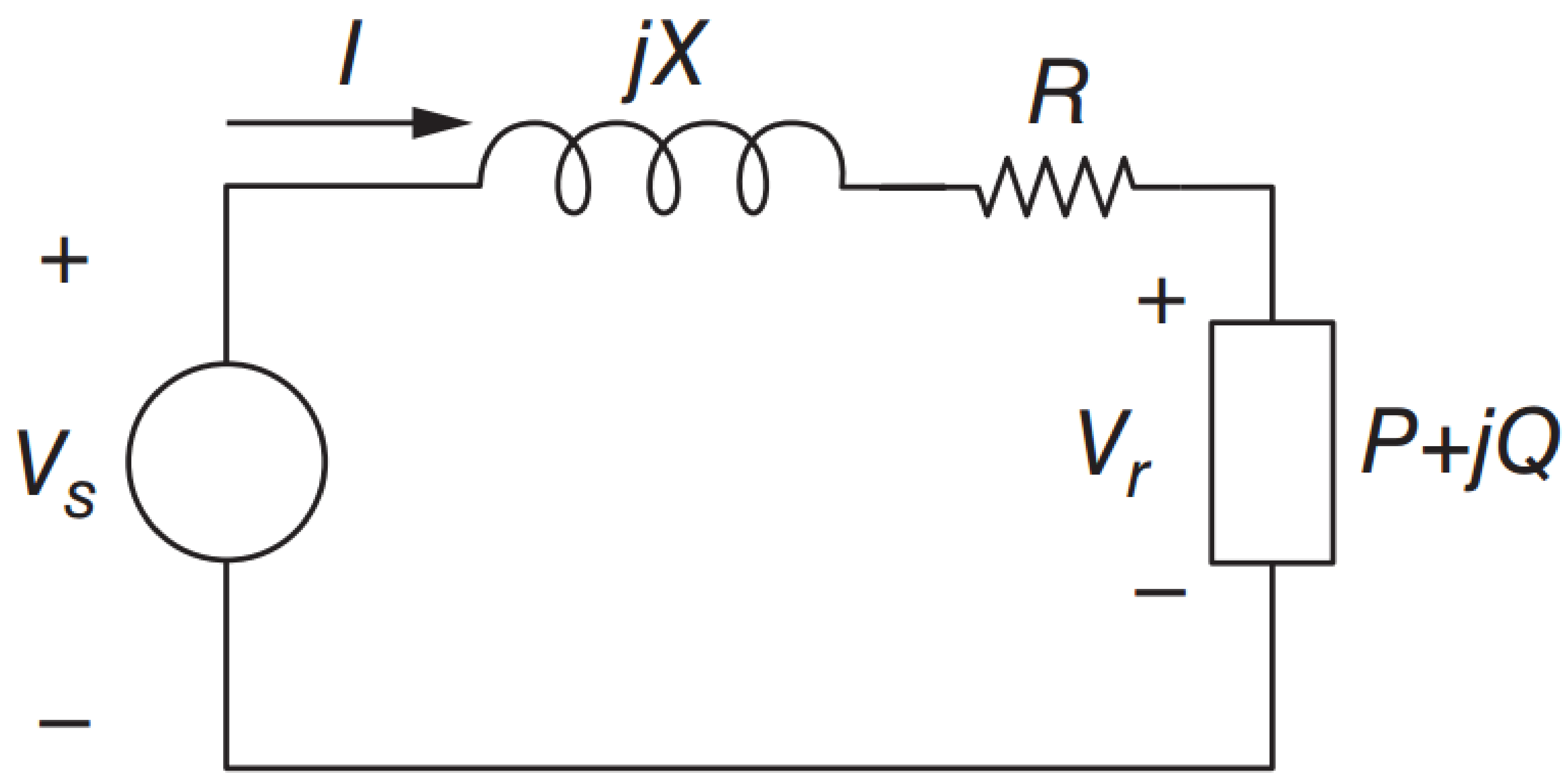
1. Local issue on the HV grid (e.g. loss of a generation unit)
2. Frequency fluctuation
3. Intervention of DG protections (under-frequency threshold)
4. DG disconnection
5. Additional power imbalance
6. Worsening of the frequency imbalance
7. Disconnection of additional DG
8. Risk of power outage

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

Power regulation under overfrequency conditions

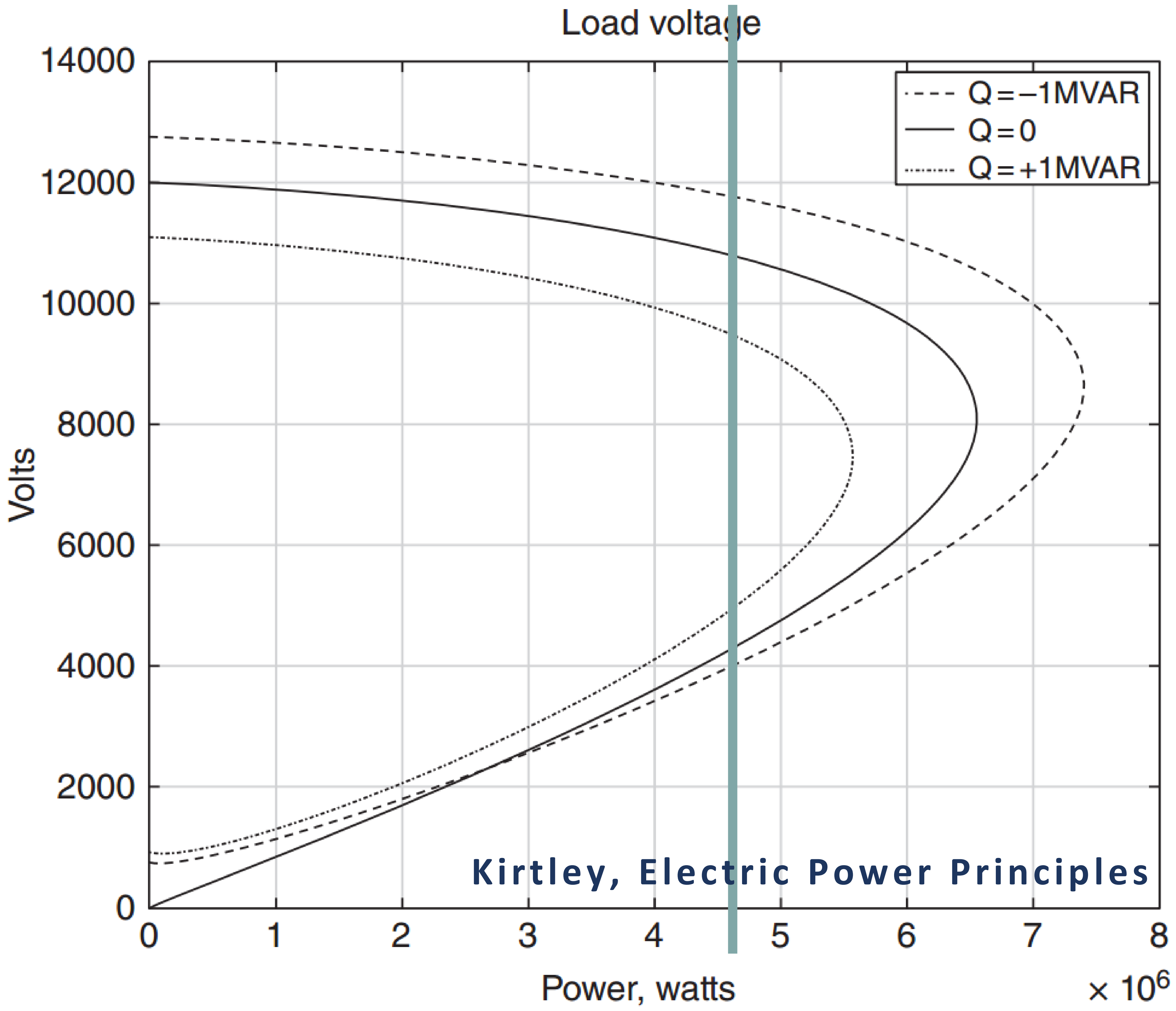


After 300 seconds from the end of the disturbance the DG can return to produce at full power



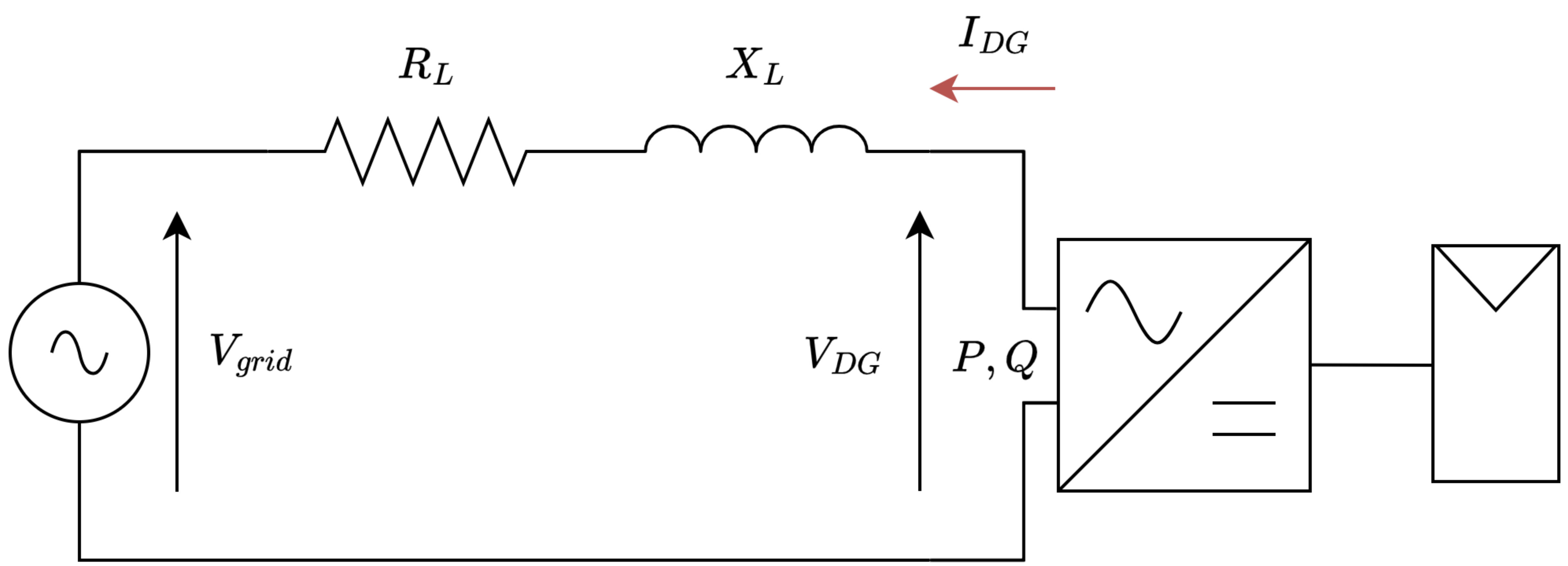
$$P + jQ = \frac{1}{2}\bar{V}_r \bar{I}^*$$

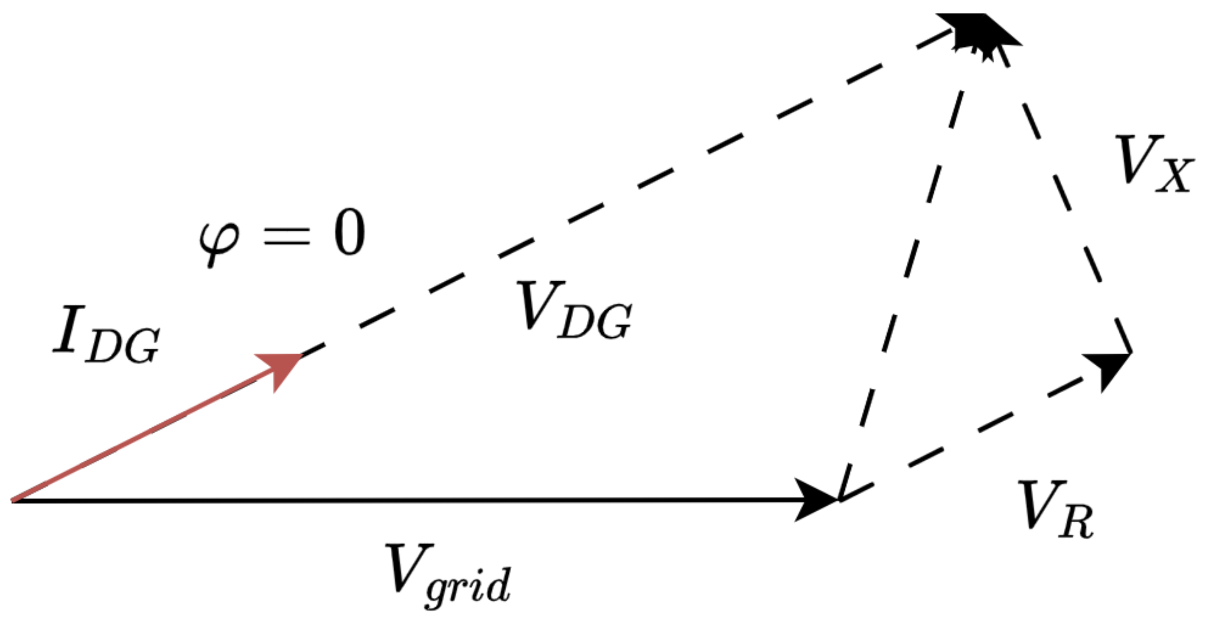
- Inductive reactive power reduces voltage and maximum power transfer
- If Q is constant: ↑P ↓V
- If P is constant: ↑Q ↓V



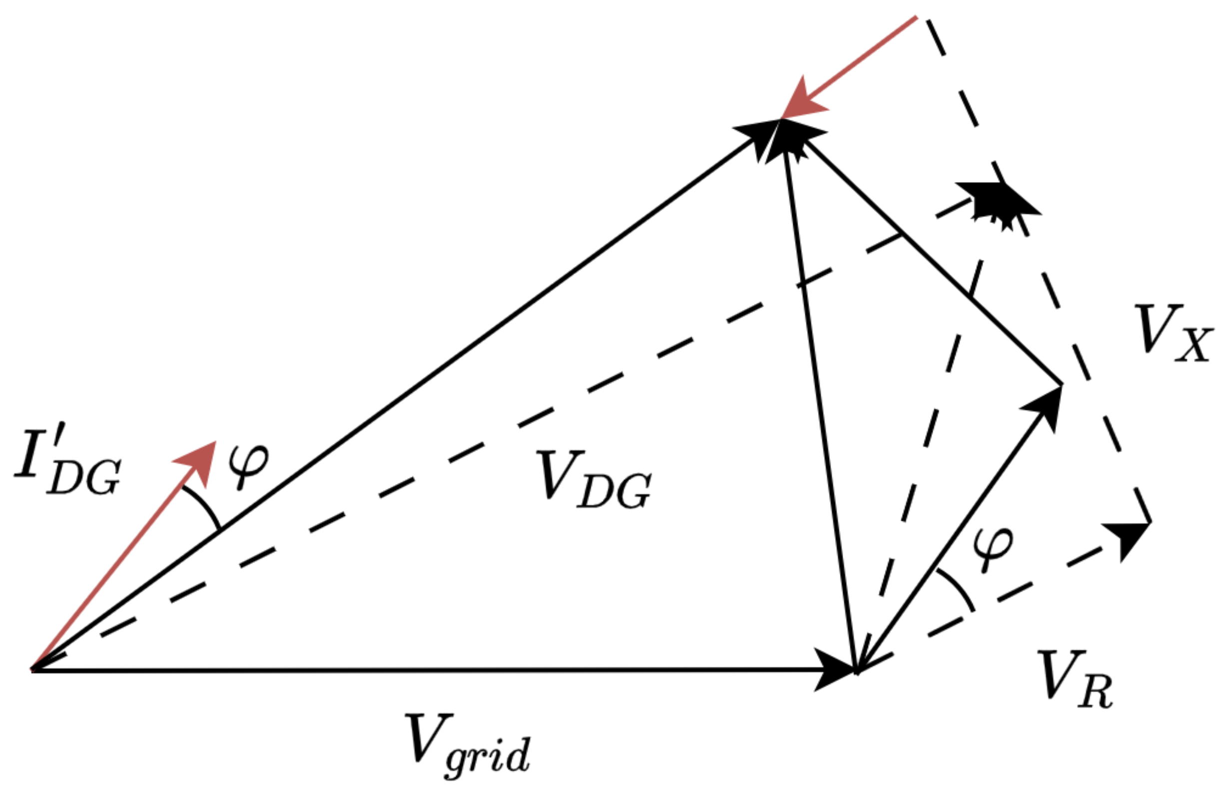
$$V_r^2 = \frac{1}{2}(V_s^2 - 2XQ - 2RP) \pm \sqrt{\left(\frac{1}{2}(V_s^2 - 2XQ - 2RP)\right)^2 - |Z|(P^2 + Q^2)}$$

Participation in voltage regulation





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

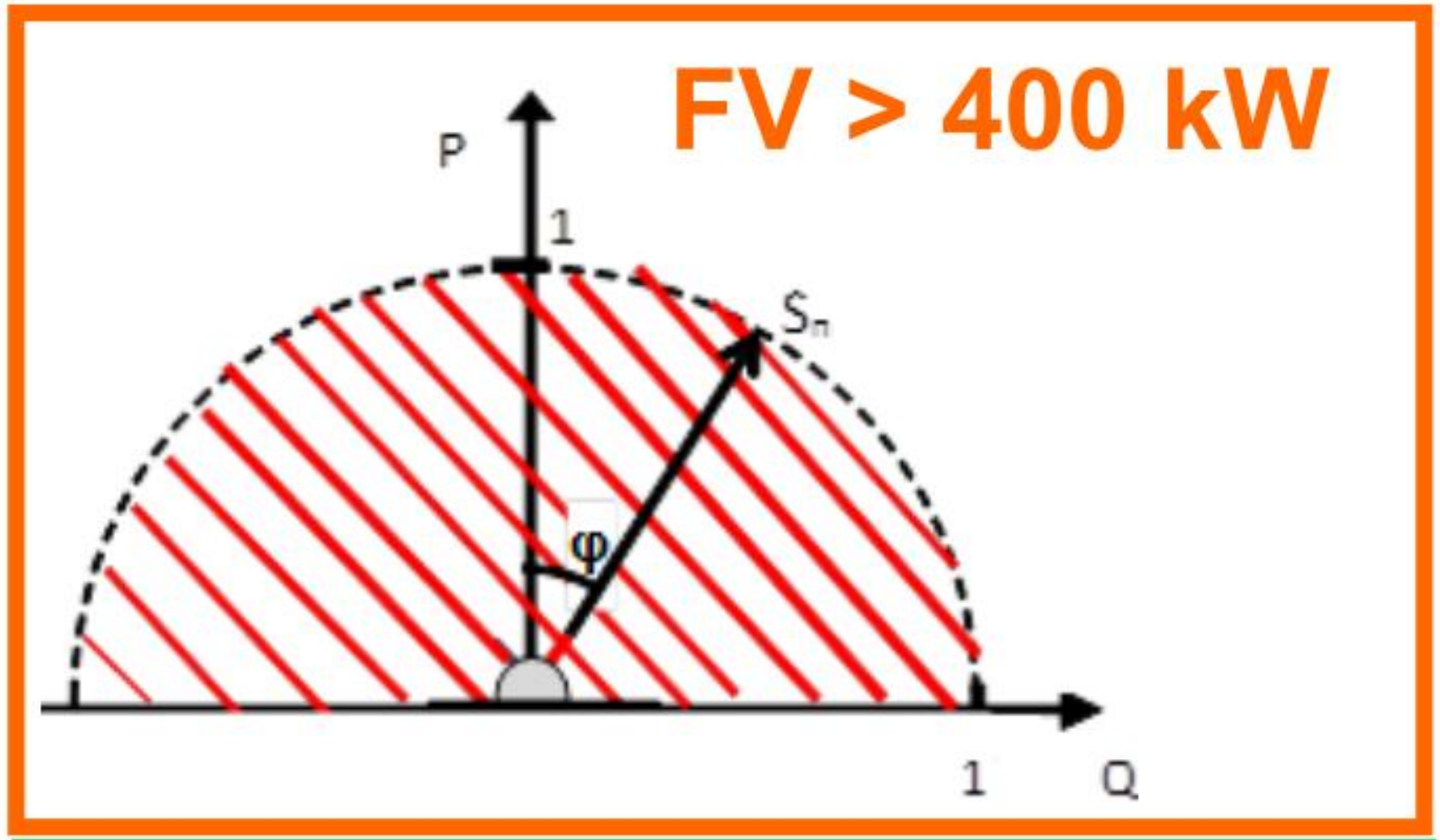


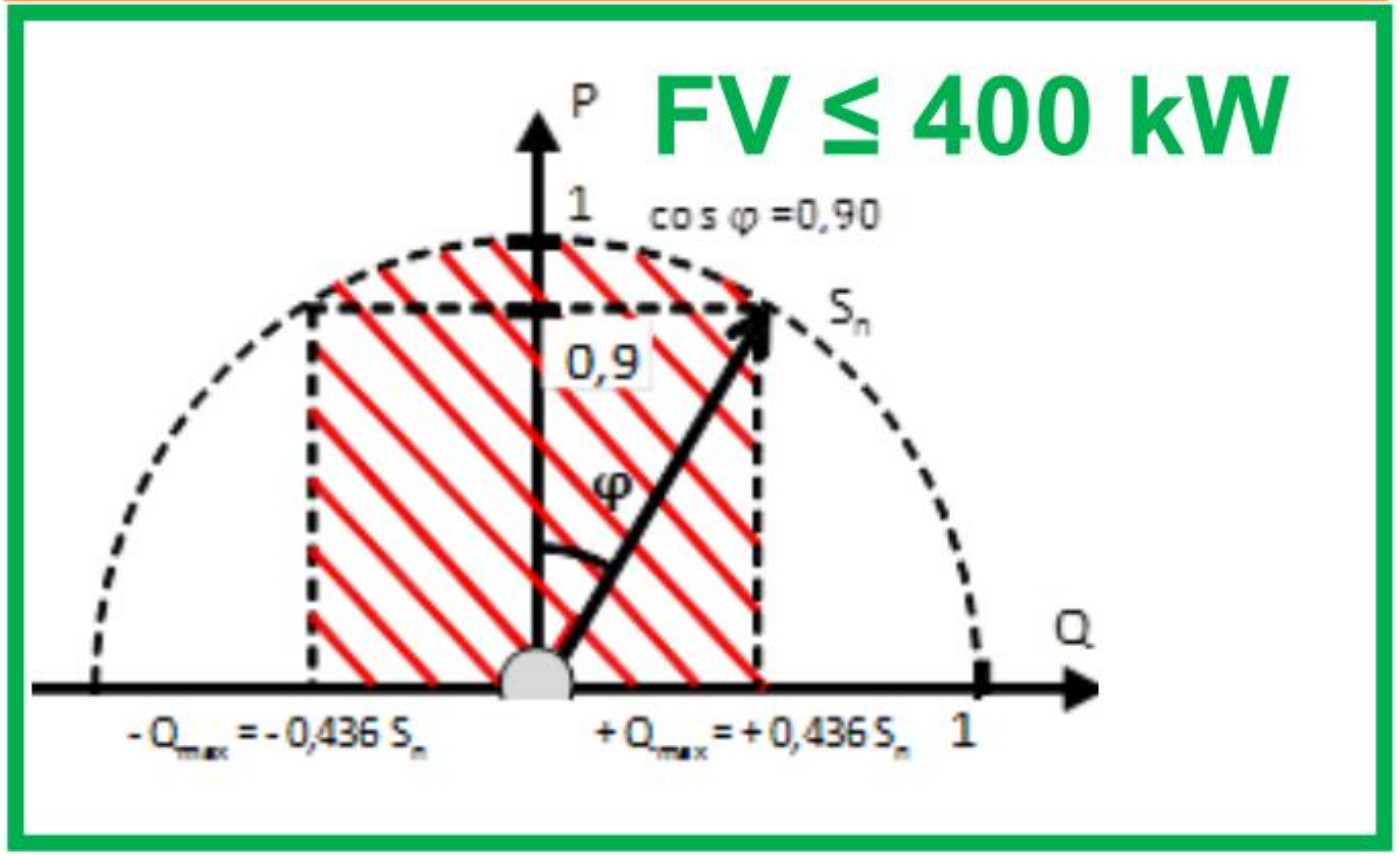
$cos\varphi = 0,9 \quad (P\, and\, Q)$

- 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

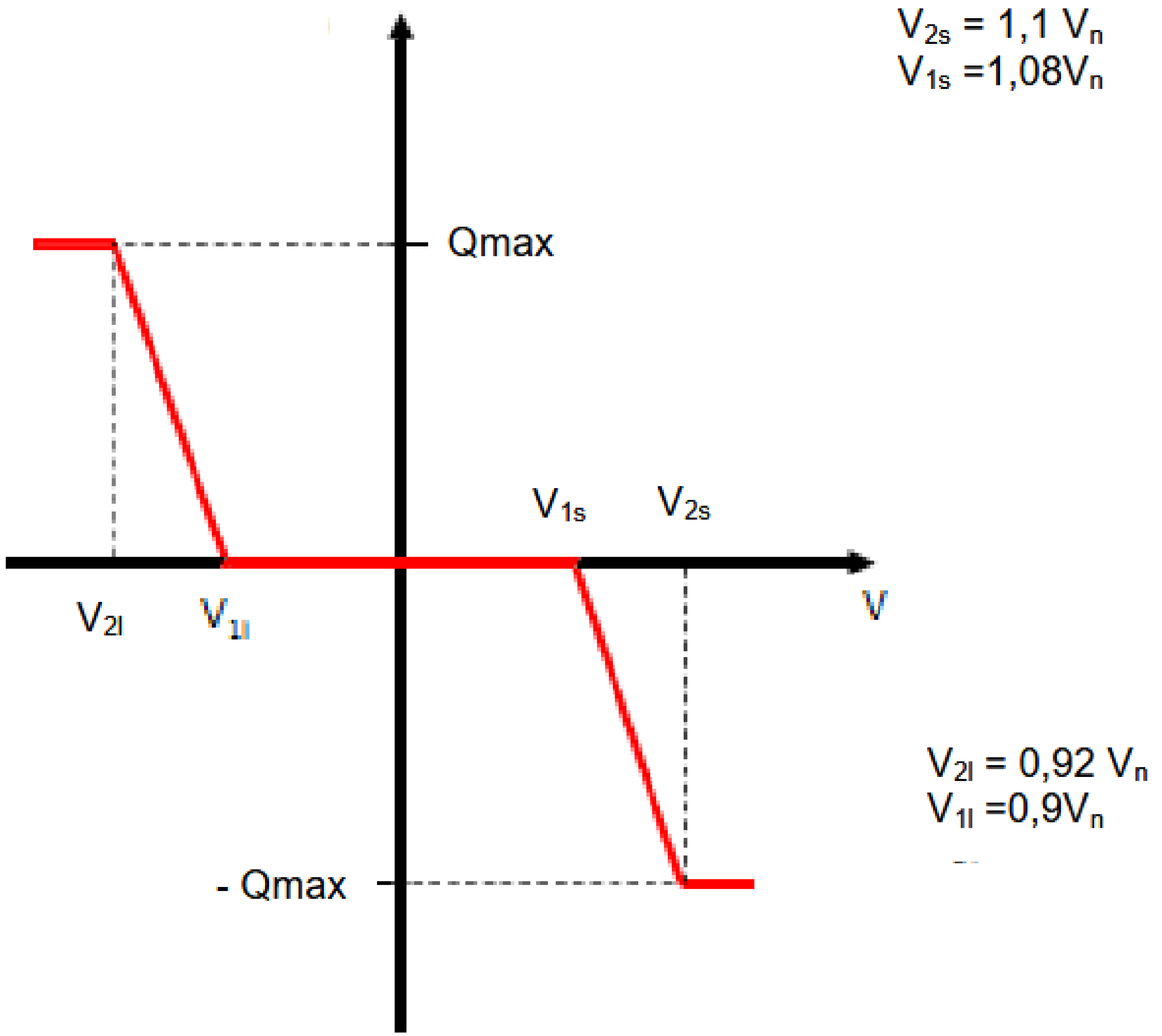




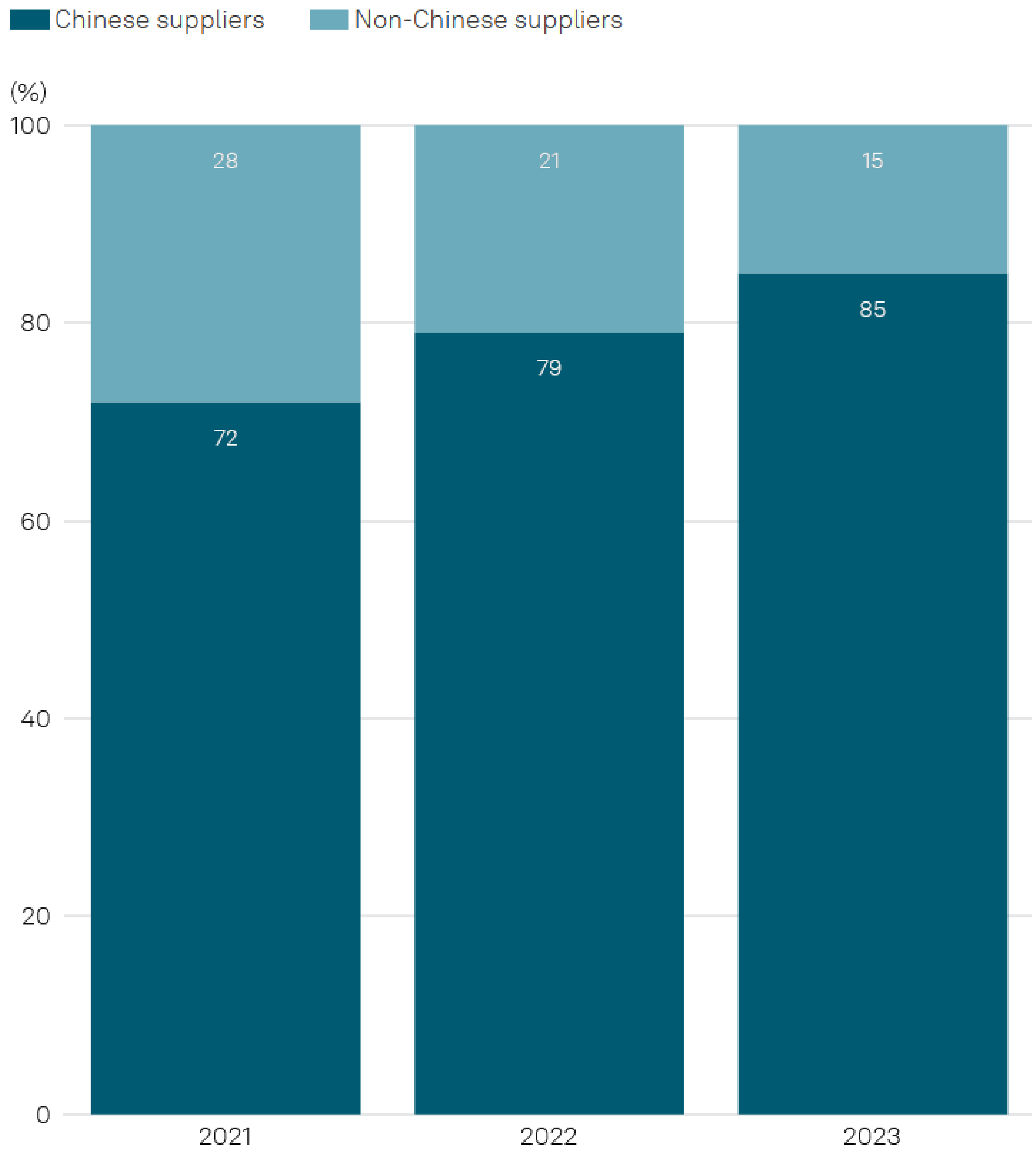
Voltage regulation

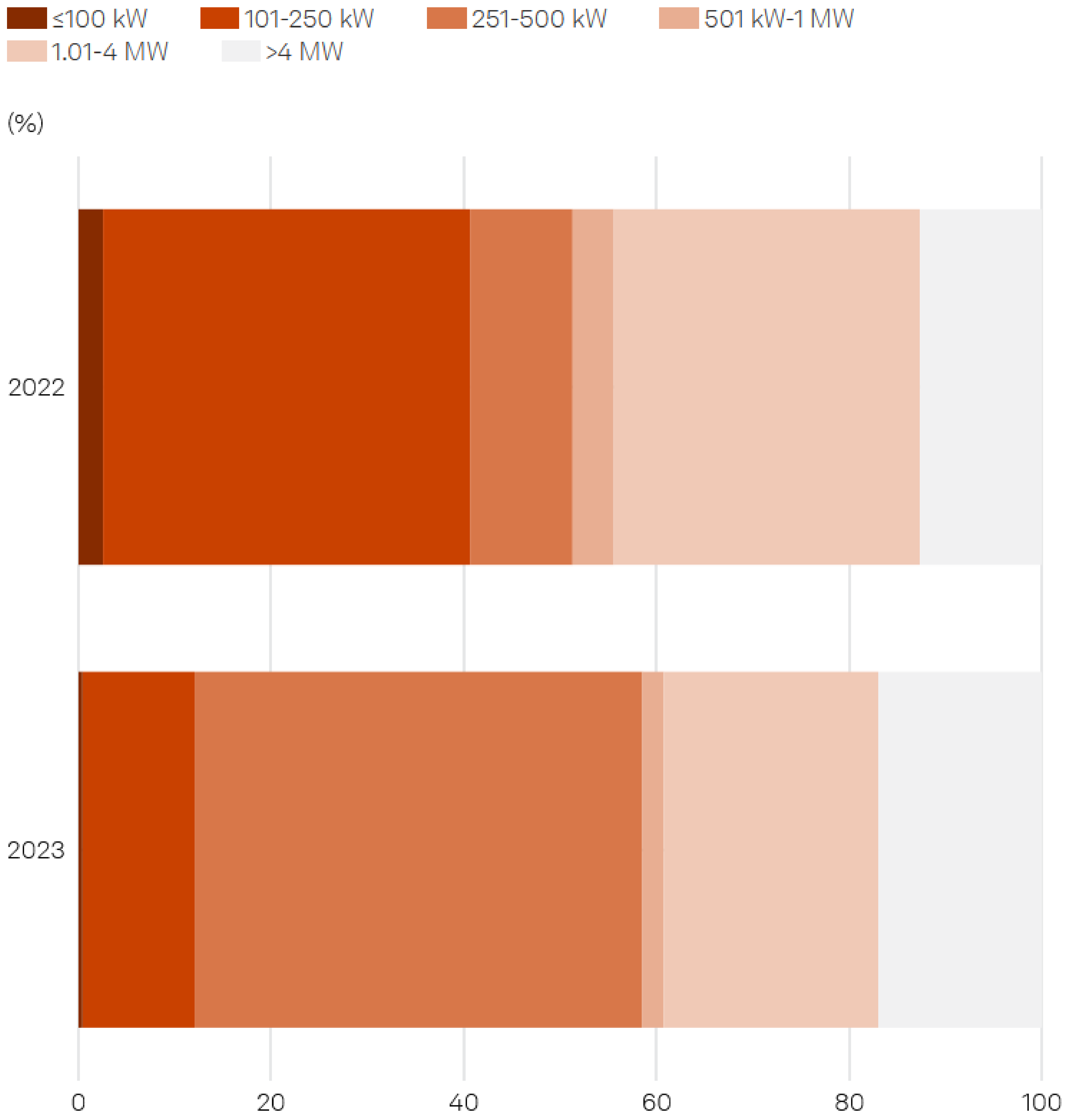
The voltage regulation can be implemented:

- 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

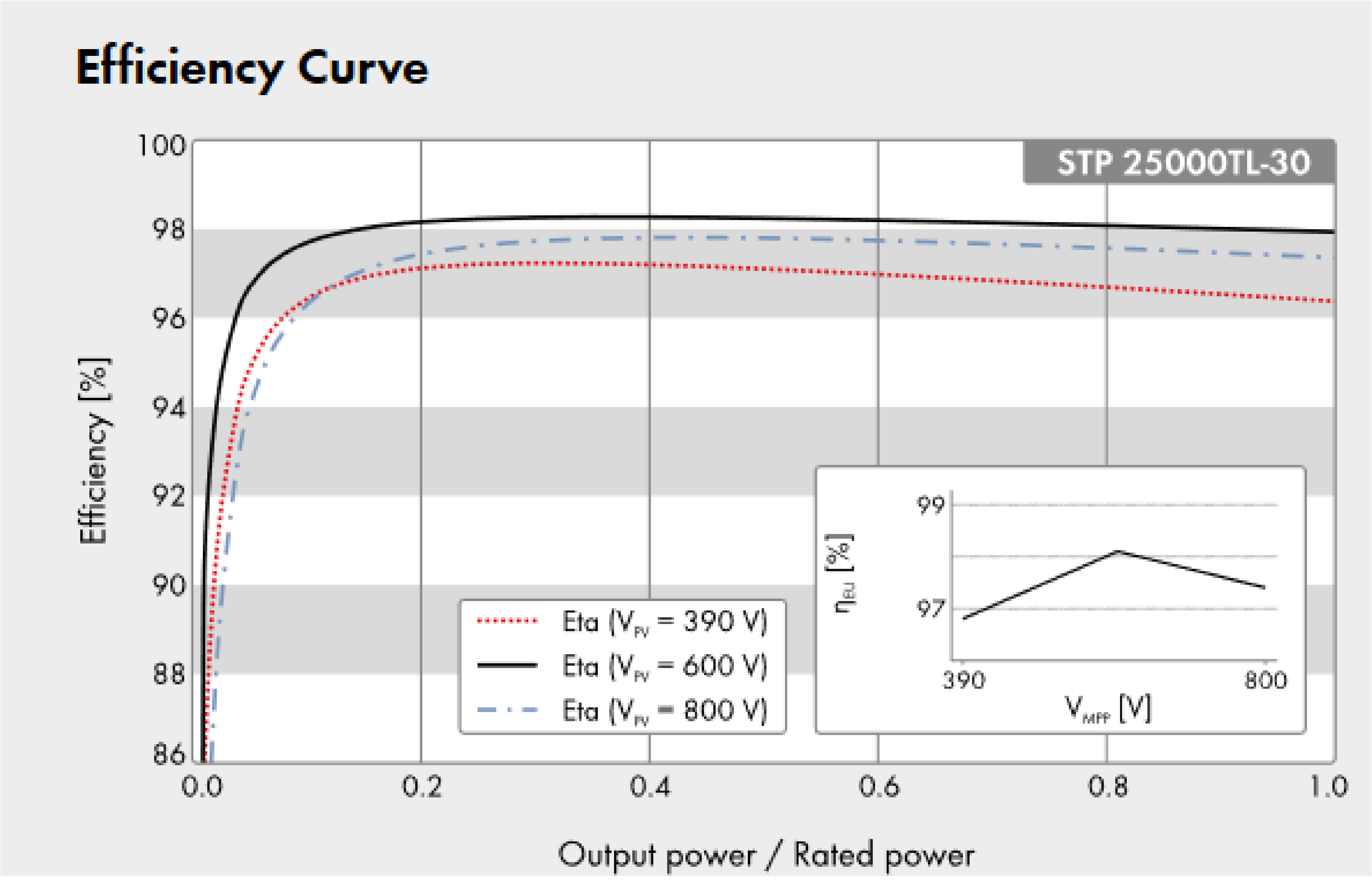




Datasheet of a pv grid-connected inverter

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%

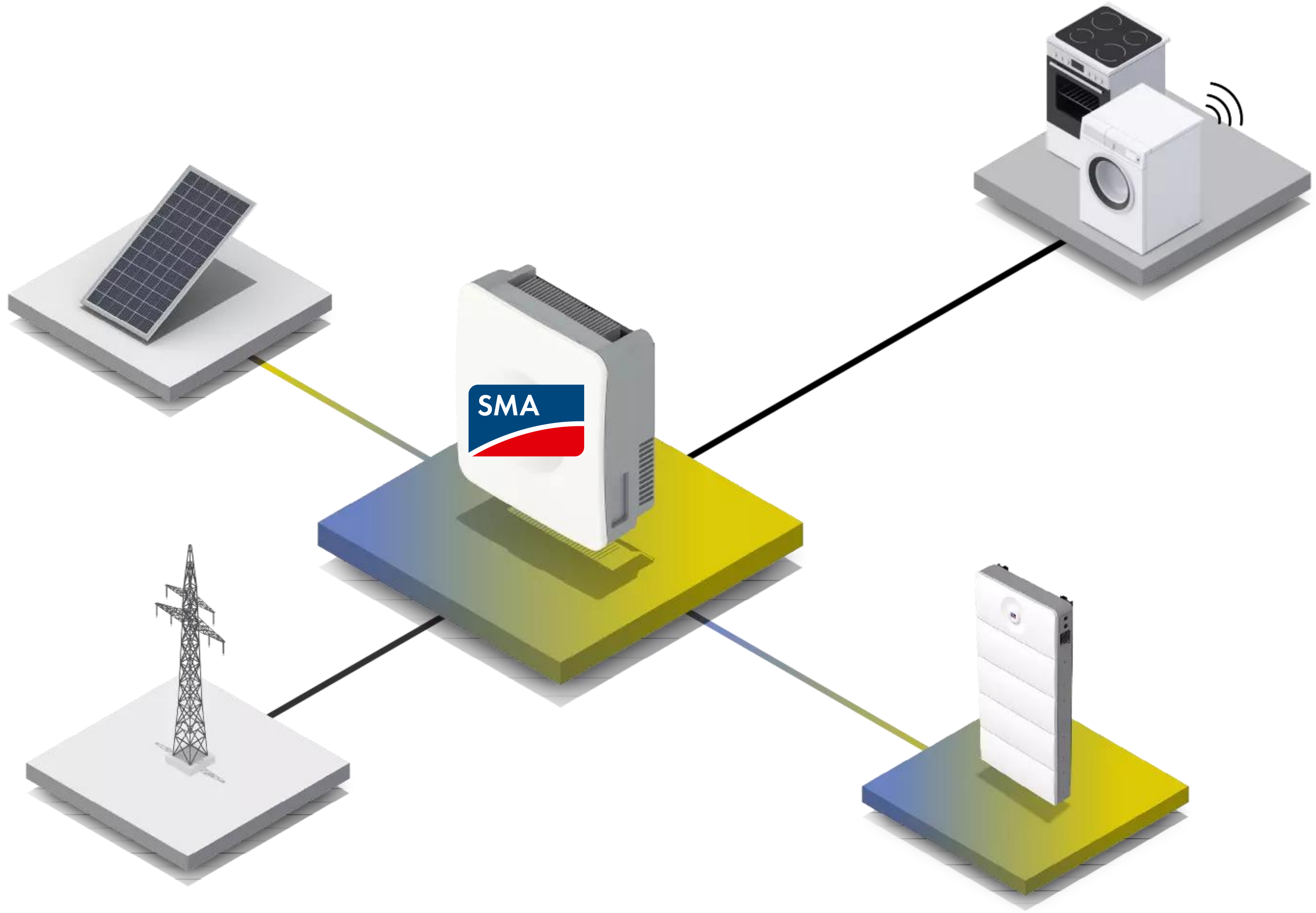
Datasheet of a pv grid-connected inverter



General data

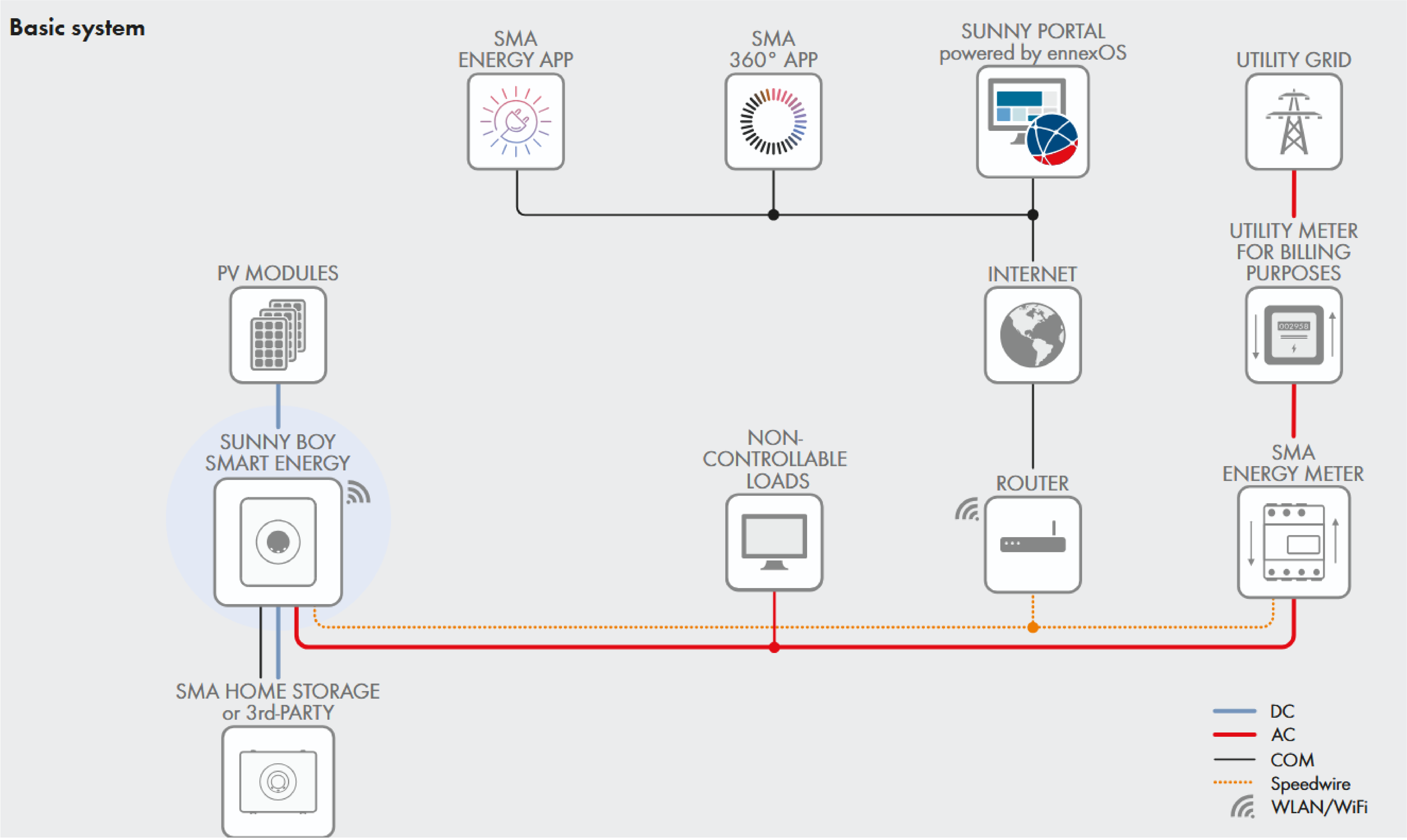
Dimensions (W / H / D)	661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)
Weight	61 kg (134.48 lb)
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)
Noise emission (typical)	51 dB(A)
Self-consumption (at night)	1 W
Topology / cooling concept	Transformerless / Opticool
Degree of protection (as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

Hybrid Inverter

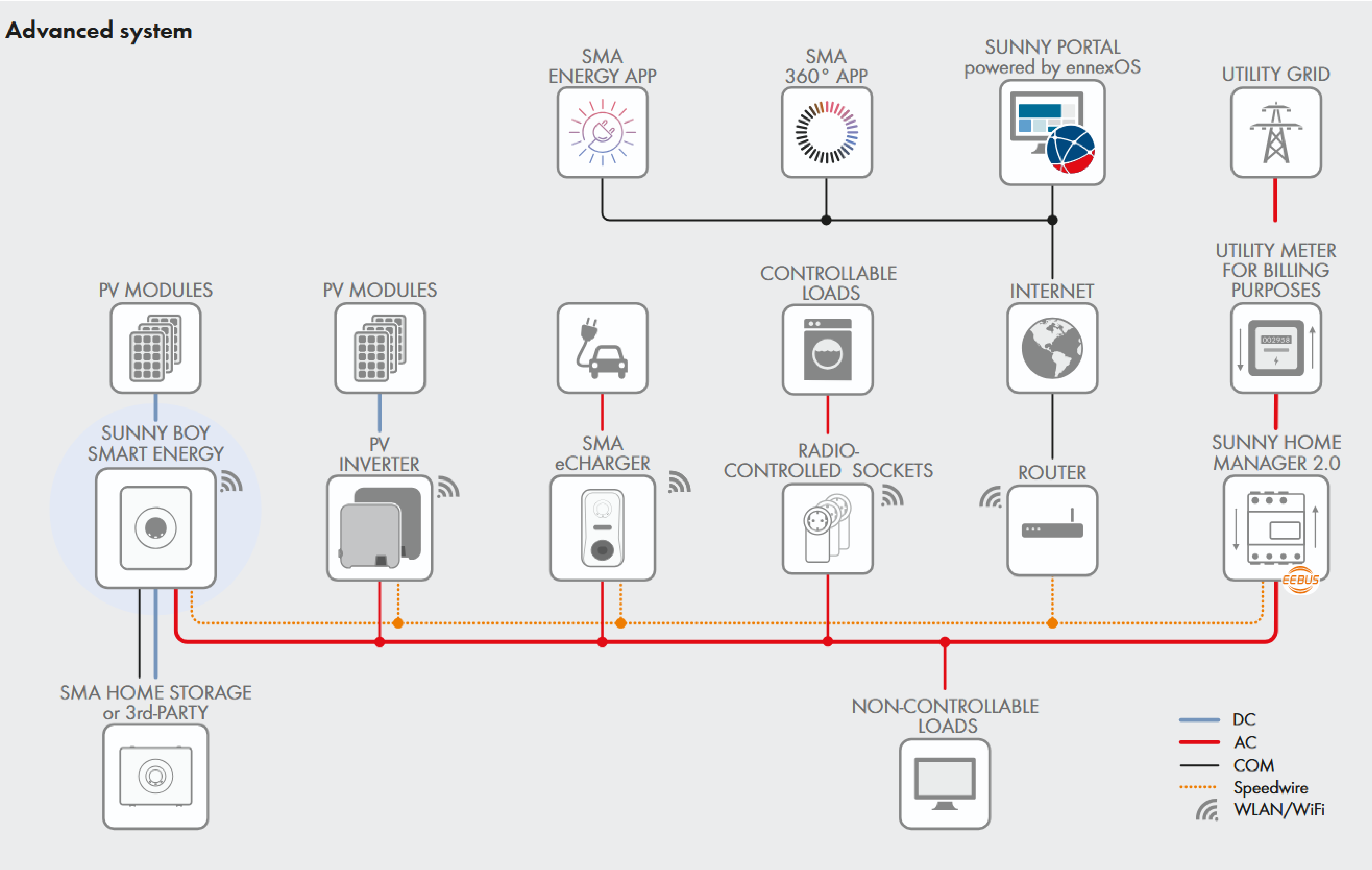


- **Combined functionalities** in one device: battery and photovoltaic
- May ensure access to electricity in case of **blackout**

Hybrid Inverter



Hybrid Inverter

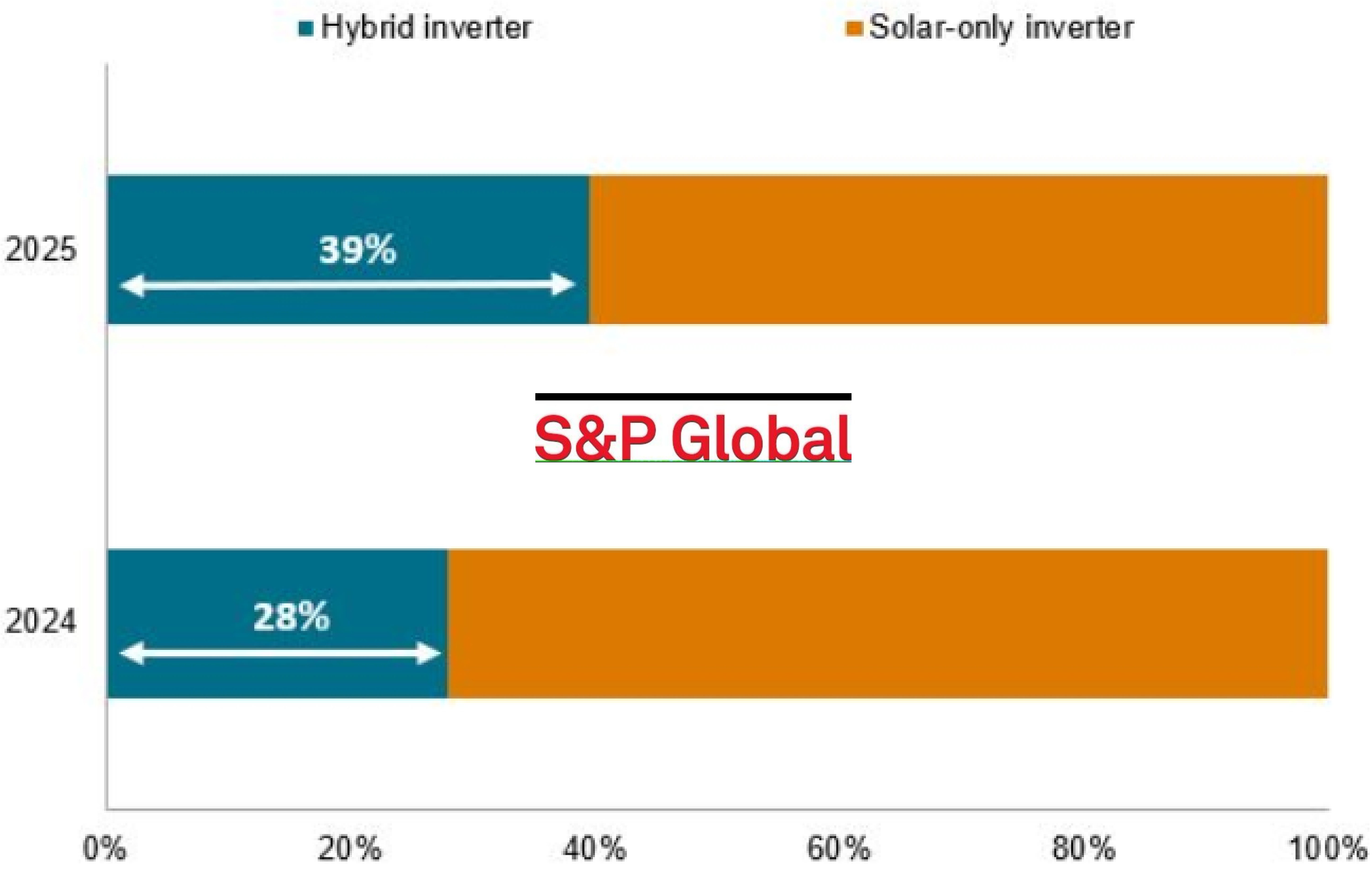


Hybrid Inverter

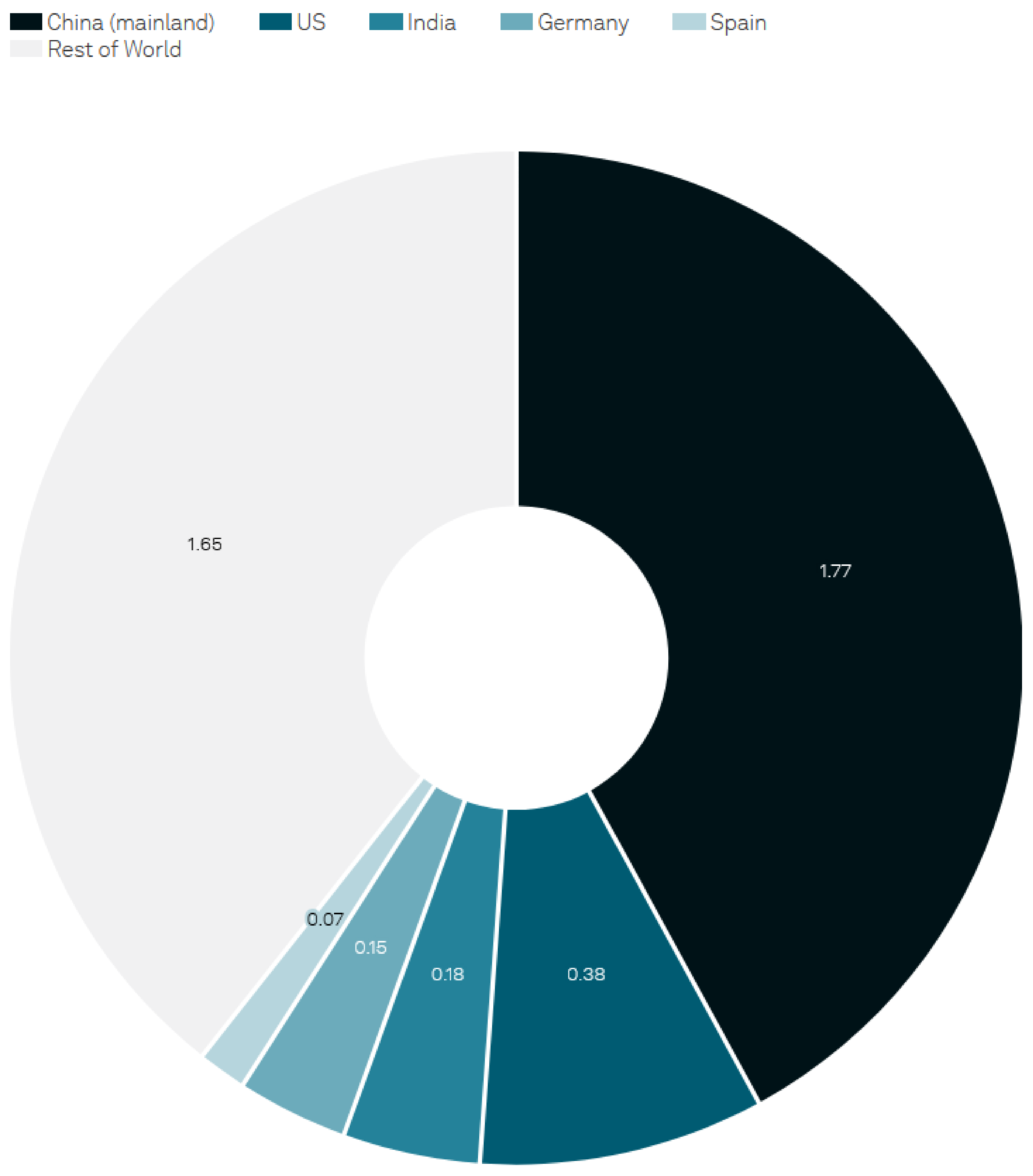
SMA

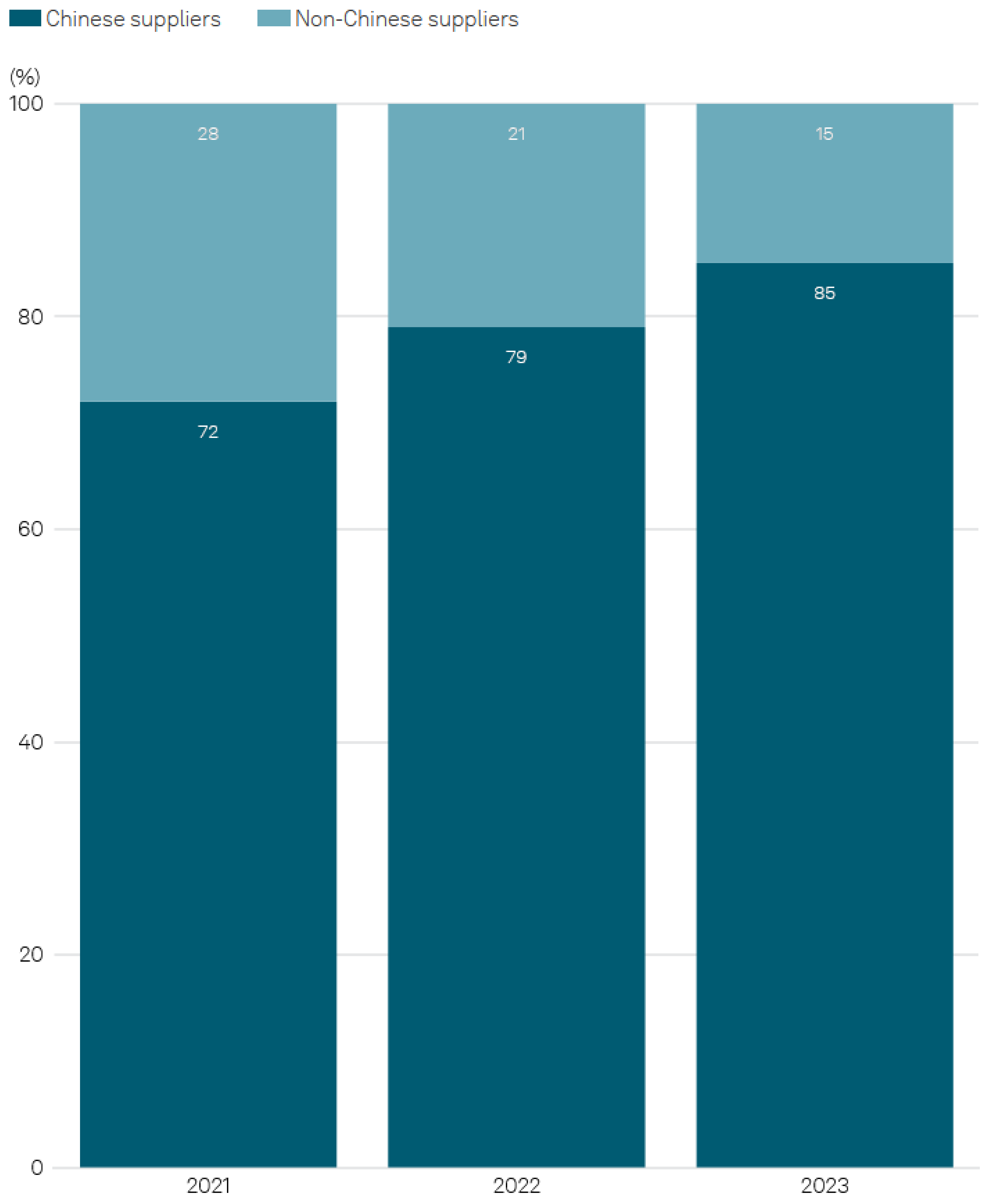
Technical data	Sunny Boy Smart Energy 3.6	Sunny Boy Smart Energy 4.0	Sunny Boy Smart Energy 5.0	Sunny Boy Smart Energy 6.0
Input PV (DC)				
Max. PV array power	7200 Wp	8000 Wp	10000 Wp	12000 Wp
Max. input voltage	600 V			
Min. input voltage	60 V			
MPP voltage range	60 V to 480 V			
Startup input voltage	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

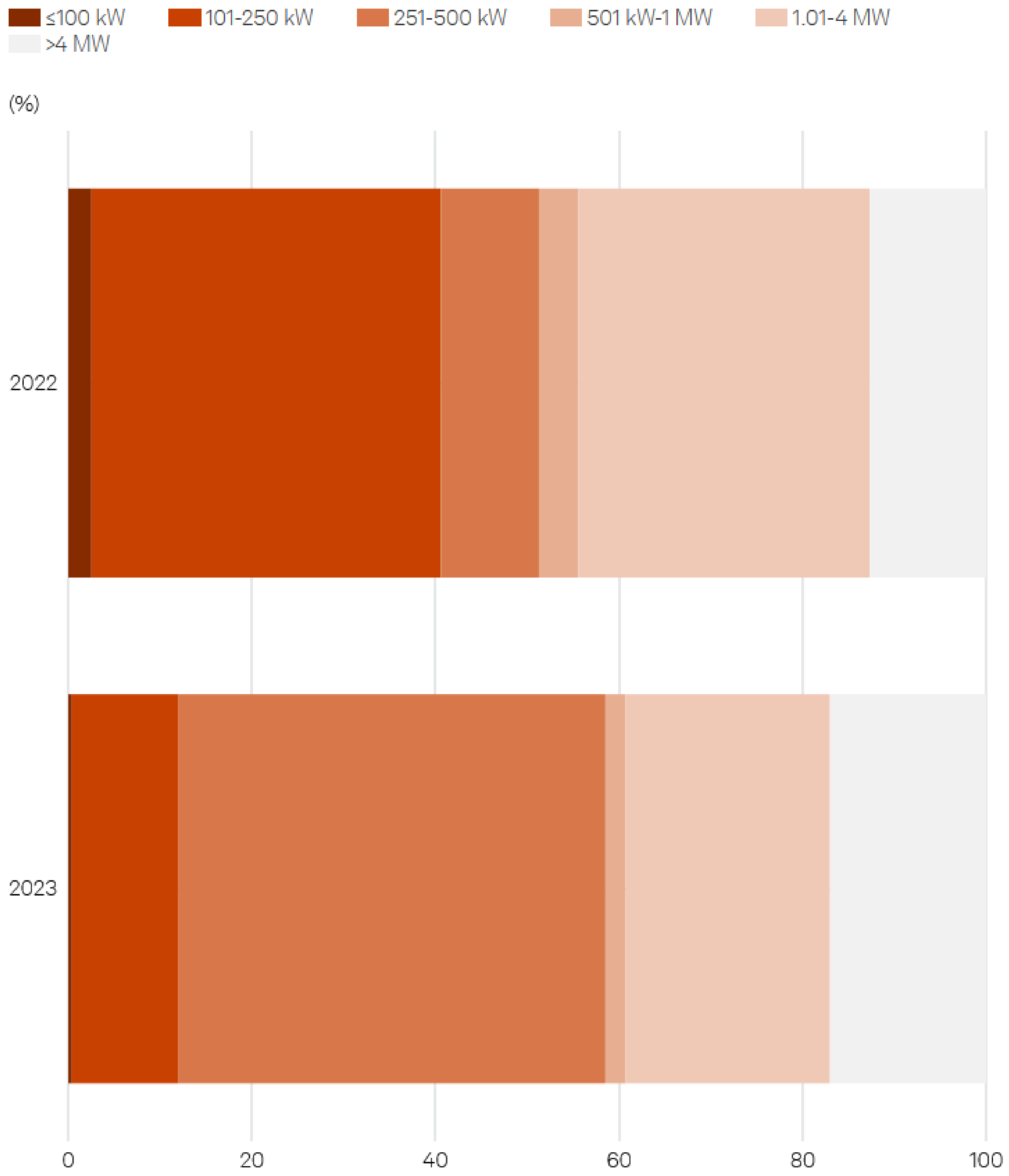
Solar-only and hybrid Inverter



Inverter market

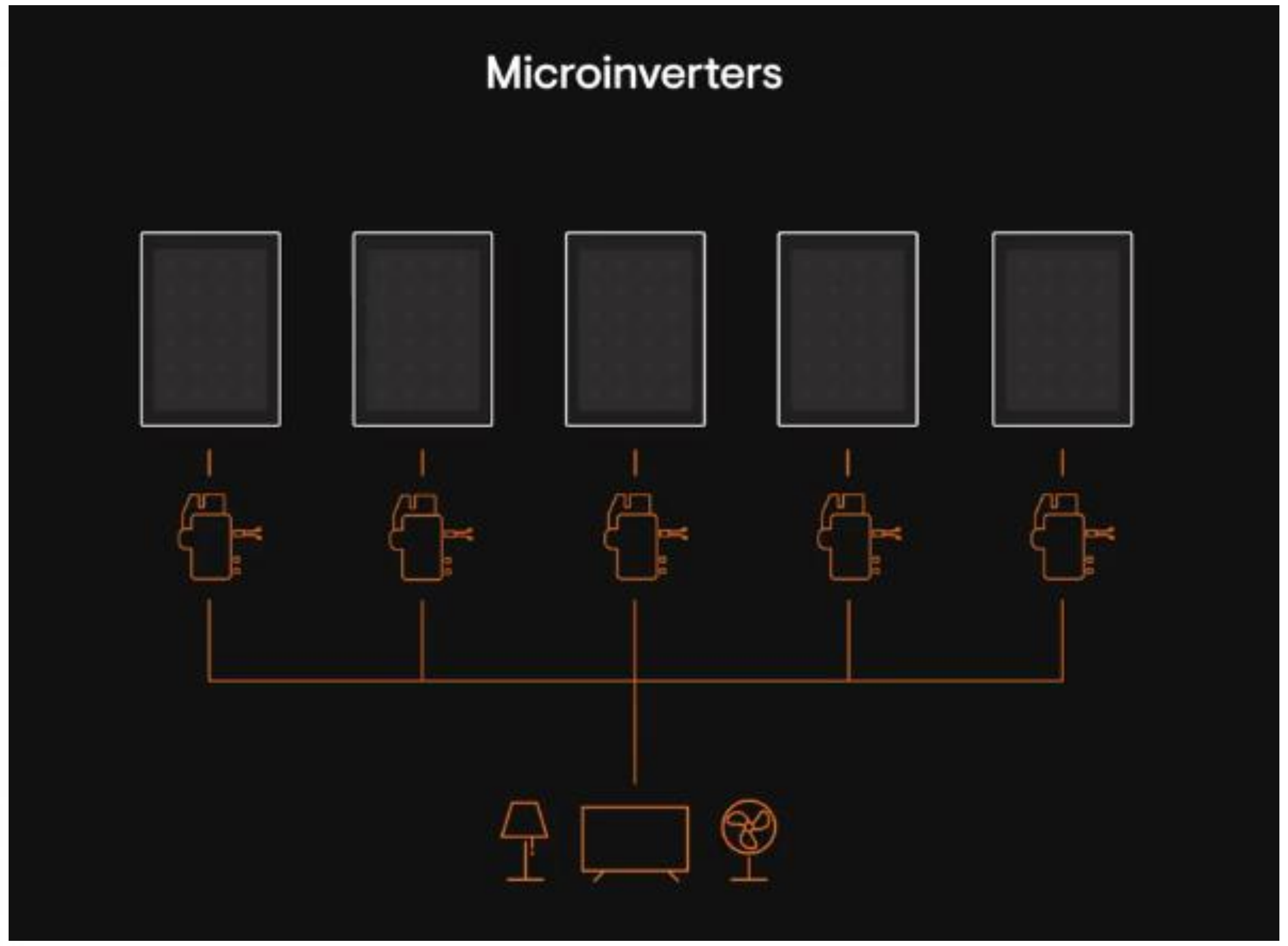


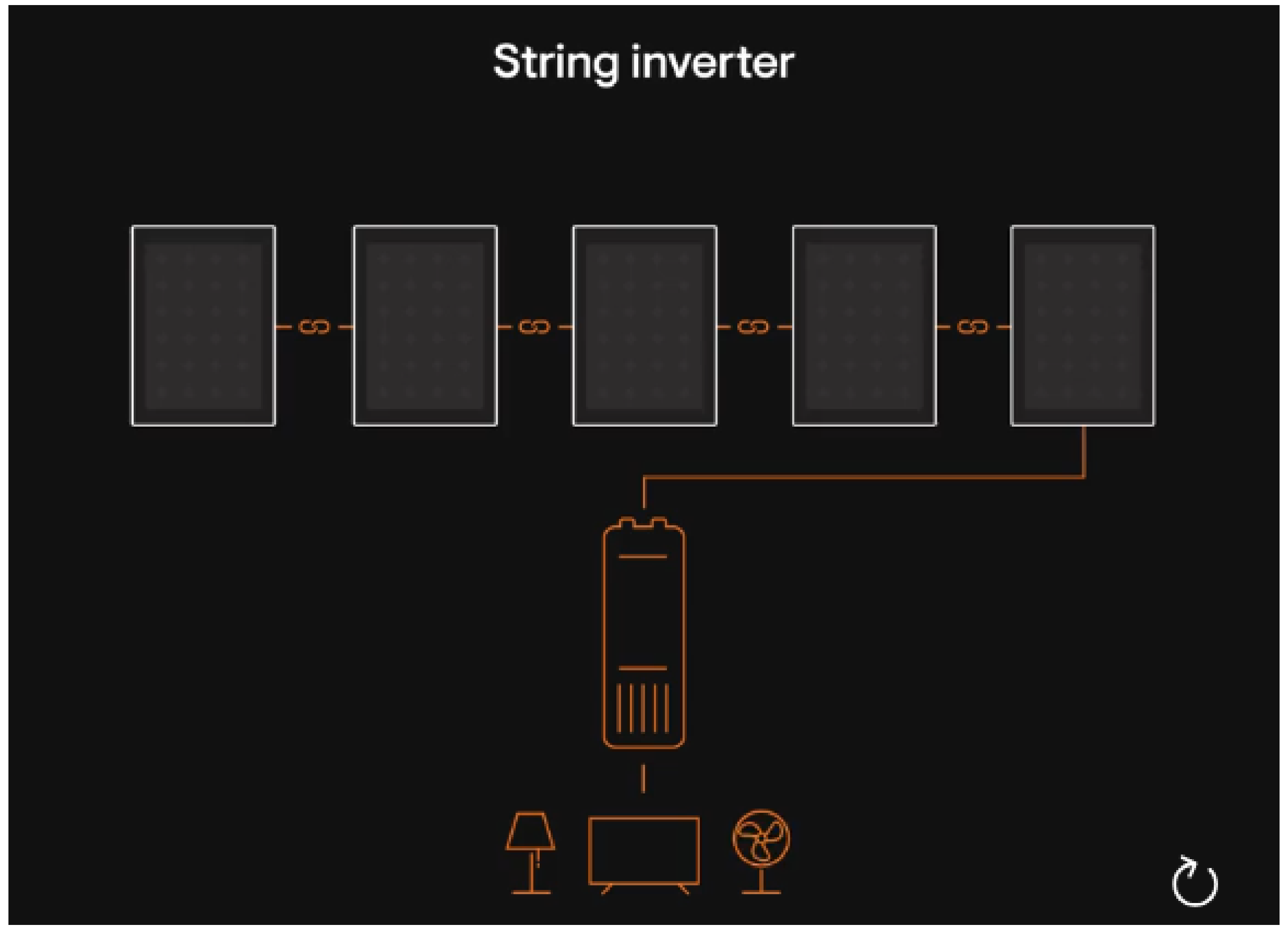




S&P Global

Microinverter

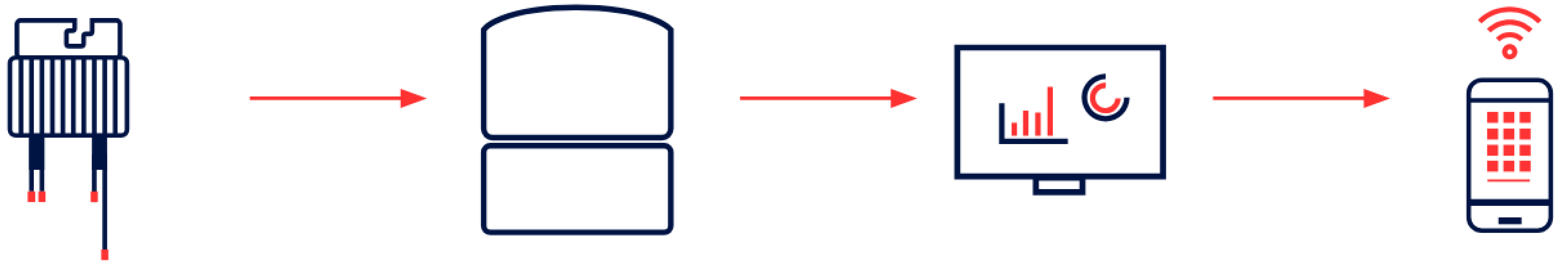




INPUT DATA (DC)		IQ8-60-2-US	IQ8PLUS-72-2-US	IQ8M-72-2-US	IQ8A-72-2-US	IQ8H-240-72-2-US	IQ8H-208-72-2-US[1]
Commonly used module pairings[2]	W	235 – 350	235 – 440	260 – 460	295 – 500	320 – 540+	295 – 500+
Module compatibility		60-cell/120 half-cell	60-cell/120 half-cell, 66-cell/132 half-cell and 72-cell/144 half-cell				
MPPT voltage range	V	27 – 37	29 – 45	33 – 45	36 – 45	38 – 45	38 – 45
Operating range	V	25 – 48	25 – 58				
Min/max start voltage	V	30 / 48	30 / 58				
Max input DC voltage	V	50	60				
Max DC current[3] [module Isc]	A	15					

Power optimizer

	S440	S500	S500B	S650B	UNIT
INPUT					
Rated Input DC Power[1]	440[2]	500[3]		650	W
Absolute Maximum Input Voltage (Voc)	60		125	85	Vdc
MPPT Operating Range	8 – 60		12.5 – 105	12.5 – 85	Vdc
Maximum Short Circuit Current (Isc) of Connected PV Module	14.5[2]	15			Adc
Maximum Efficiency	99.5				%
Weighted Efficiency	98.6				%
Overvoltage Category	II				
OUTPUT DURING OPERATION					
Maximum Output Current	15				Adc
Maximum Output Voltage	60		80		Vdc



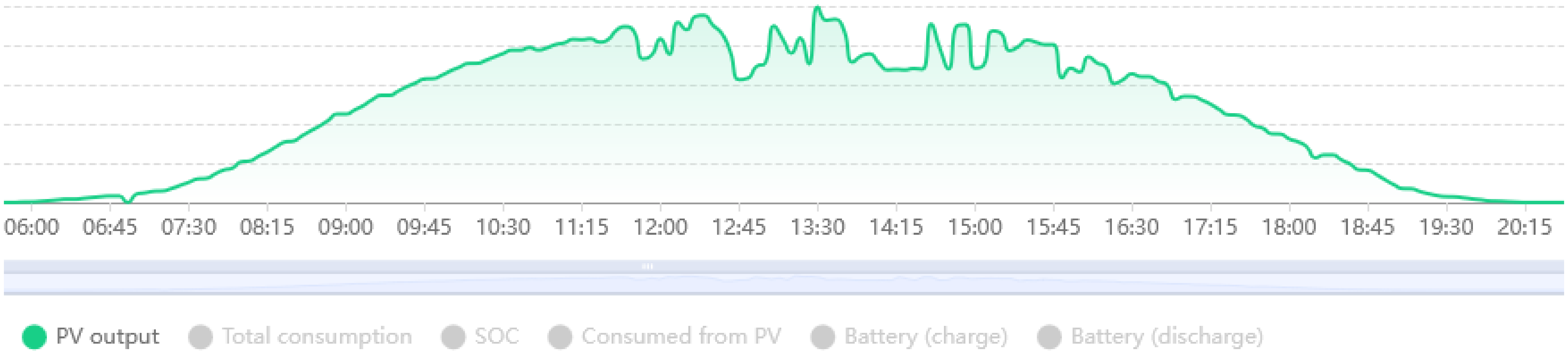
Sense
Identifies connector temperature as abnormal

React
Shuts down inverter production

Identify
Monitoring Platform
Connector location is visible in the physical layout

Notify
Monitoring App
Notifies installer, including location identification

Shading


06:00
06:45
07:30
08:15
09:00
09:45
10:30
11:15
12:00
12:45
13:30
14:15
15:00
15:45
16:30
17:15
18:00
18:45
19:30
20:15
PV output
Total consumption
SOC
Consumed from PV
Battery (charge)
Battery (discharge)

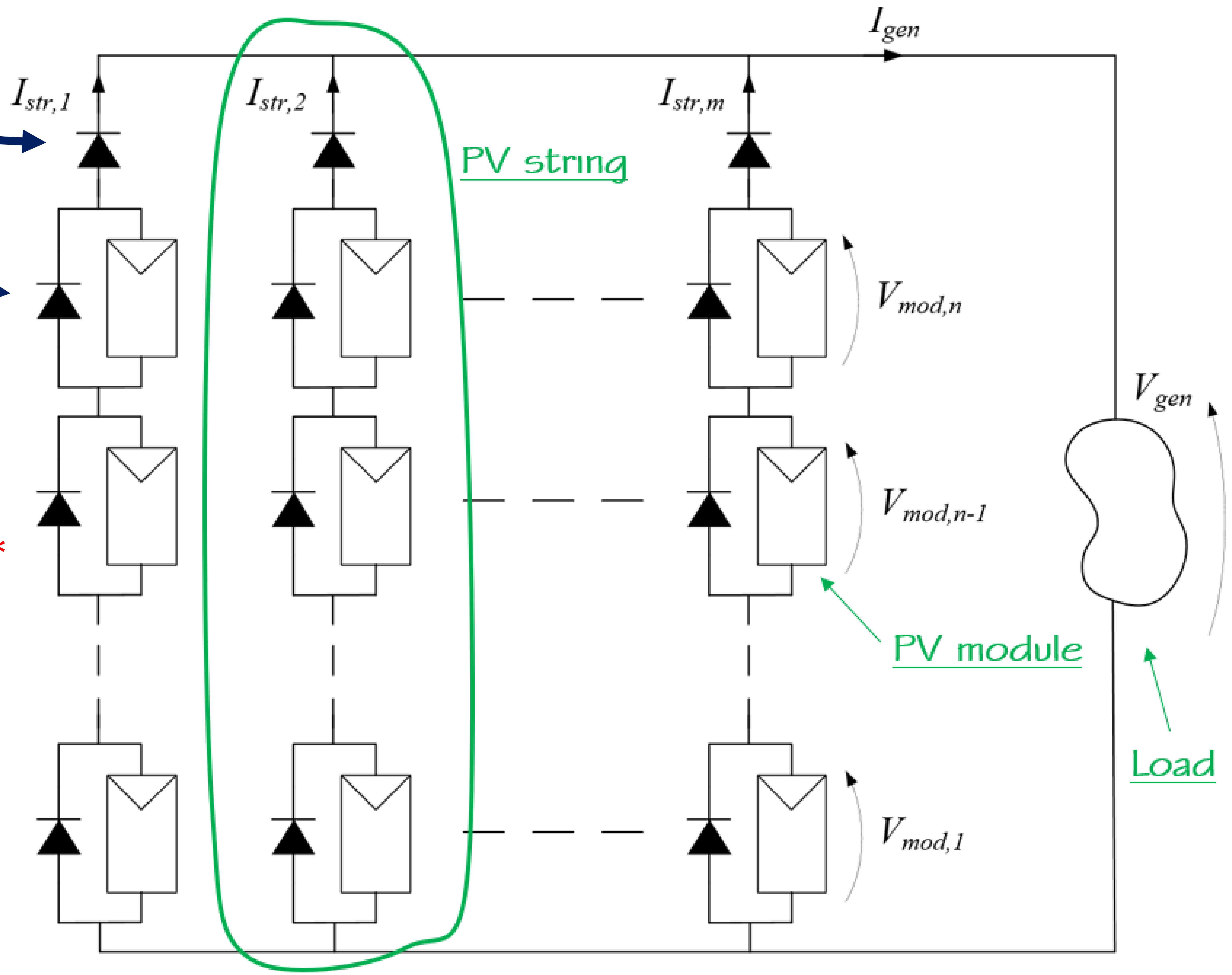
Photovoltaic generator

Blocking diode
Optional
Stand-alone systems

Bypass diode
More than one inside the junction box

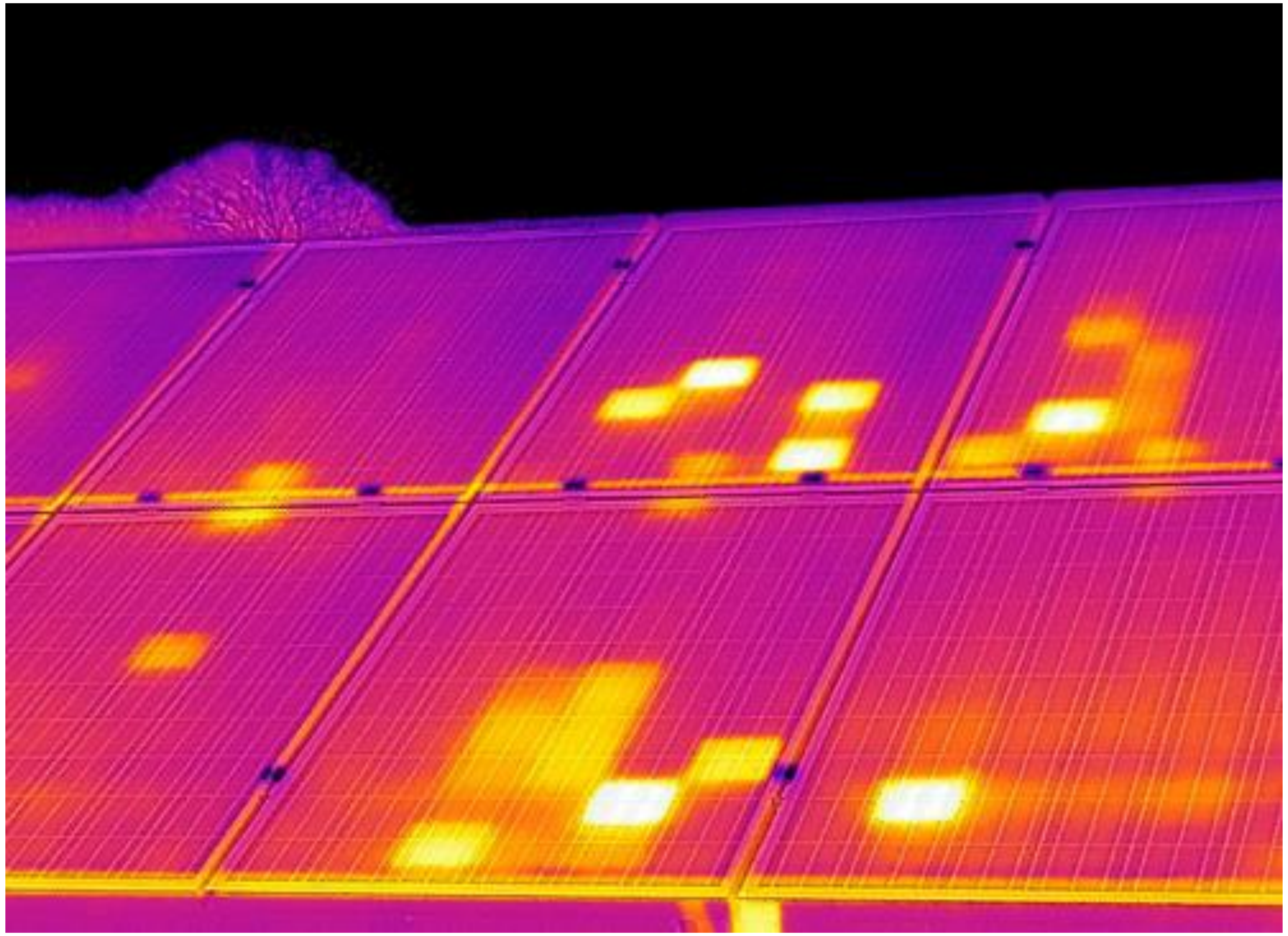
$$I_{str,i} = I^*_{mod} \qquad V_{str} = \sum_{j=1}^{n} V_{mod,j}^{\quad *}$$

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



The hotspot problem

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

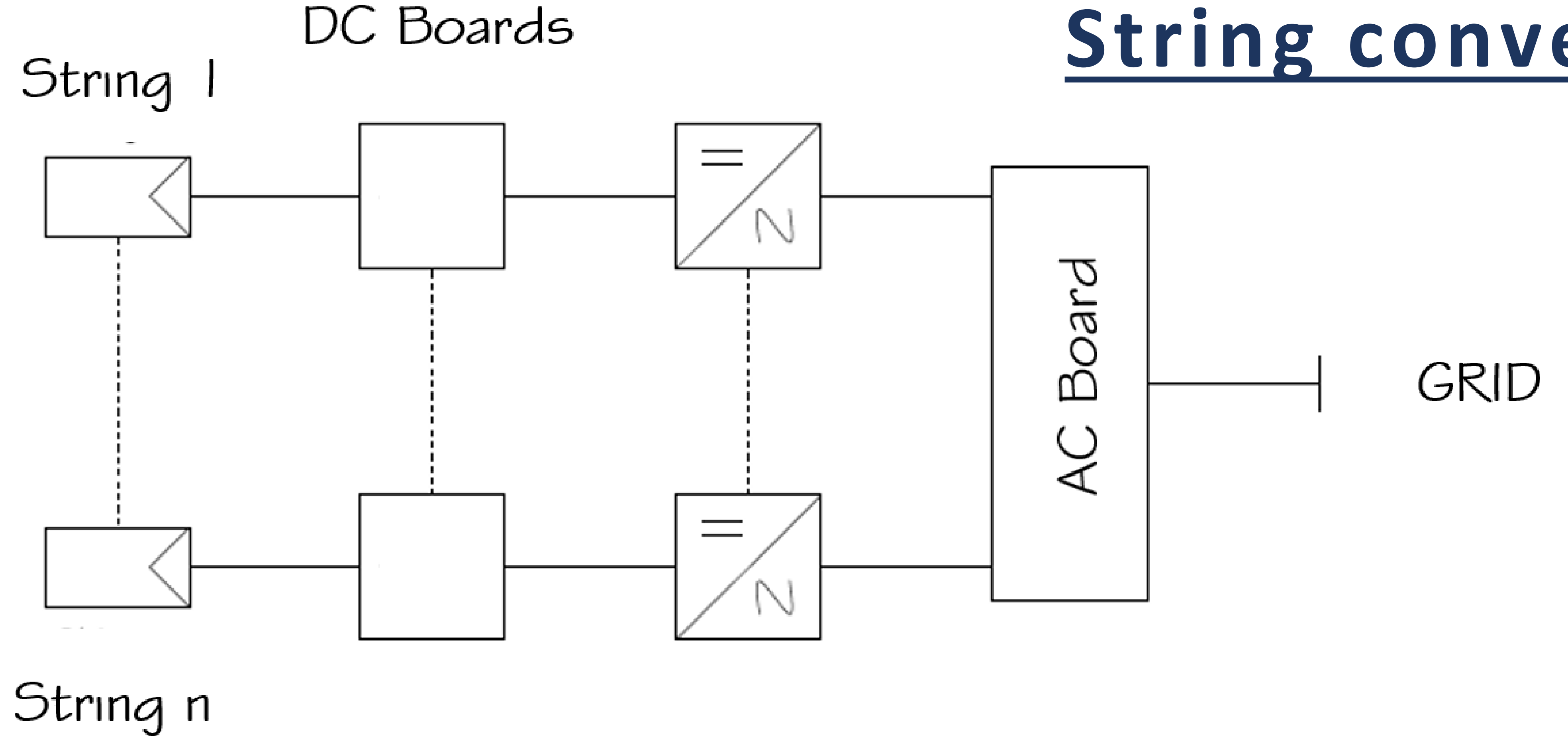


Causes:

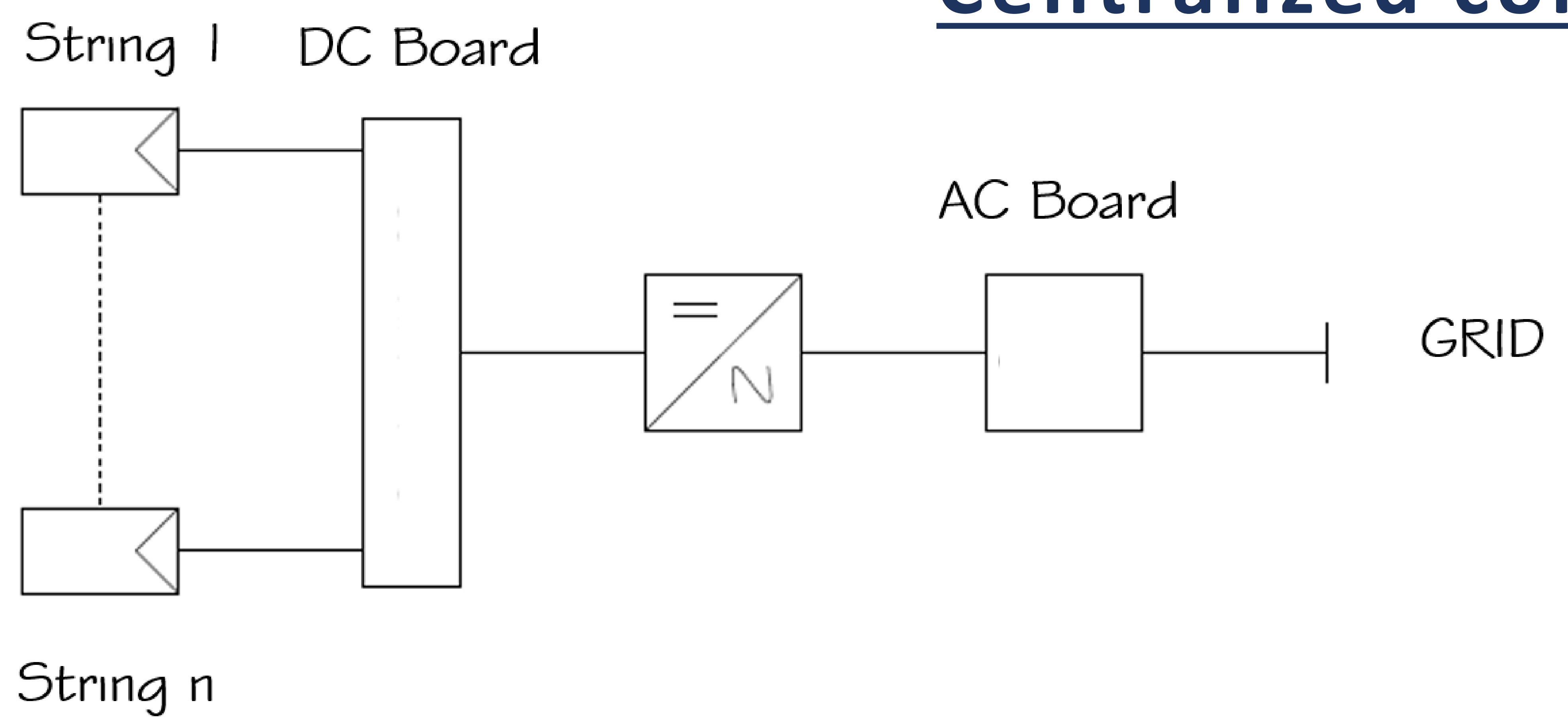
- Partial Shading: when a part of a PV module is shaded
- Current Mismatch: different photogenerated current
- Degradation: different performances

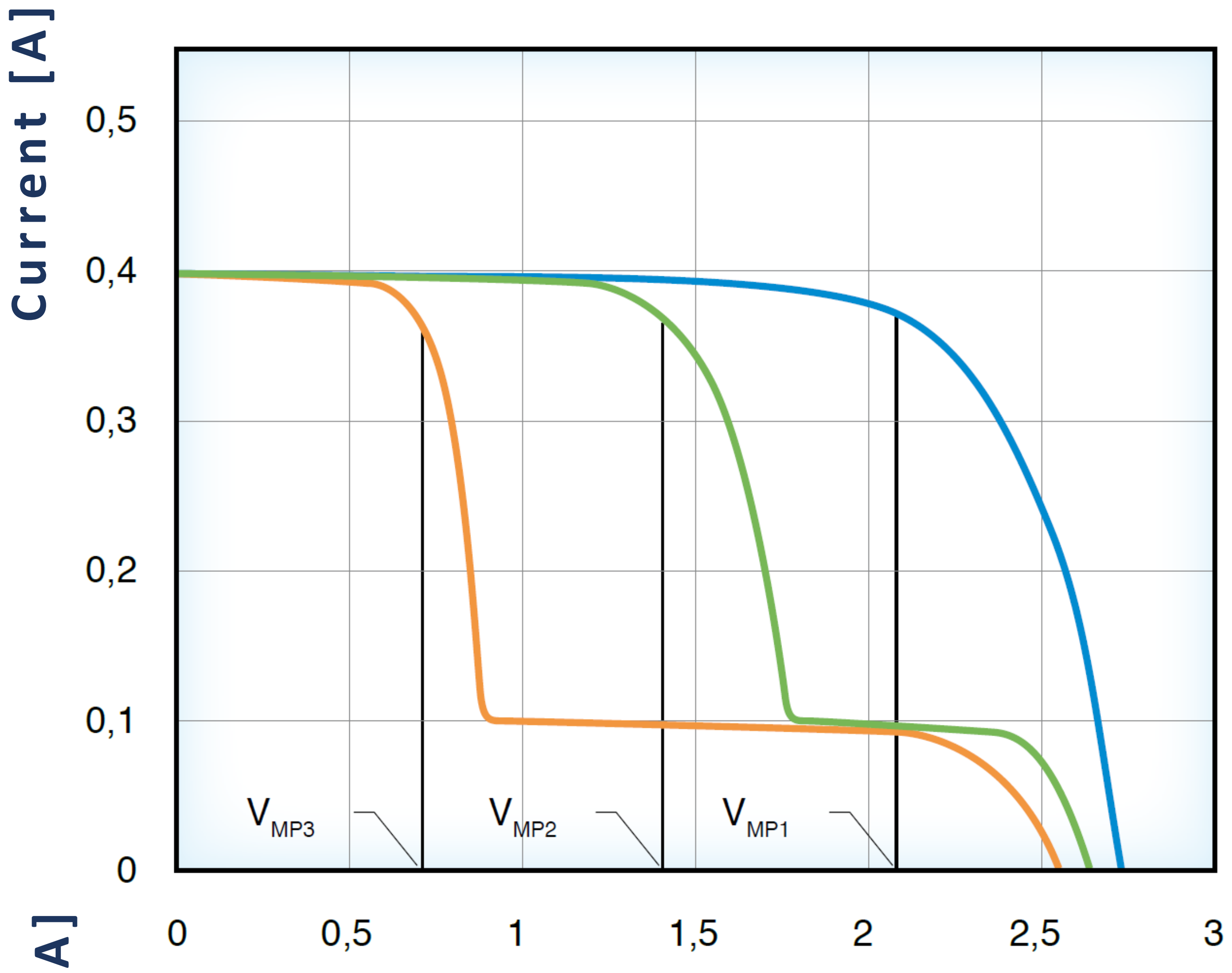
Power conversion

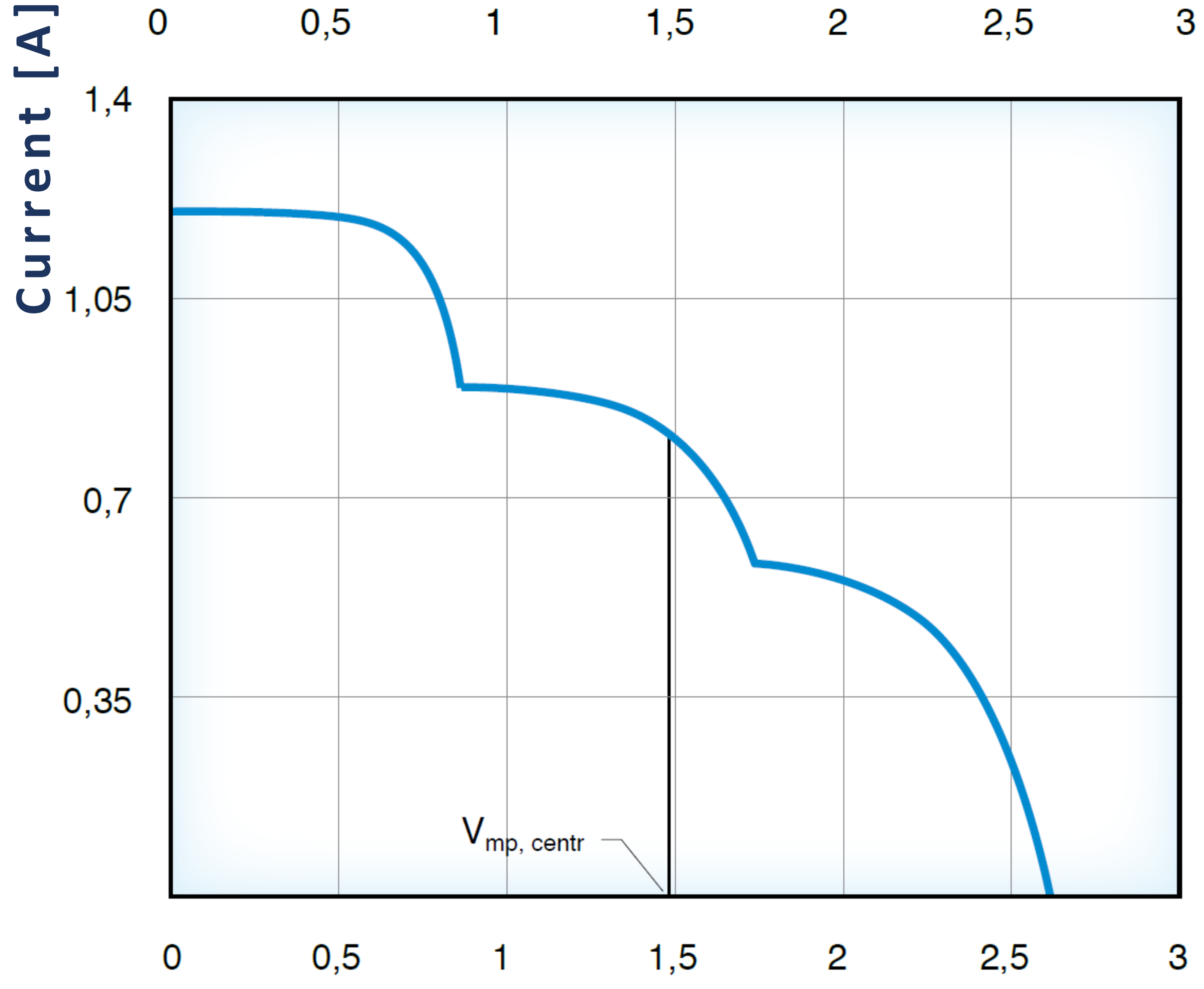
String conversion



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

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

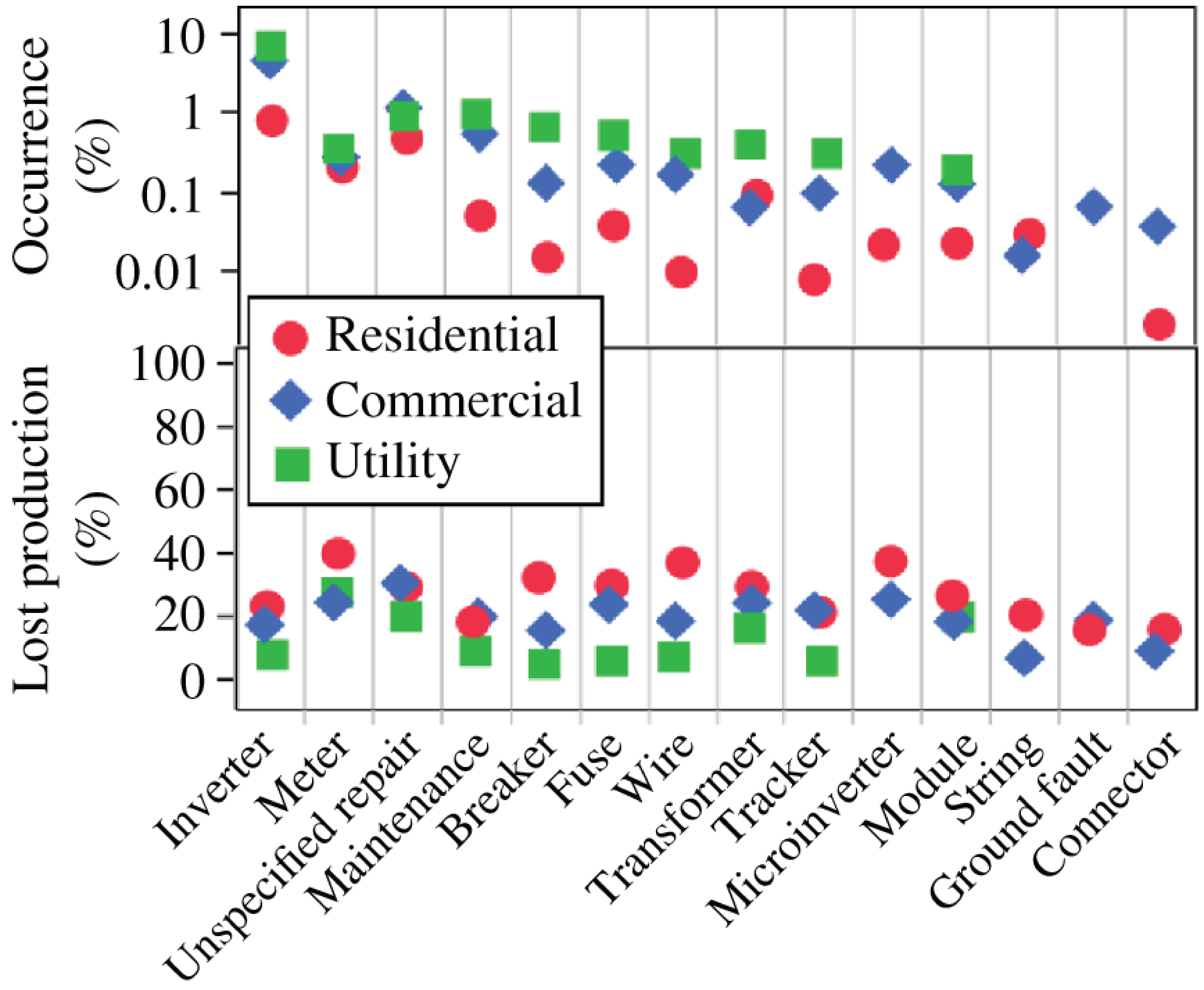
$$V_{MP\,max} > n \times V_{MP,mod\,max}$$

Maximum DC voltage

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

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

Failure and availability



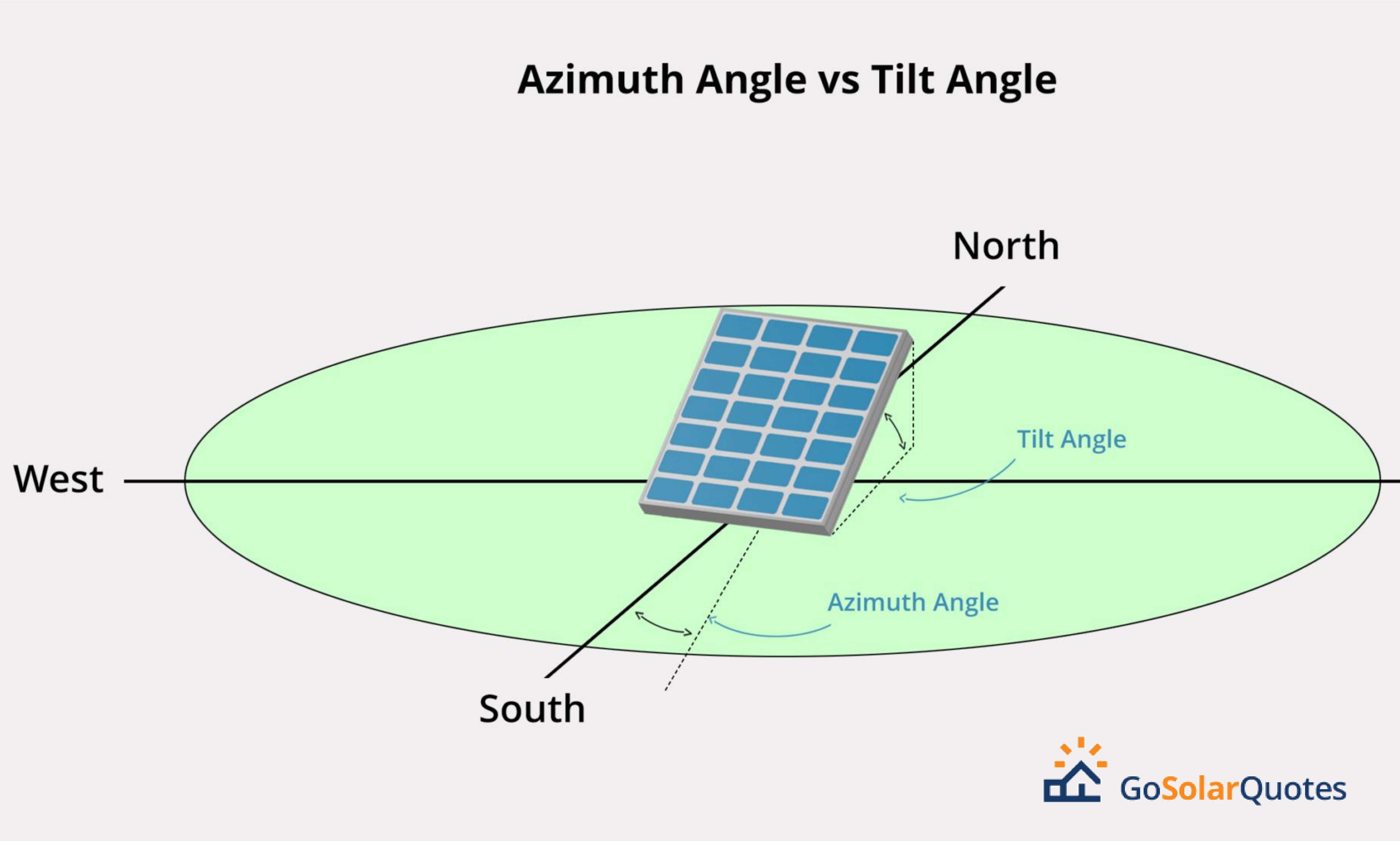
Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

Mounting options

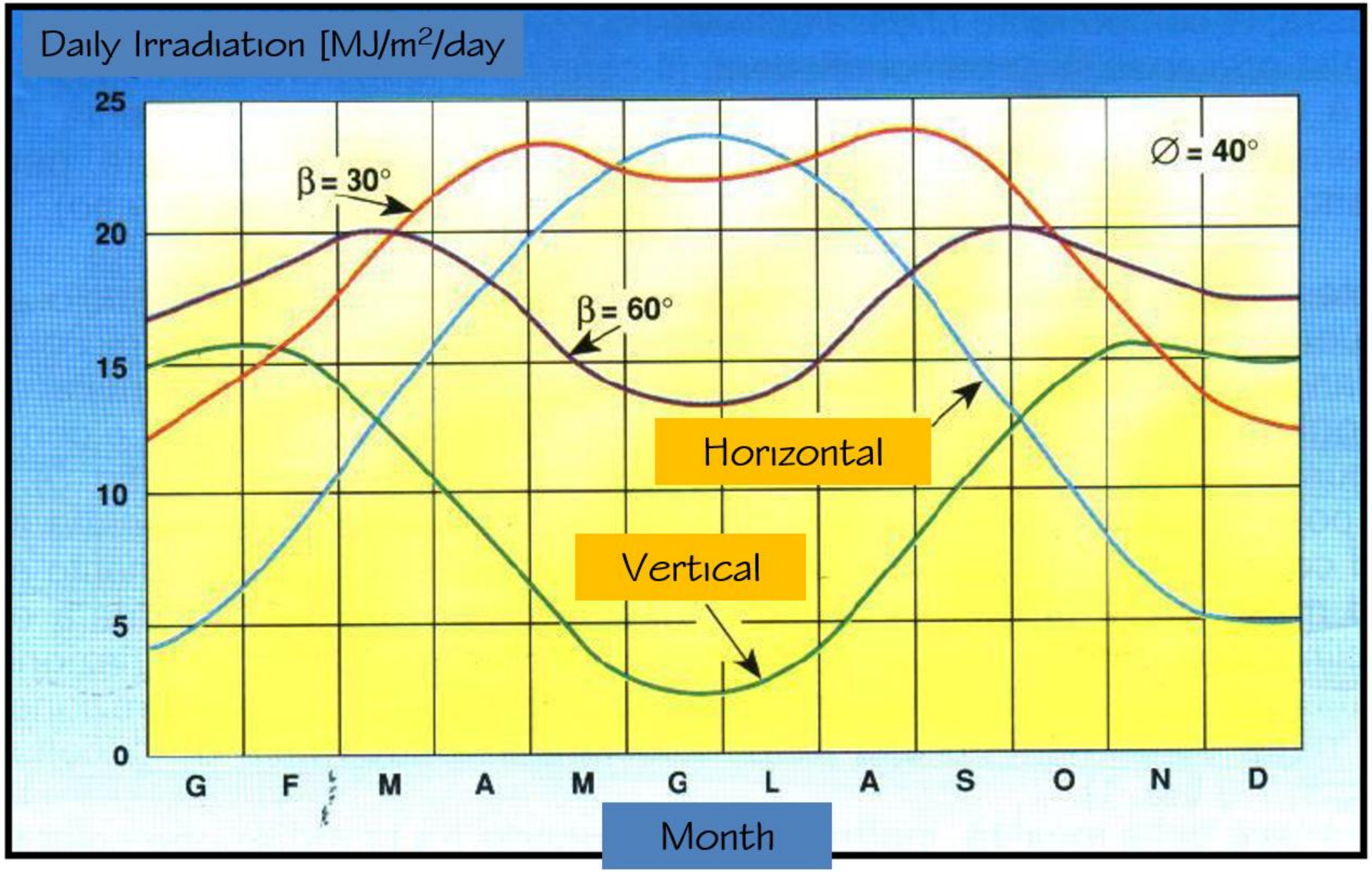
Type of system: fixed or tracking, free standing or BIPV

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

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



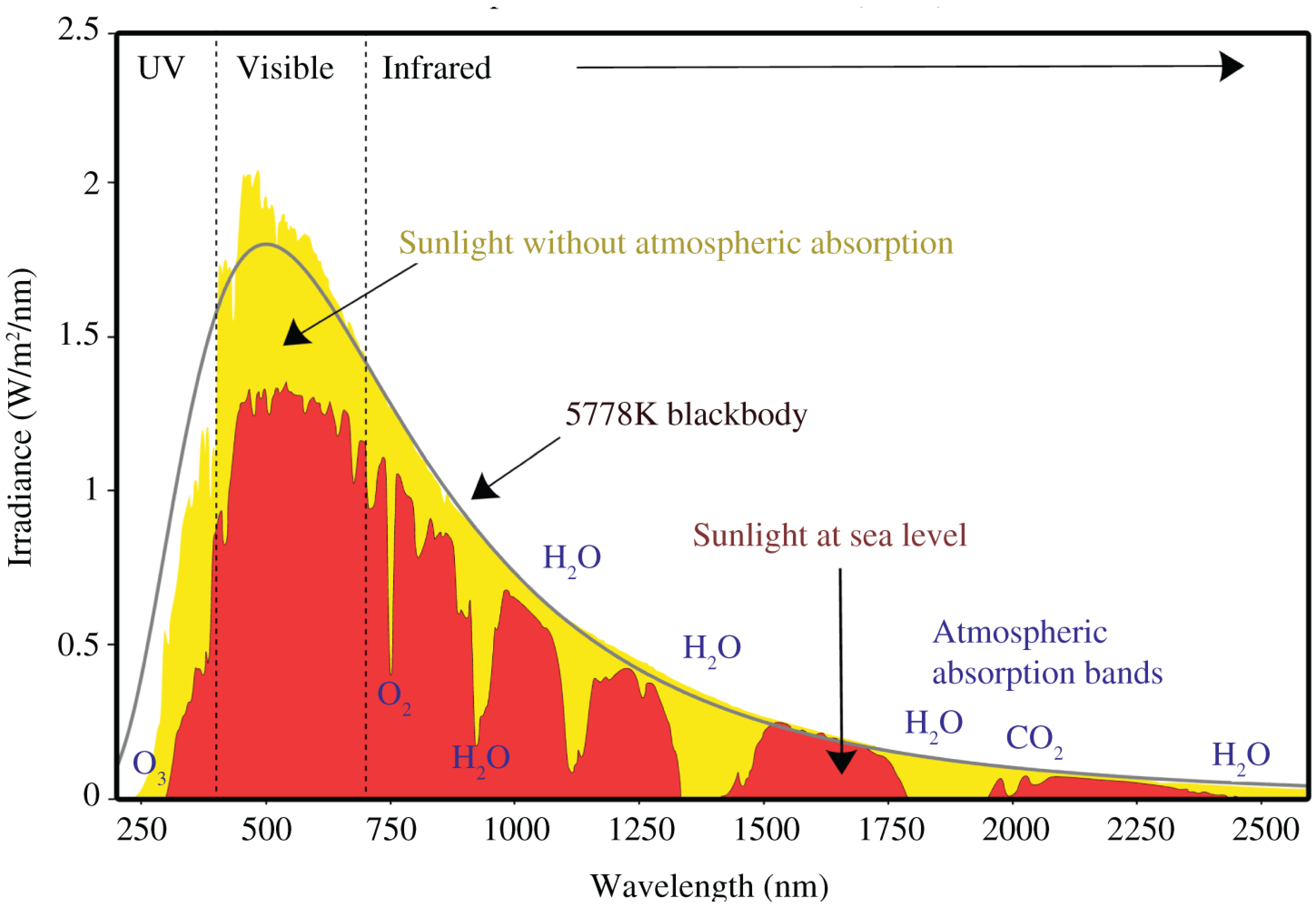
Optimizing the tilt angle



Definitions

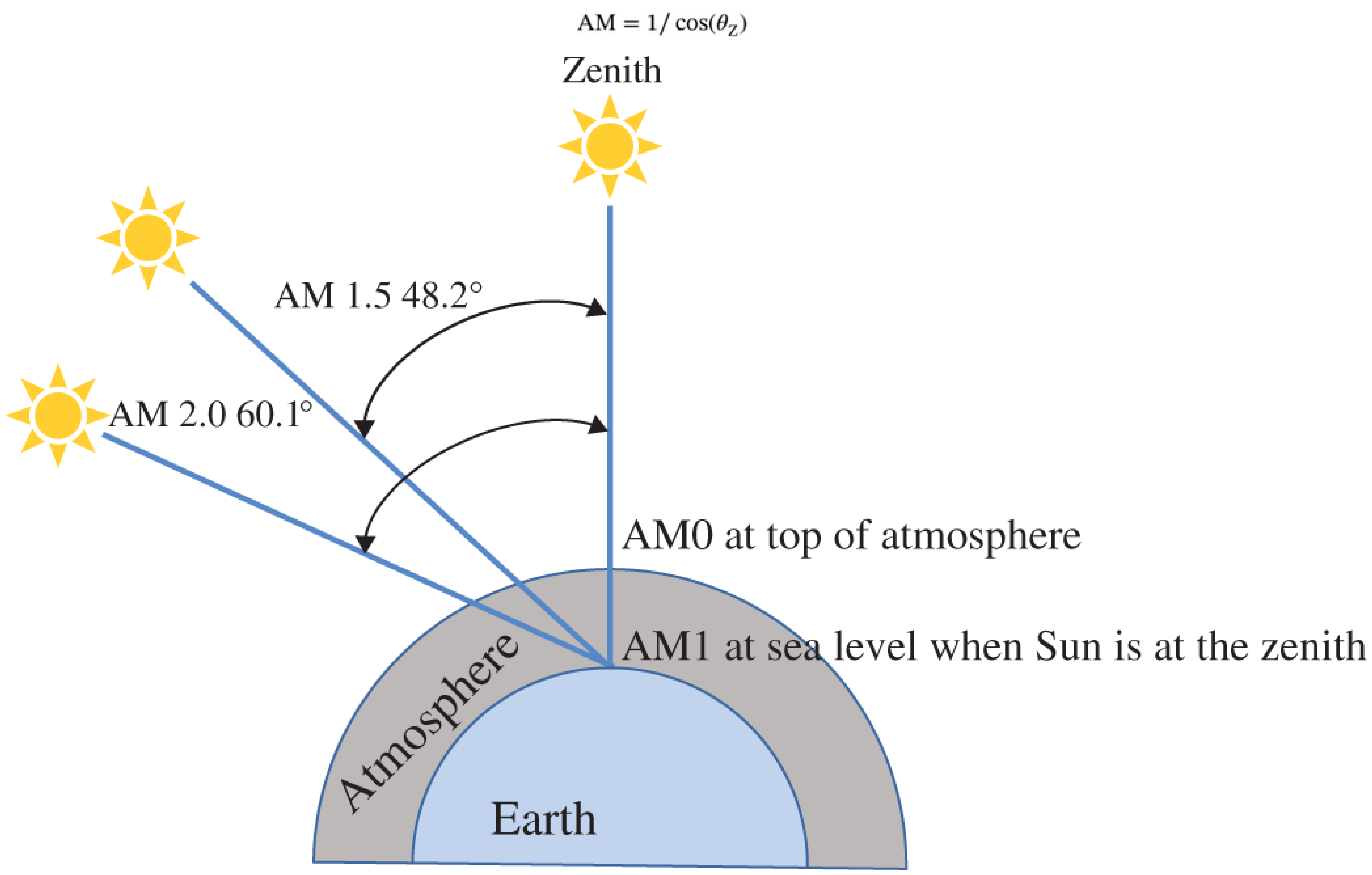
- ✓ **Solar radiation**: general meaning
- ✓ **Irradiation** [Wh/m2]: energy received per unit area
- ✓ **Irradiance** [W/m2]: power received per unit area
- ✓ **Yield** [kWh/kWp]: yearly output energy referred to the nominal power
- ✓ **Solar constant**: energy received from the Sun per unit of time 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



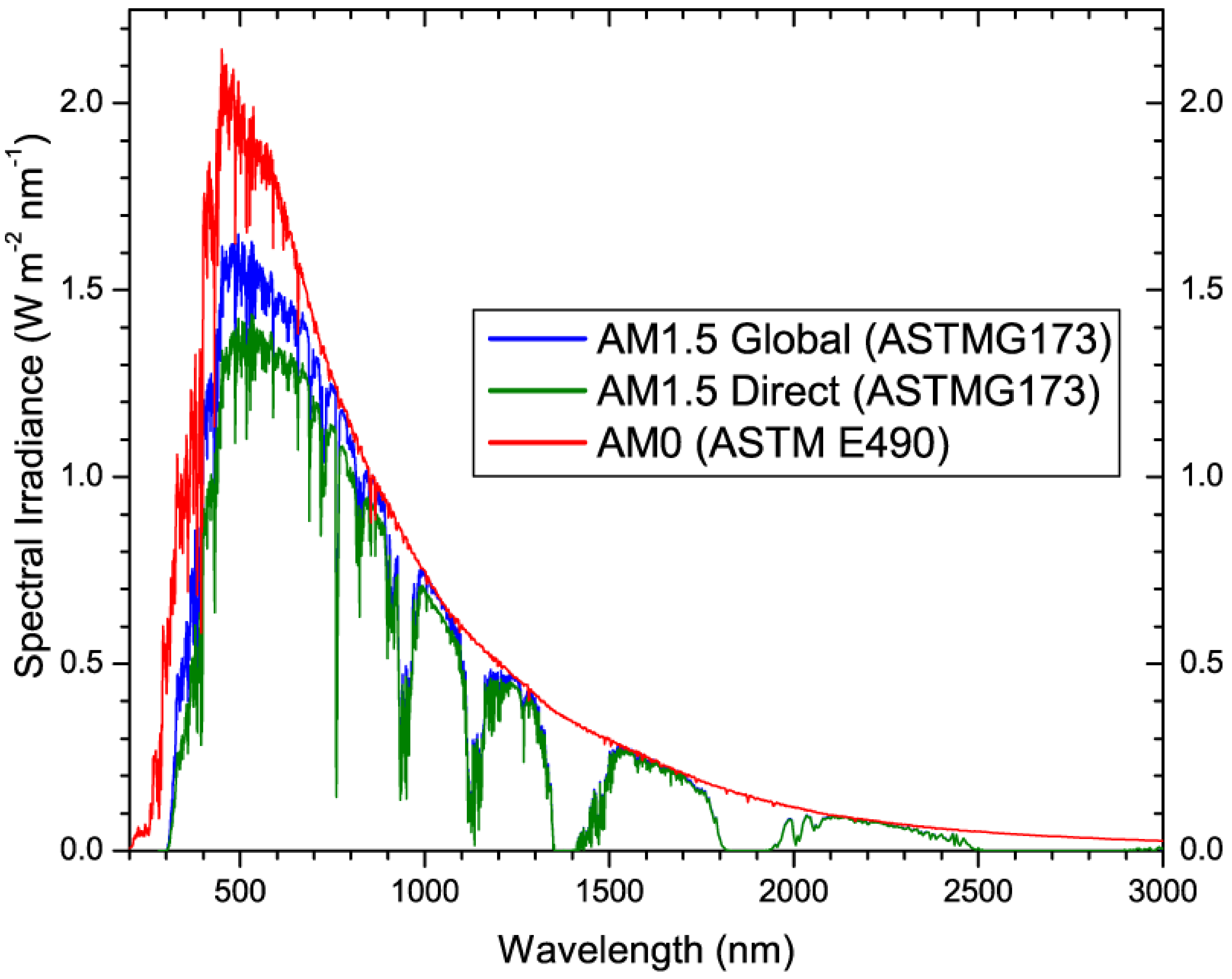
Photovoltaic Solar Energy: From Fundamentals to Applications
Volume 2, Wiley 2024

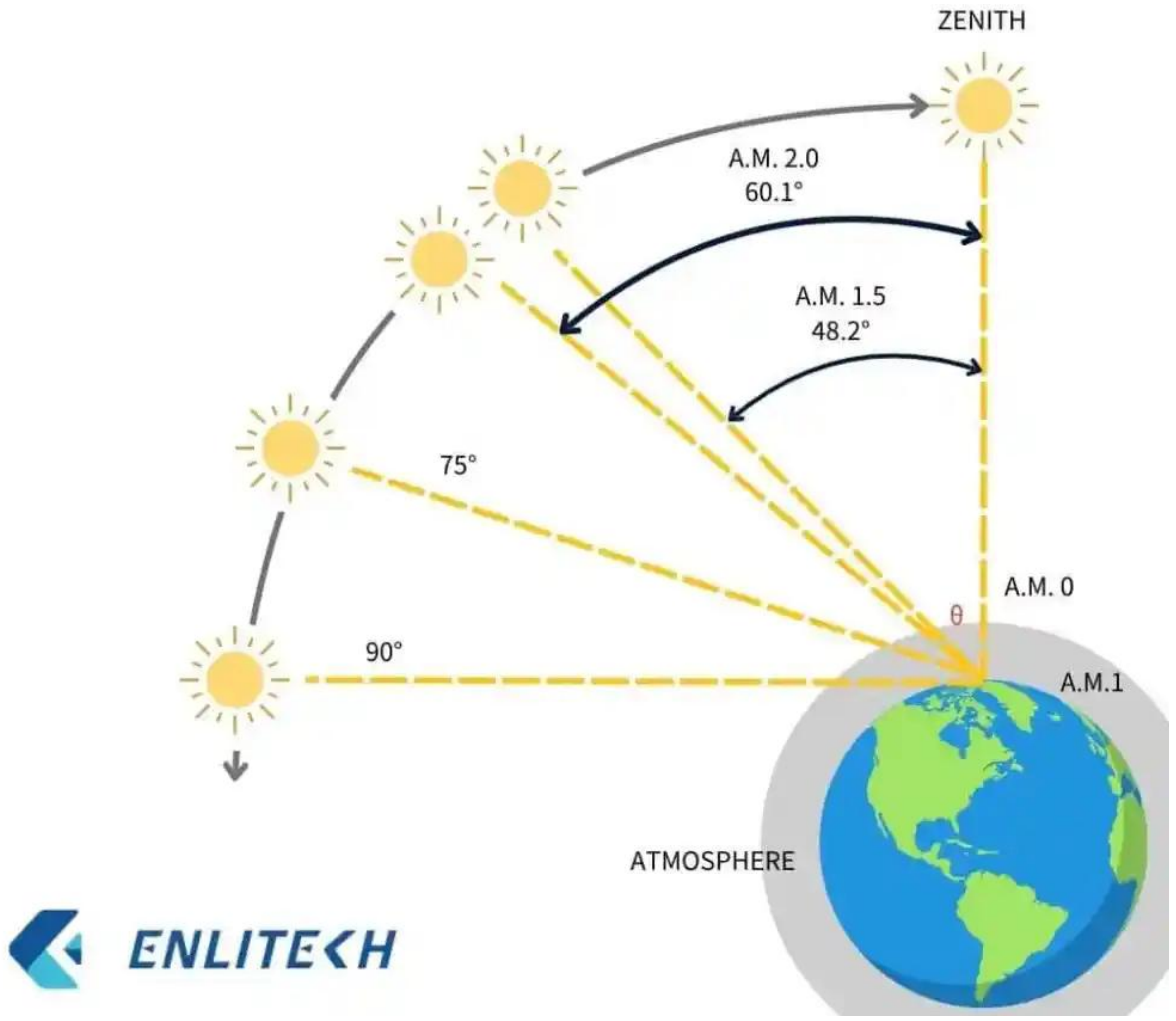
Spectral content of sunlight



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

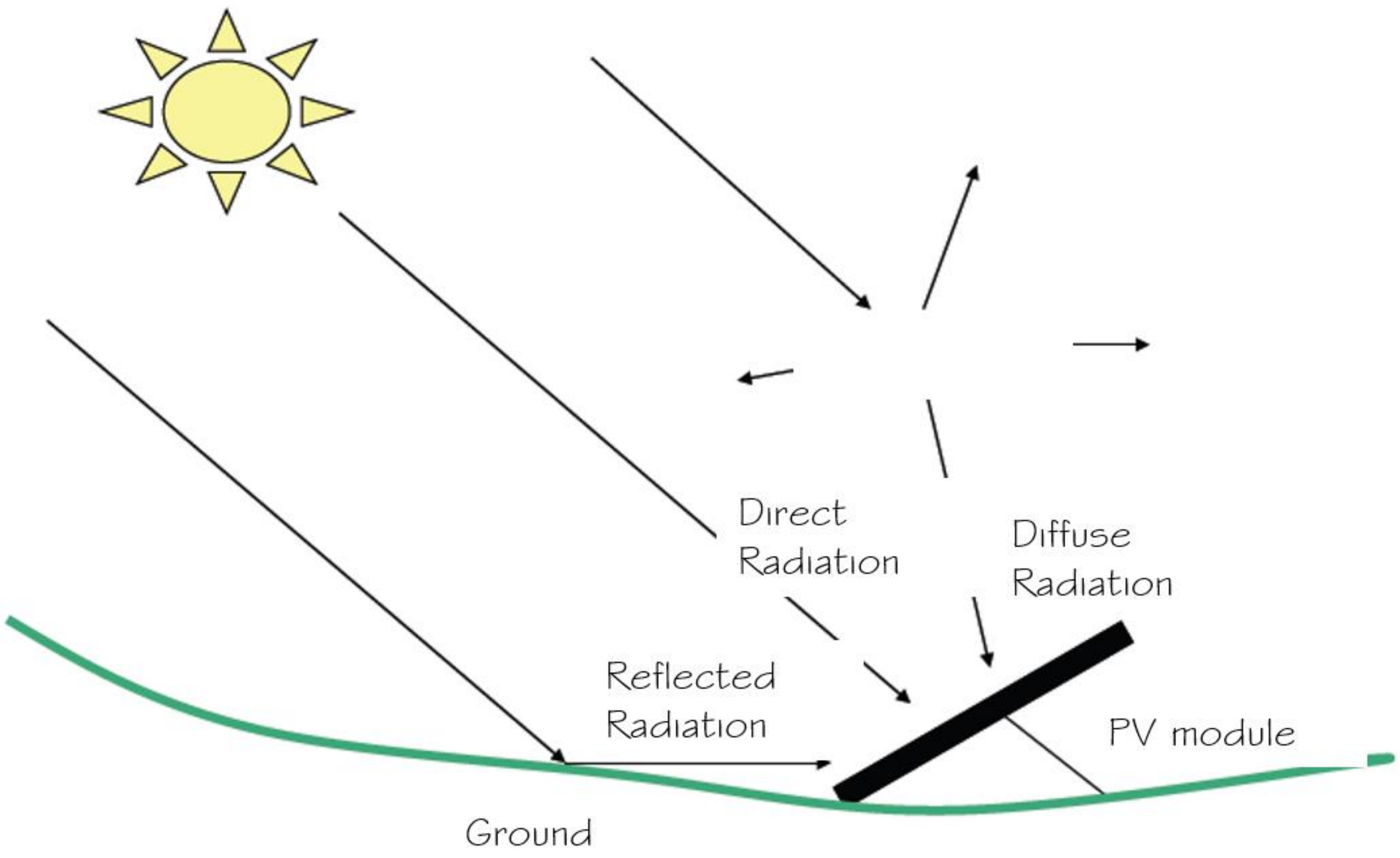
Air Mass





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

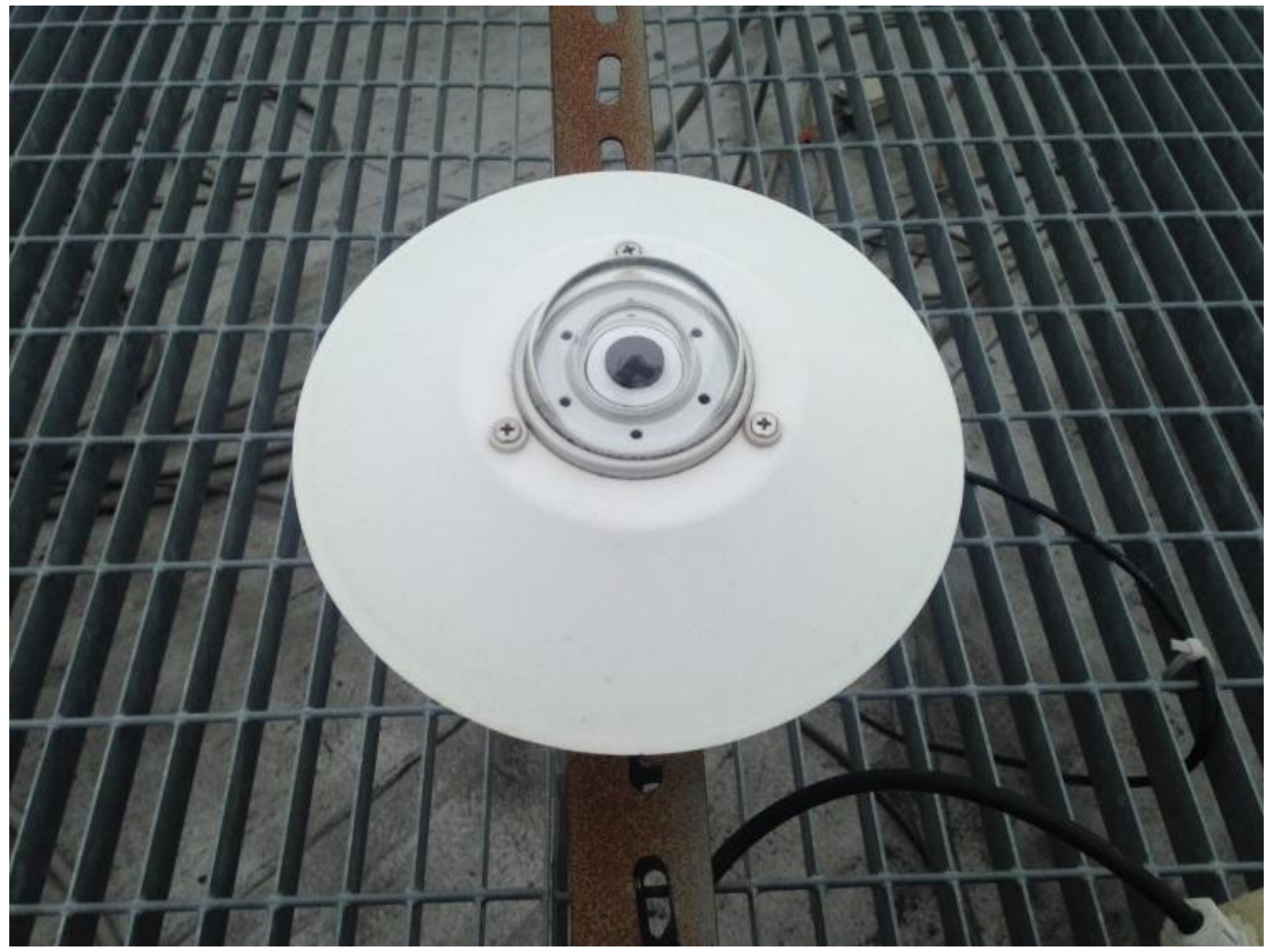
Solar radiation components



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

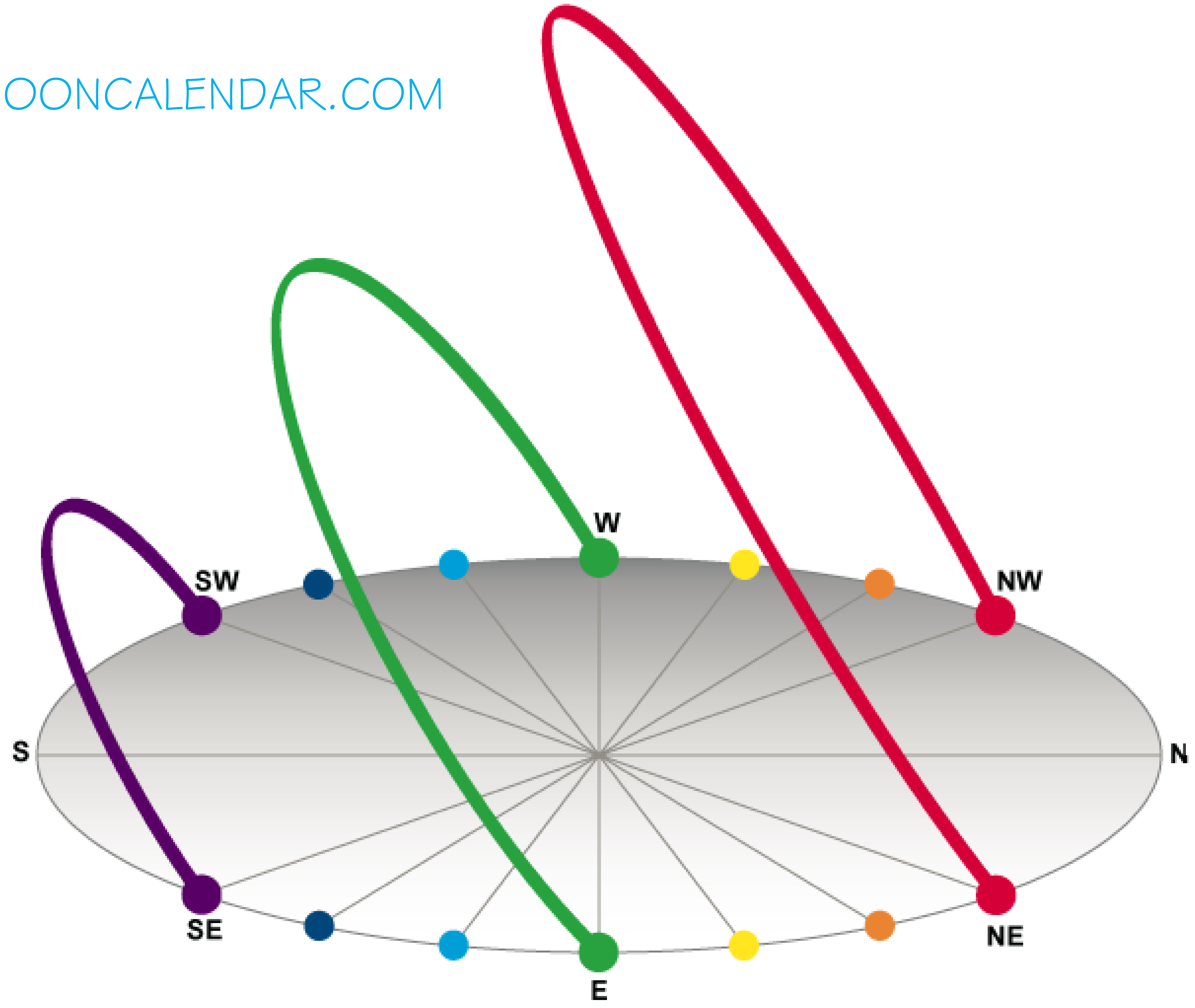
$$\omega = 15 \times (12 - t_s)$$

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

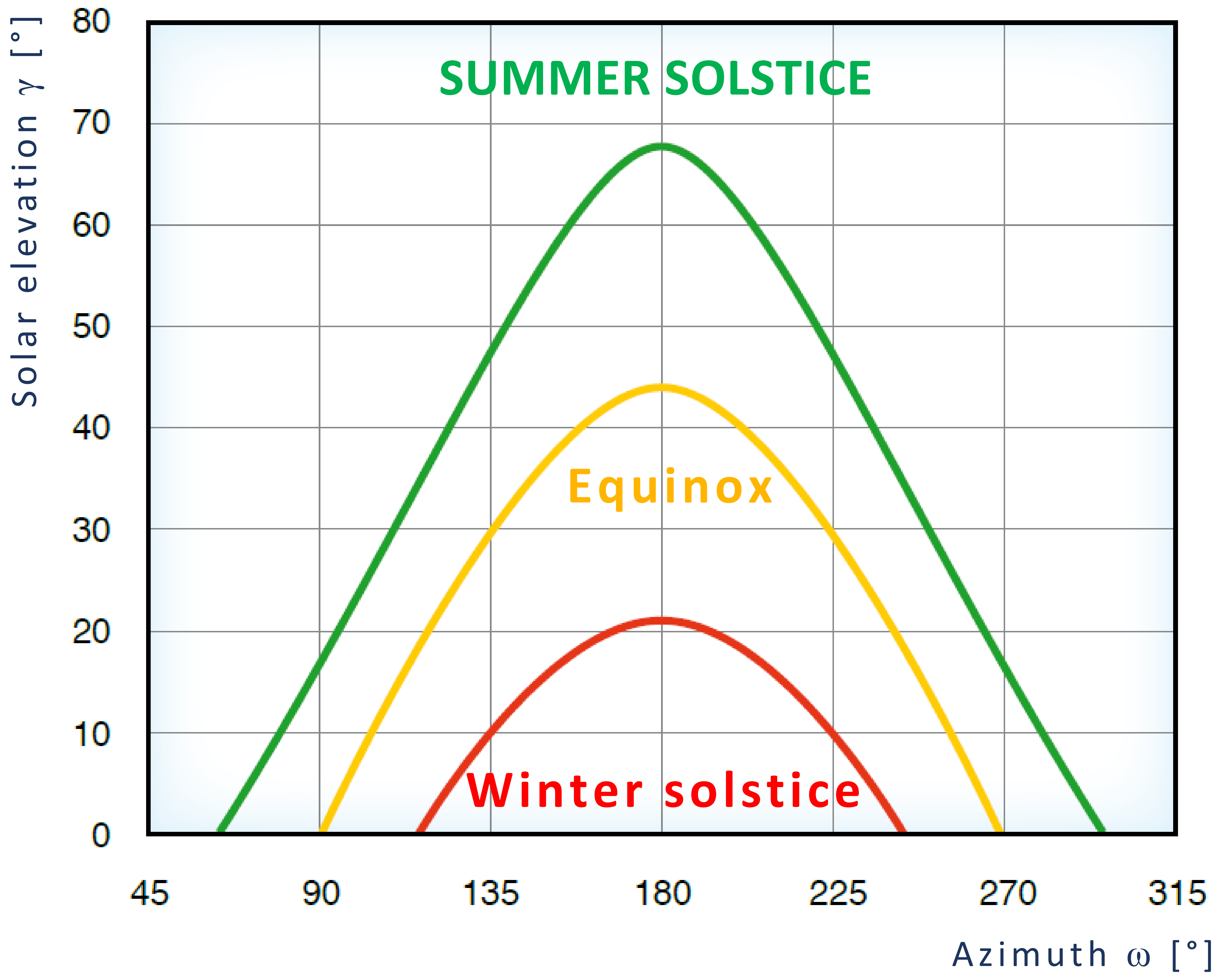
$$\delta = 23,45 \sin\left(360 \times \frac{284 + n}{365}\right)$$

Trajectories of the sun

SUNMOONCALENDAR.COM



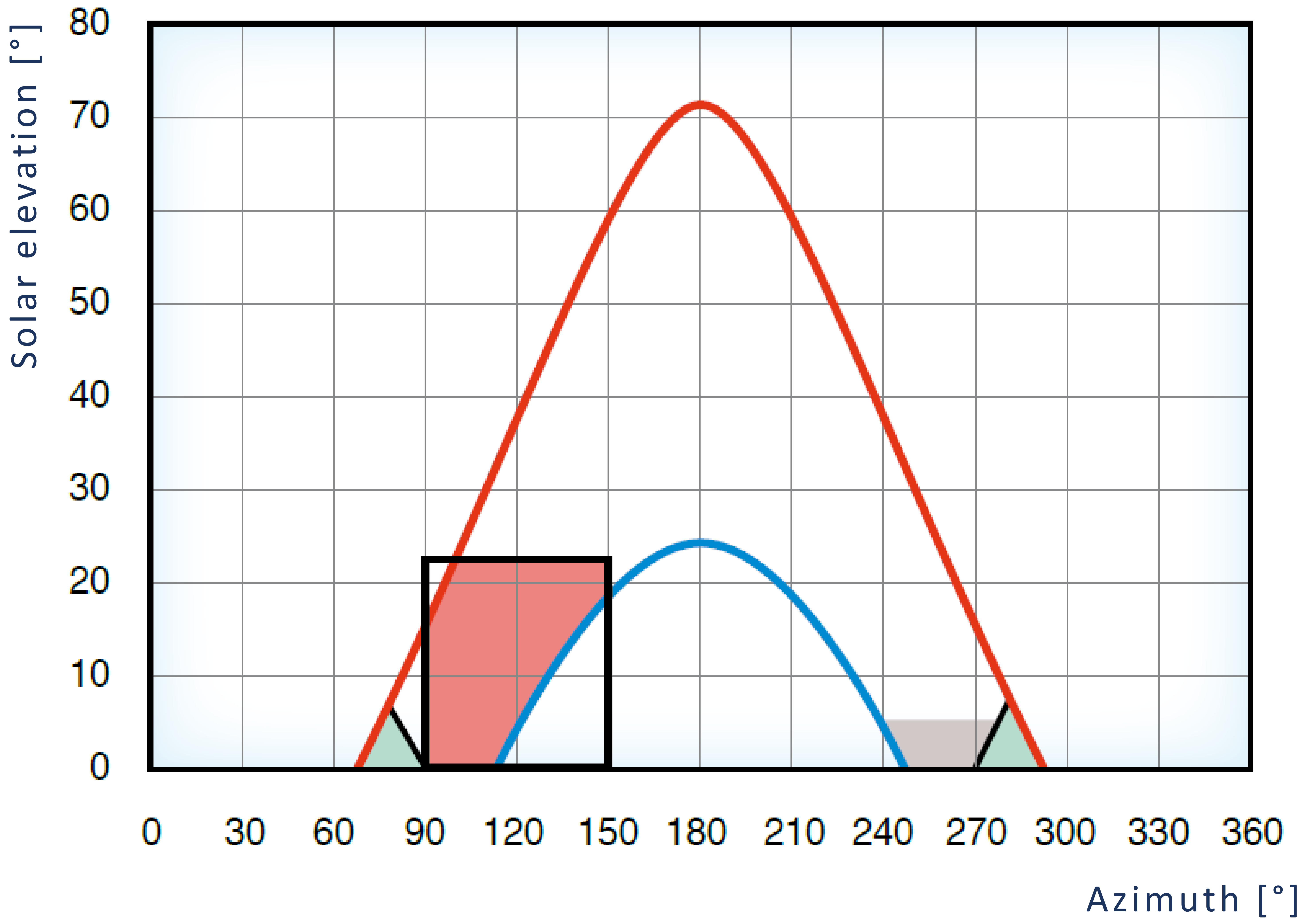
https://www.earthspacelab.com/app/solar-time/



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

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

Shading – Clinometric profile

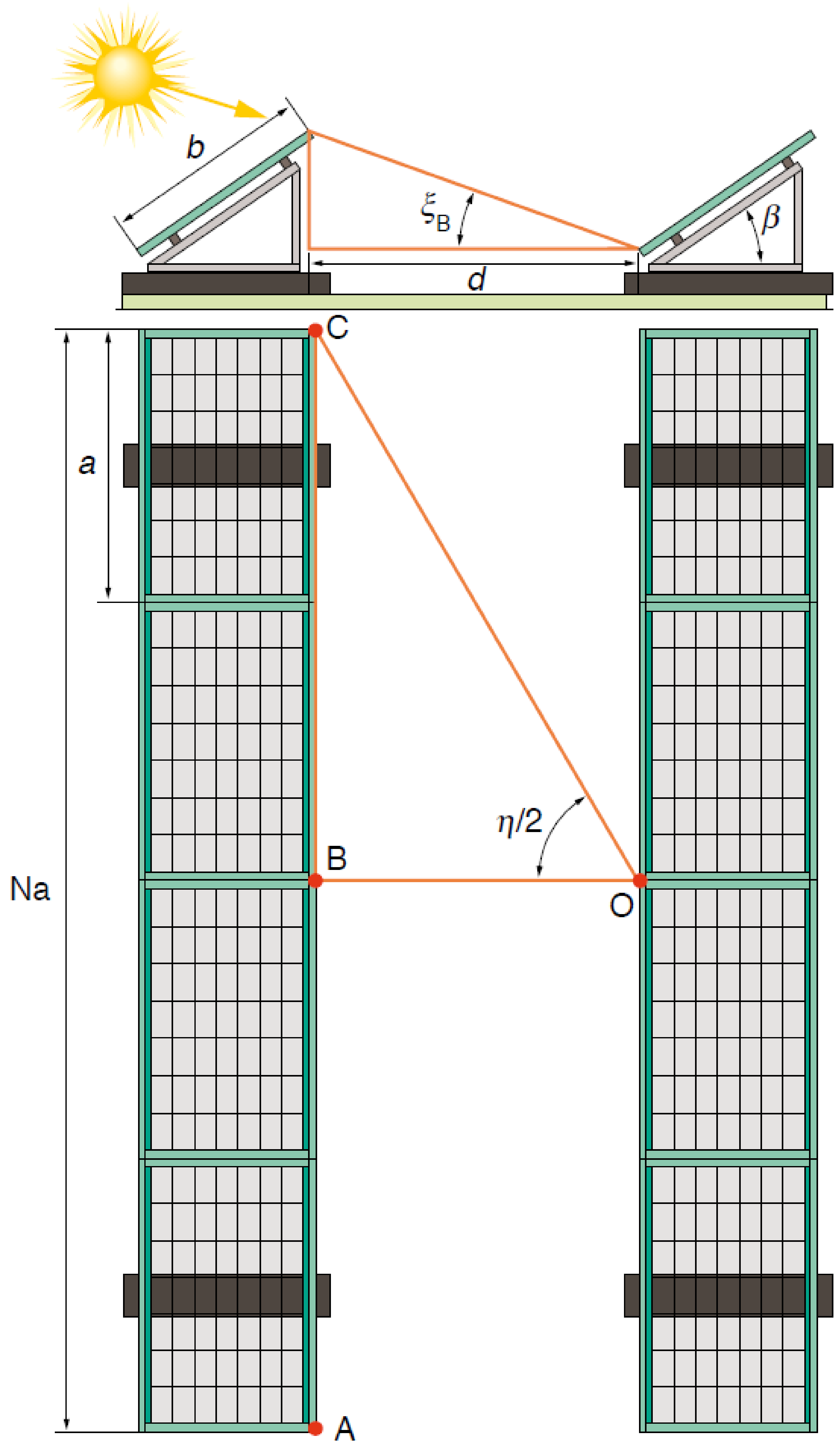


Parallel rows

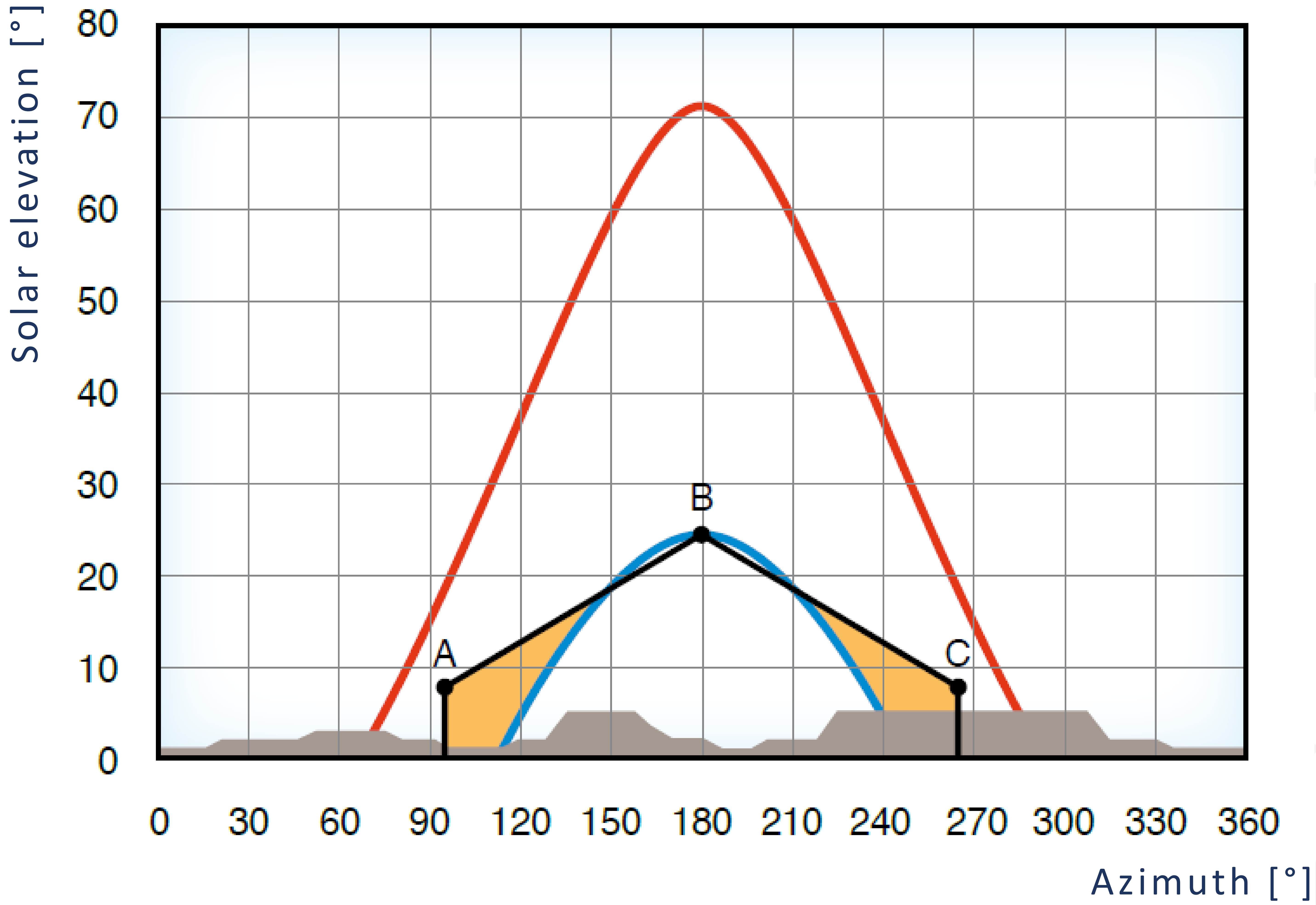
$$\xi_B < \gamma_{21dic,12:00}$$

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

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



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

Switch to version 5.1

csv | json

Sfoglia... Nessun file selezionato.

PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM

European Commission

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

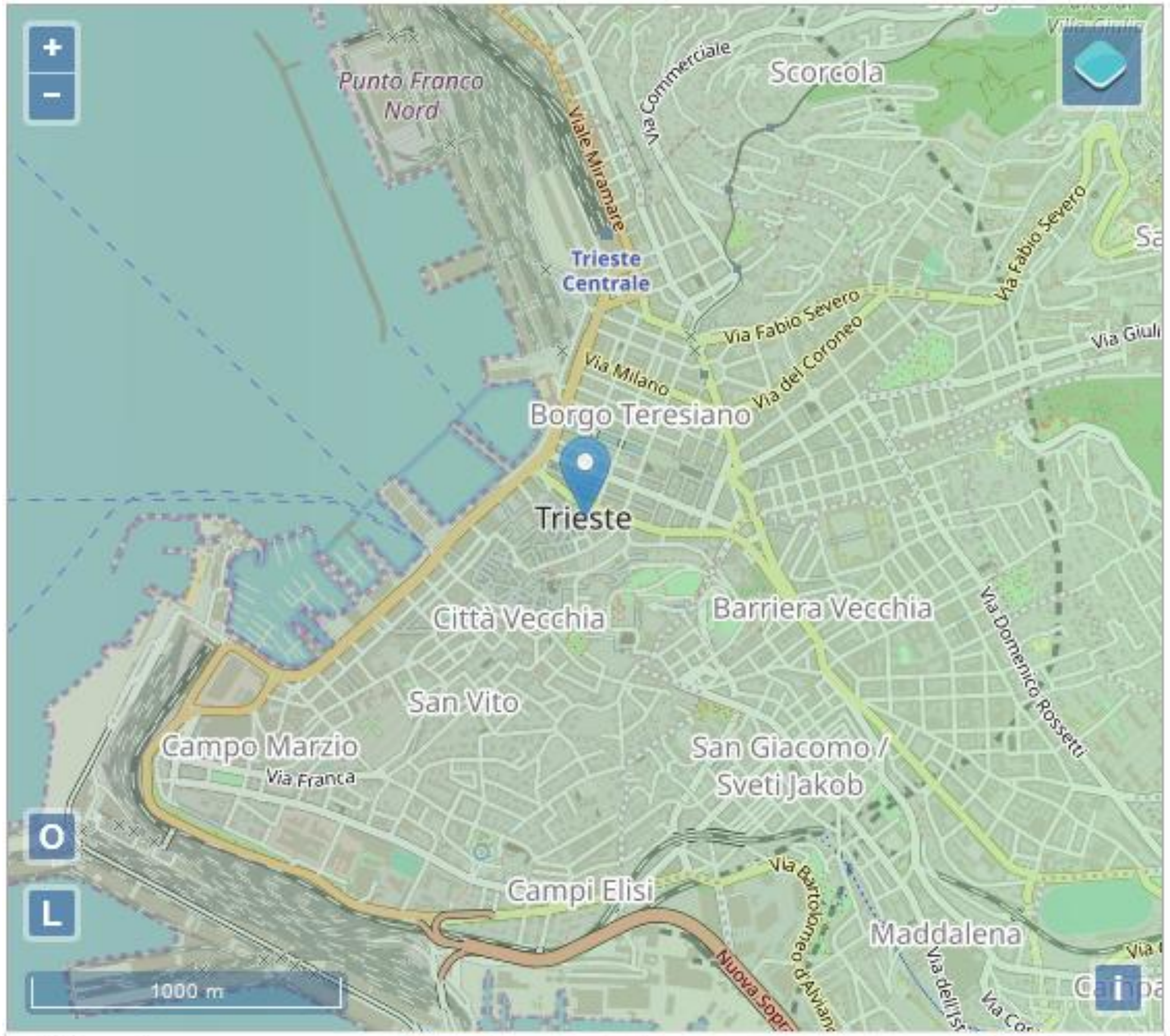
Azimuth [°]: 0

On sun-tracking plane:

- [ ] Irradiance
- [ ] Clear-sky irradiance

Temperature:

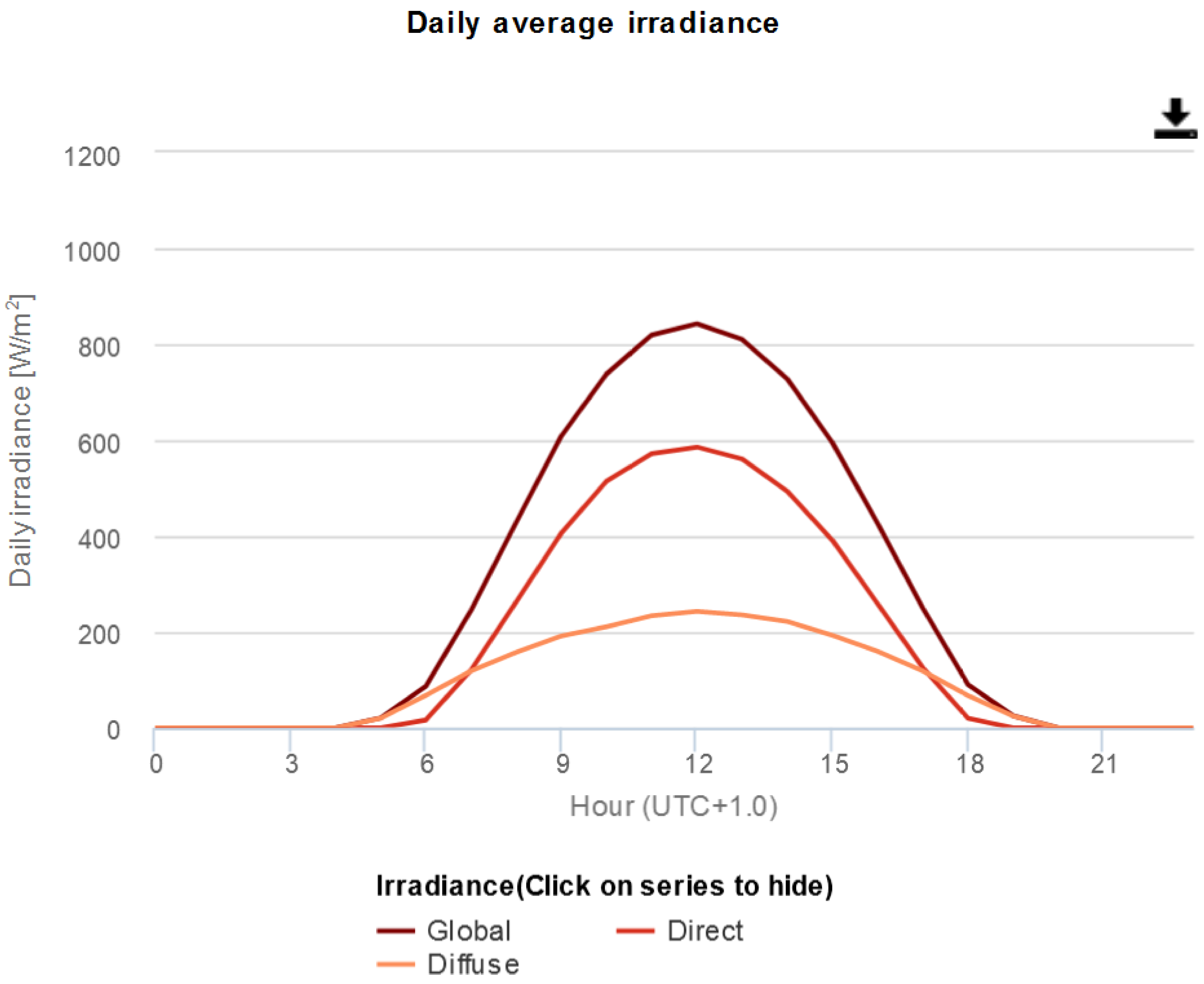
- [x] Daily temperature profile



Address: Eg.Ispra, Italy Go!

Lat/Lon: Eg. 45.8 Eg. 8.61 Go!

Results



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

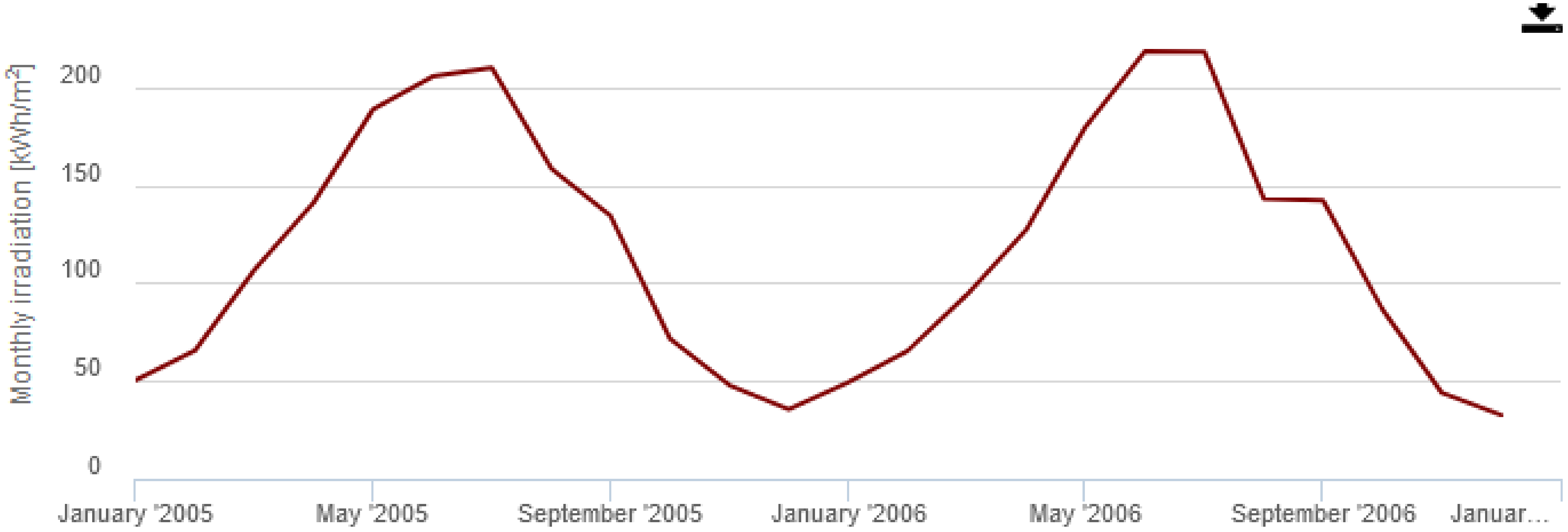
Results

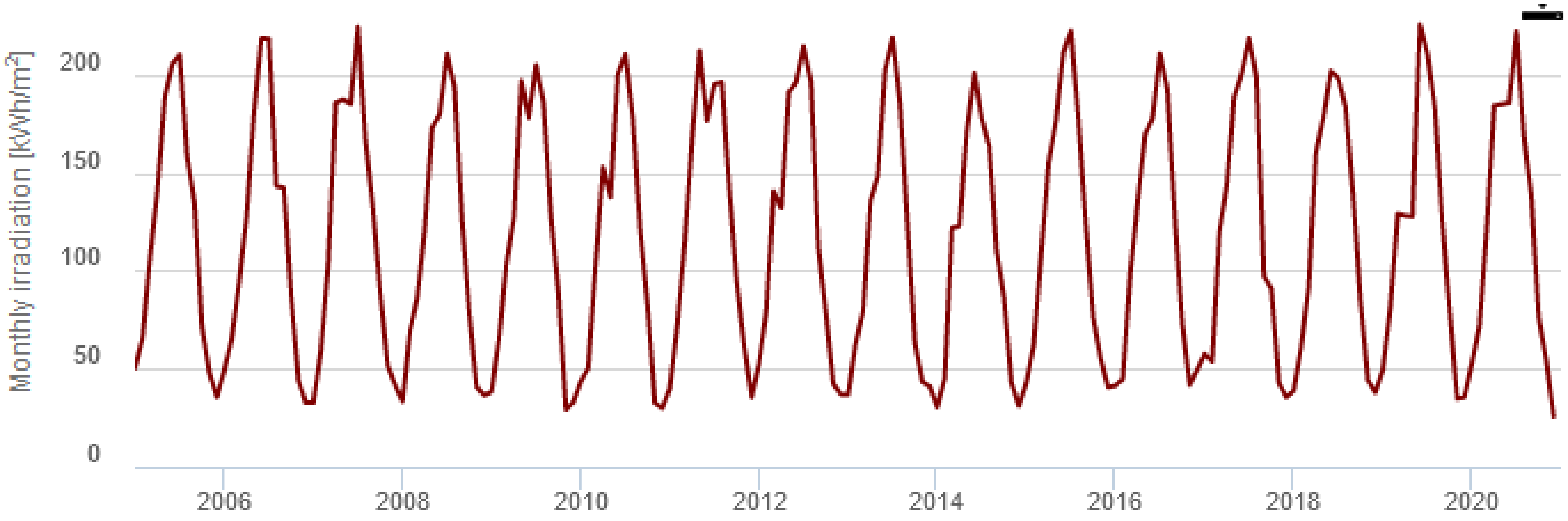
Irradiance on a fixed plane

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)
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

$$E_{in,0} \longrightarrow \boxed{1-\varepsilon_{si}} \xrightarrow{E_{in}} \boxed{\eta_{mod,STC}} \xrightarrow{E_{cc,th}} \boxed{PR} \xrightarrow{E_{out}}$$

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

- 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

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

- 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

$$\varepsilon_{gen} = \varepsilon_T + \varepsilon_{mis}$$

$$\varepsilon_T = p \times (T_{CG} - 25)$$

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

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

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

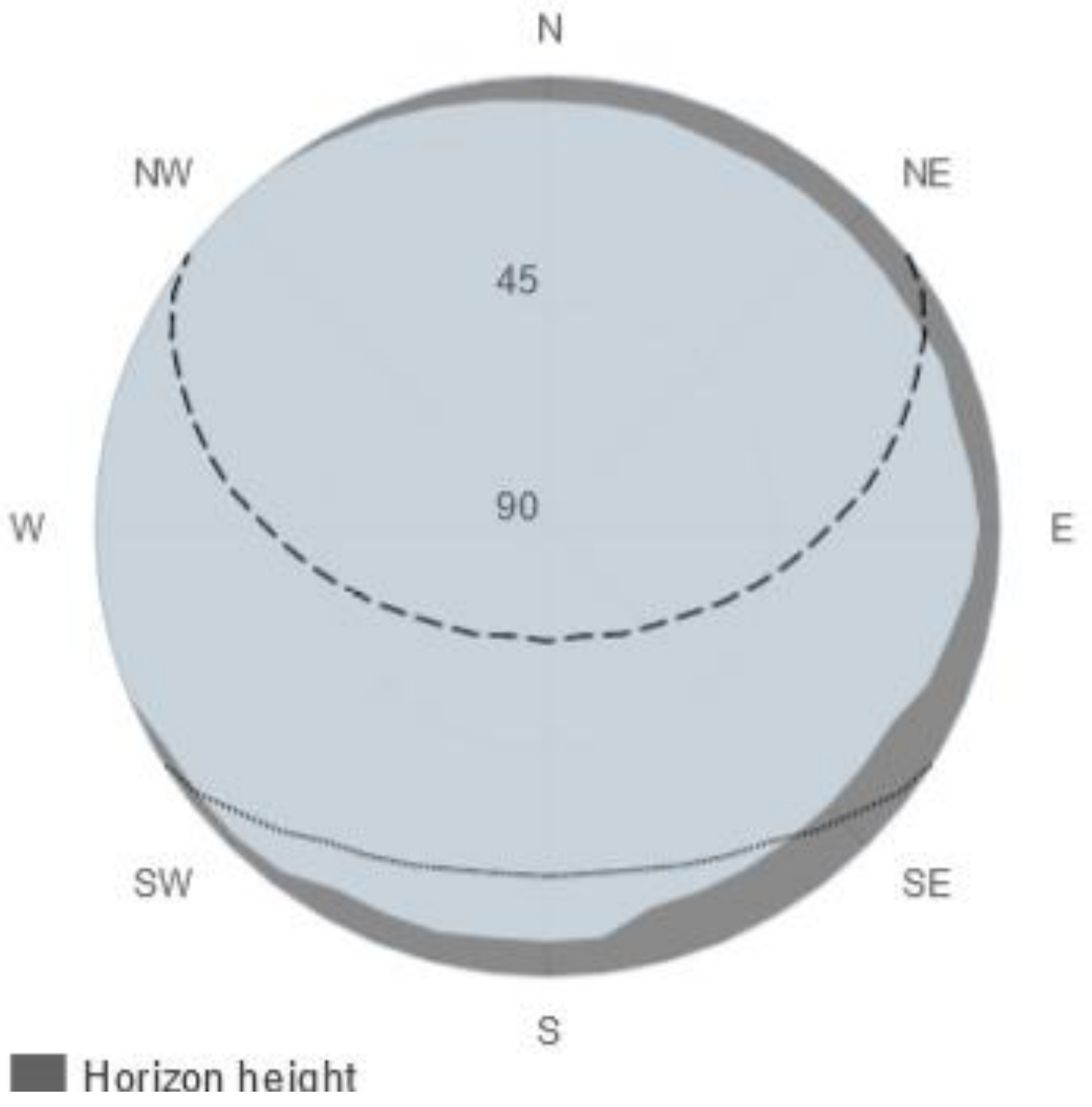
Yield in Trieste

PERFORMANCE OF GRID-CONNECTED PV

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

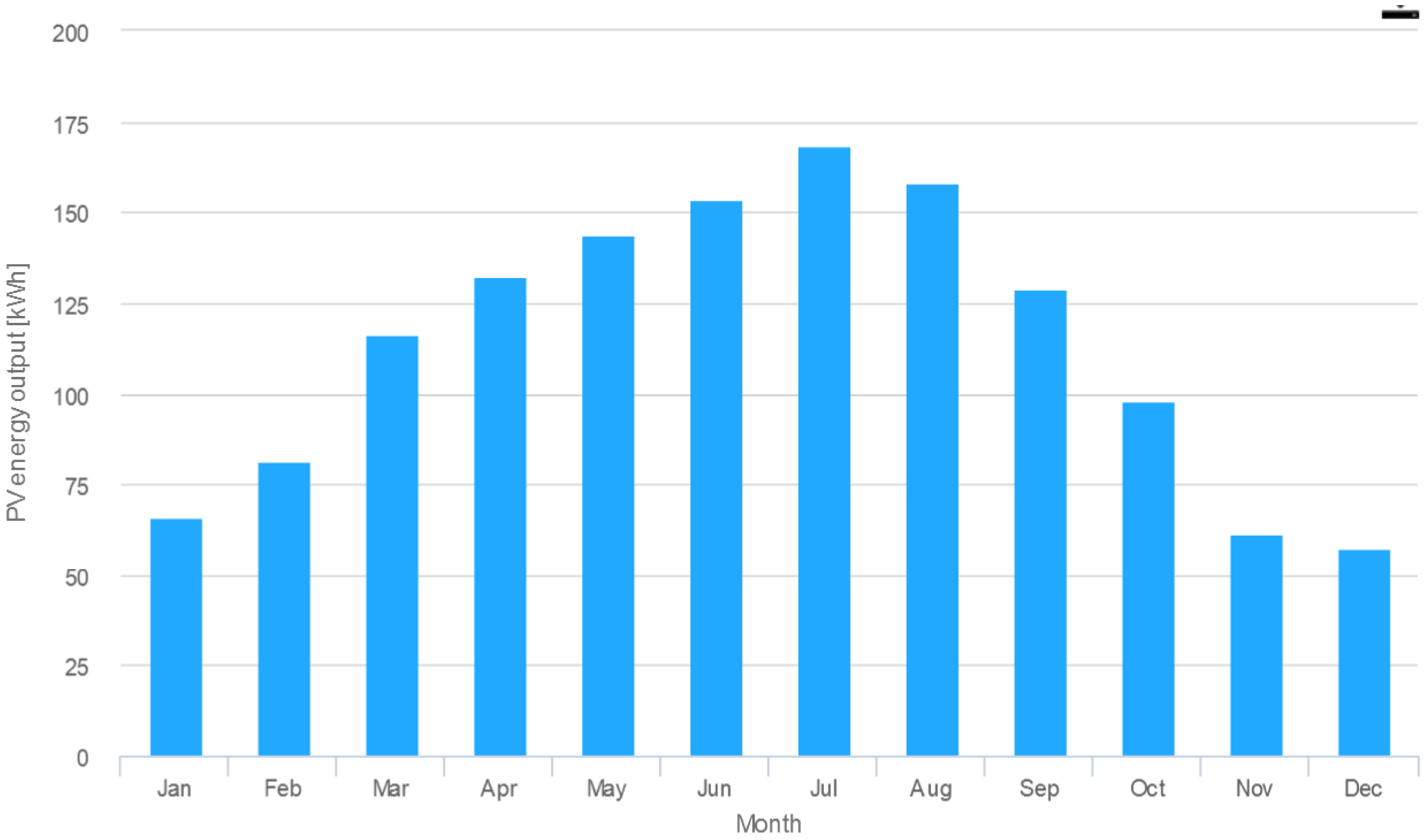
Fixed mounting options

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



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

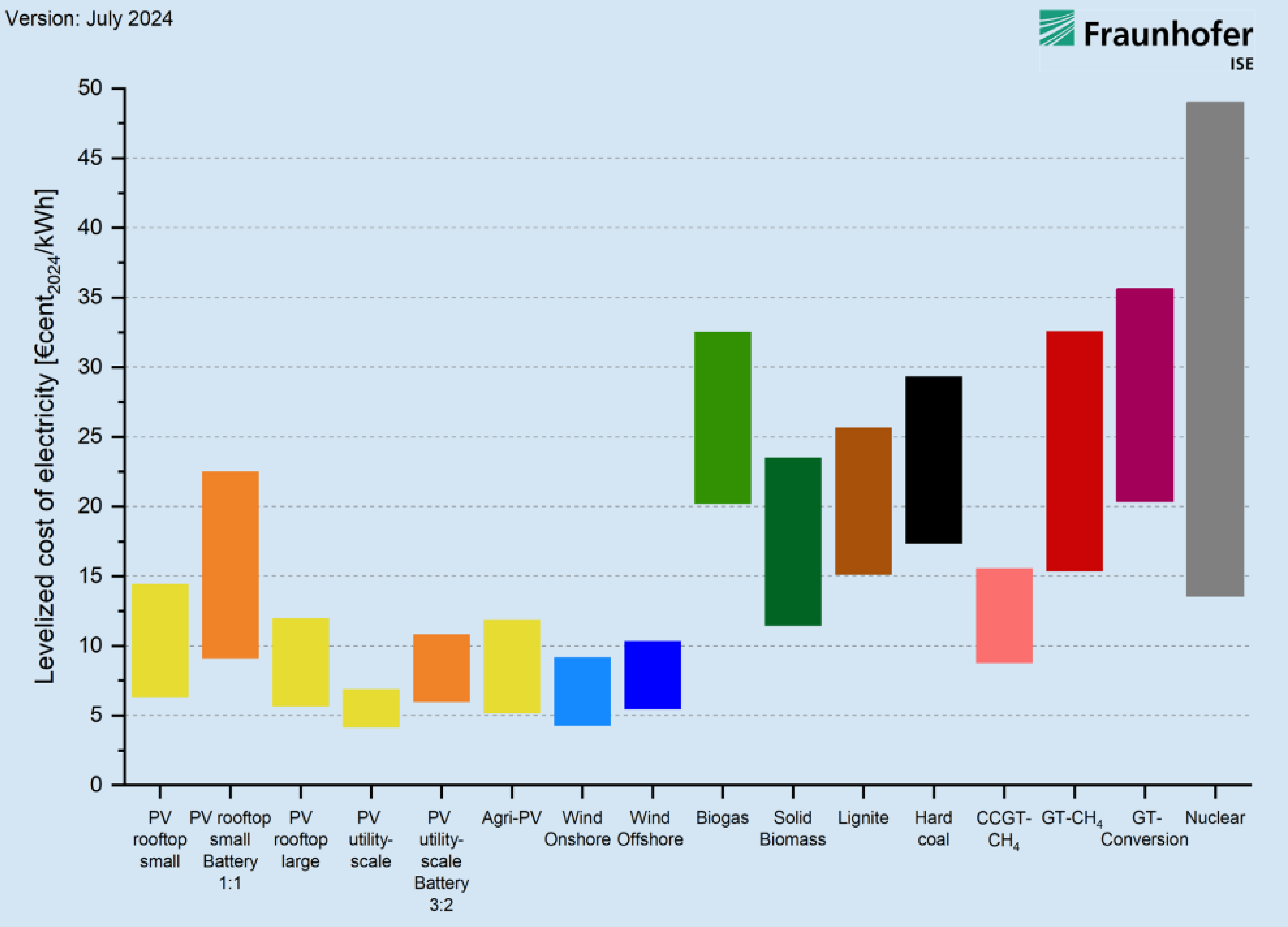
$$LCOE = \frac{OCS \times CRF \times (1 + FO\&MC)}{\frac{E_0}{N} \times \sum_{k=1}^{N} \left(1 - \frac{d_r \times (k-1)}{100}\right)}$$

- 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

Net Present Value

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

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

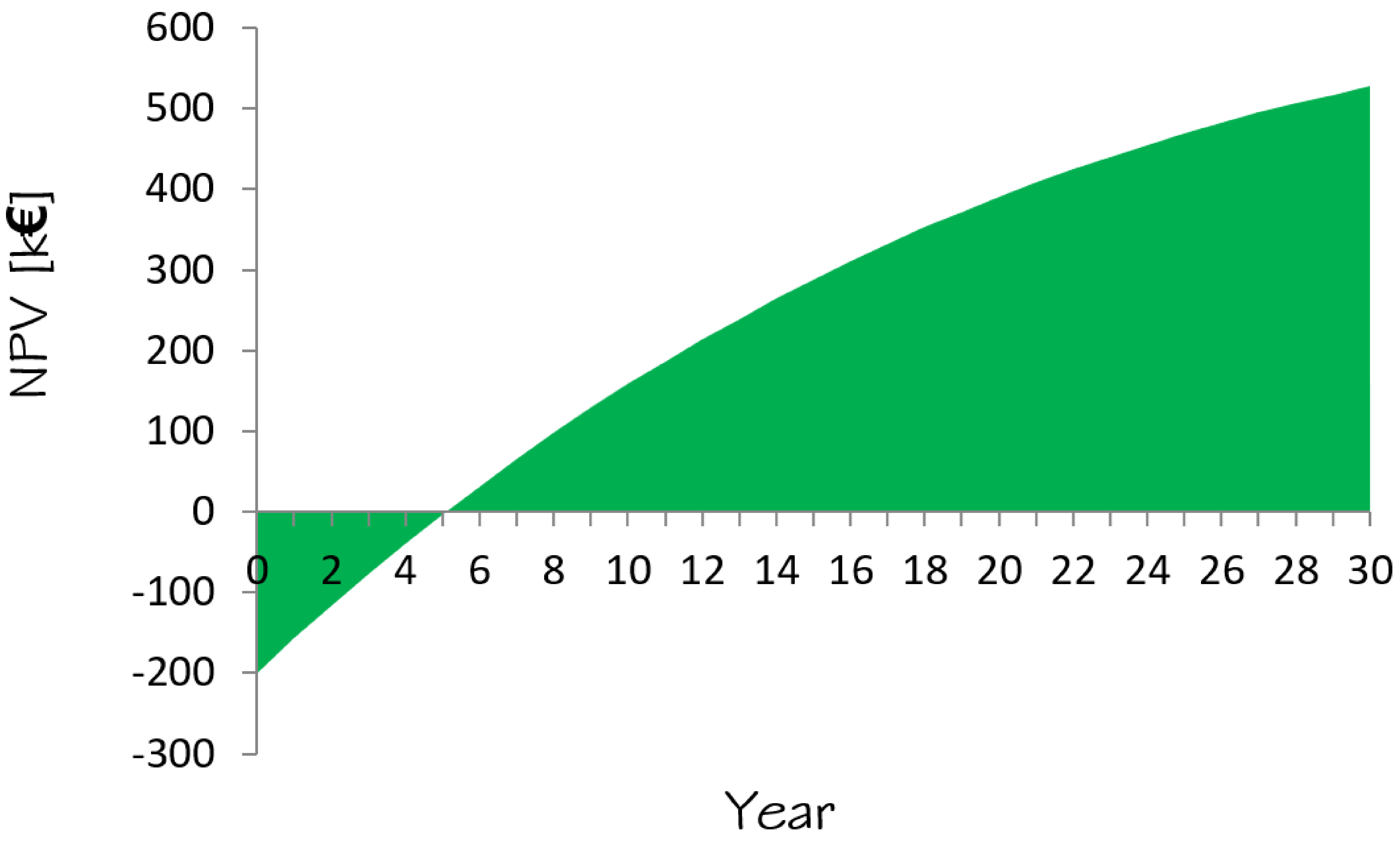
- The **payback time (PBT)** is the time corresponding to a net present value equal to zero
- The **internal rate of return (IRR)** is calculated as:

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

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%

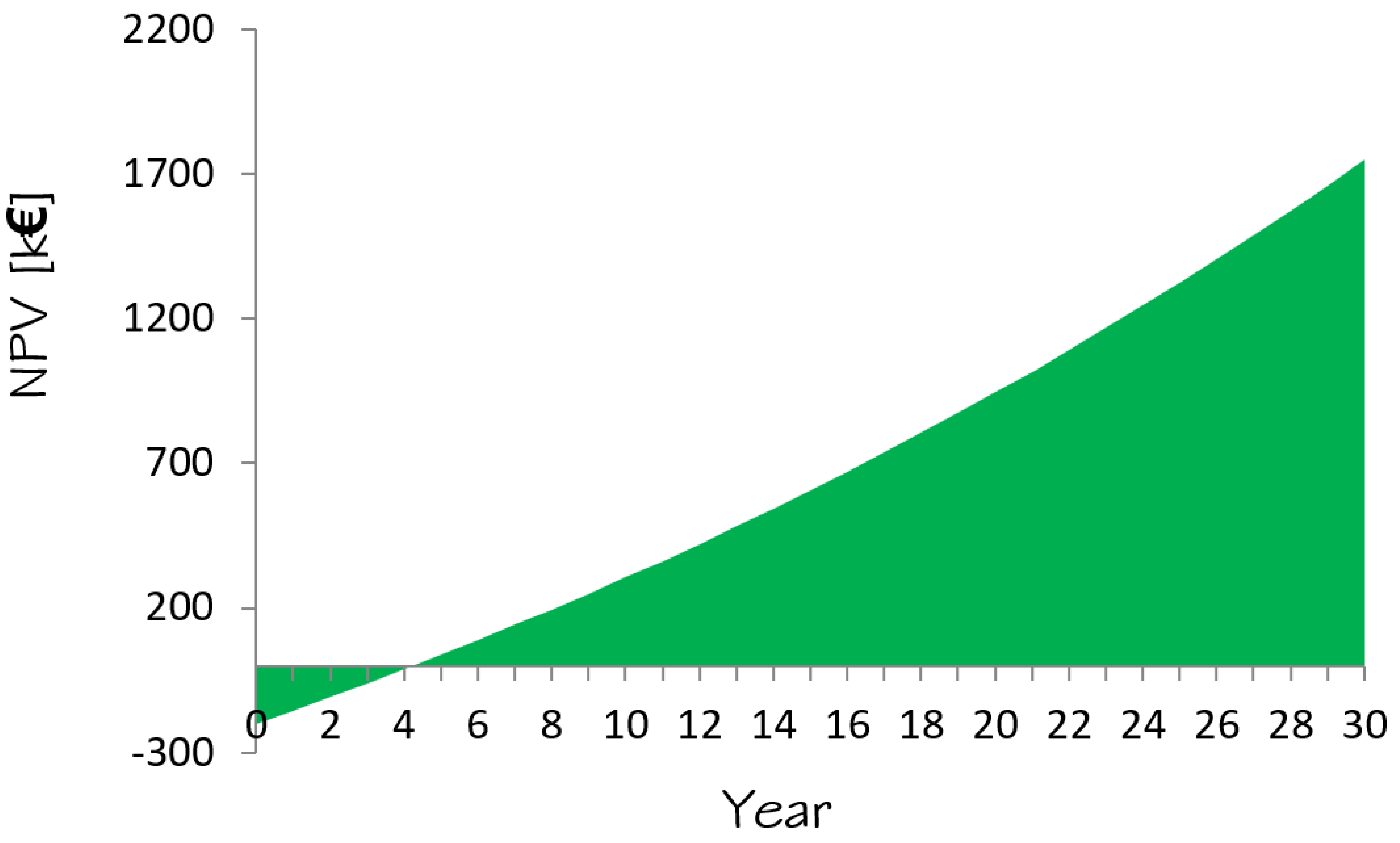
LCOE	6.62 €/kWh
PBT	5 years
IRR	12%



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%

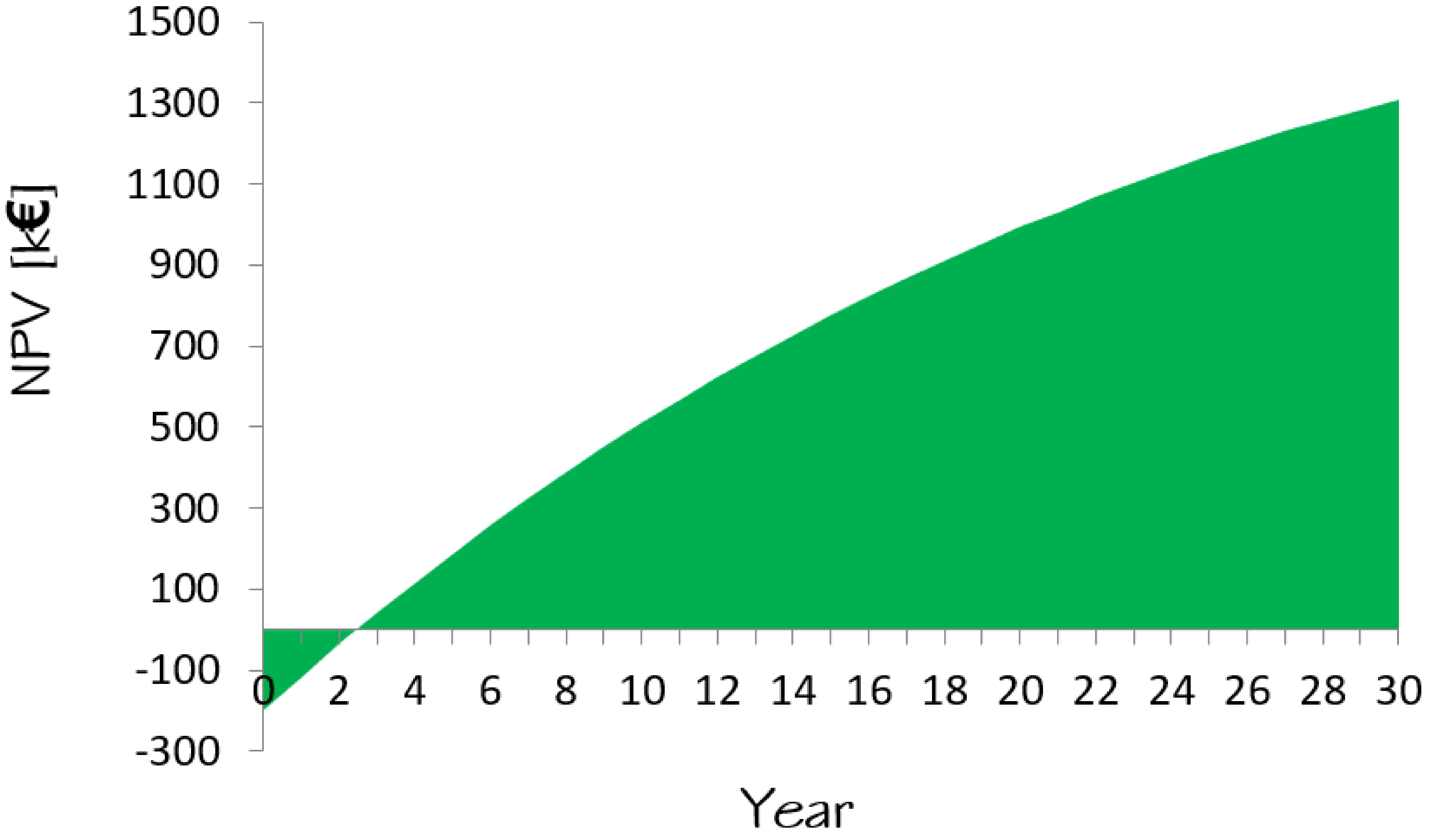
LCOE	3.33 €/kWh
PBT	4.2 years
IRR	33%



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%**

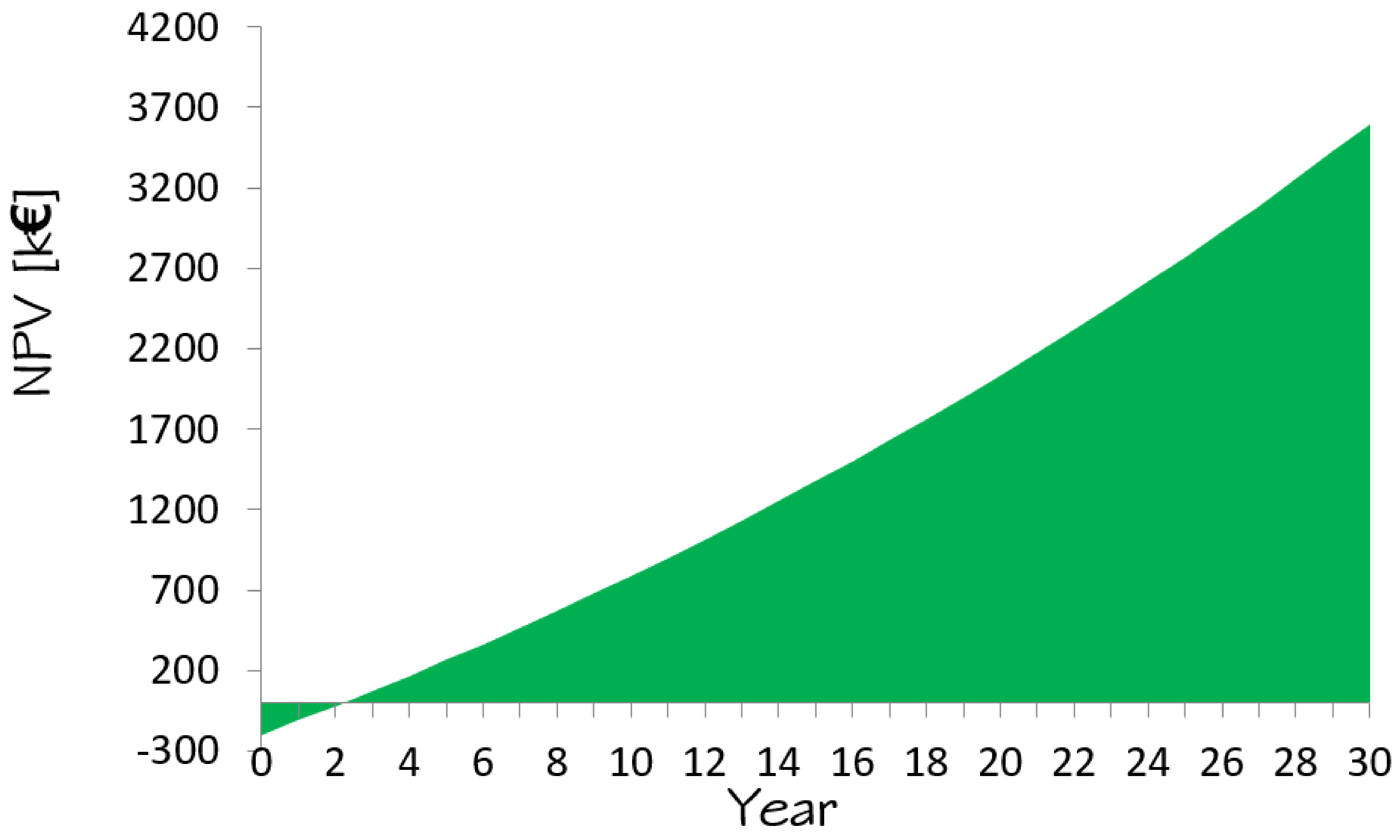


C&I – Equity only – Self-consumption 100%

Average electricity price

LCOE	3.33 €/kWh
PBT	2.2 years
IRR	63%

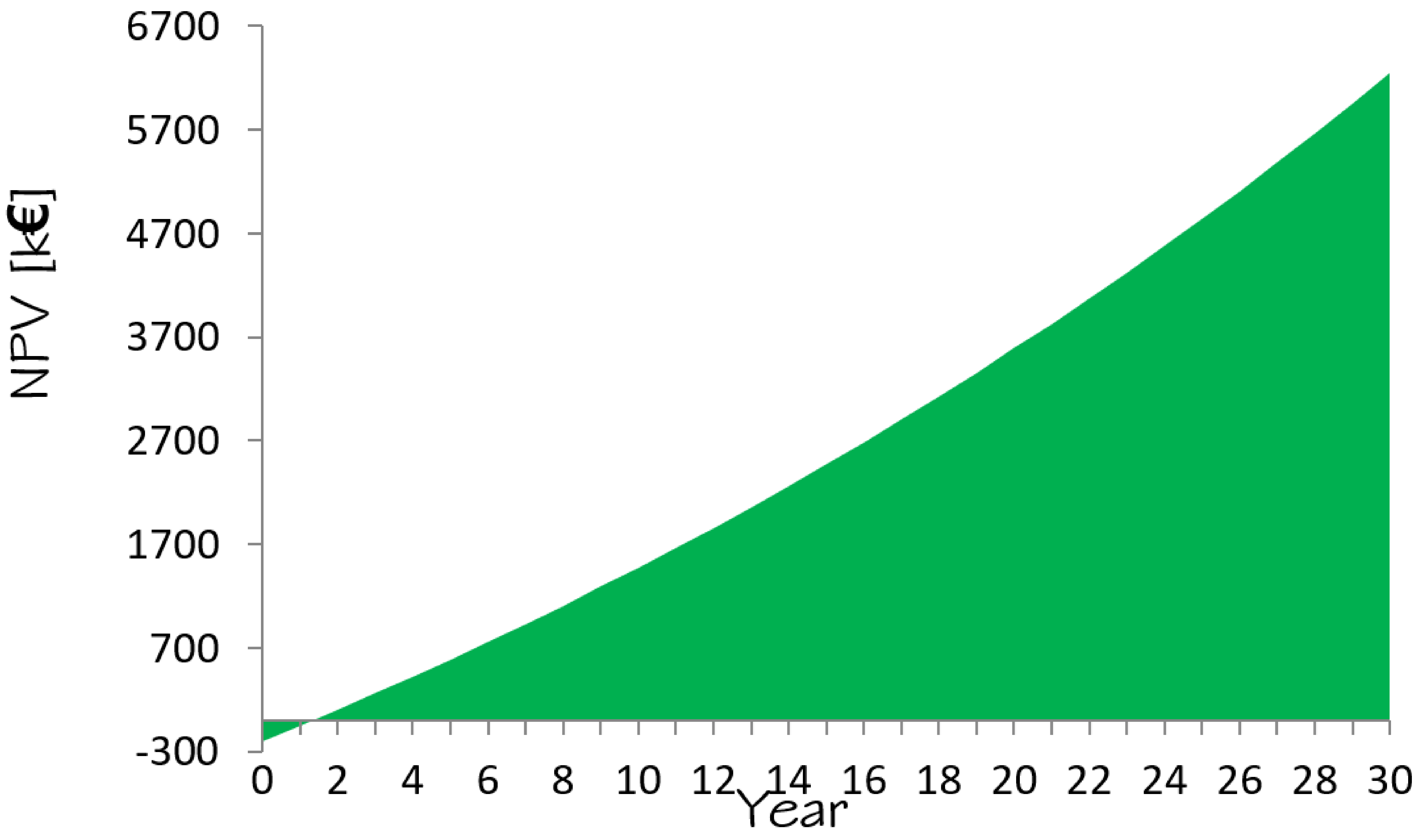
Power	200 kWp
OCS	1,000 €/kWp
FO&Mc	2%
N	30
g	2%
e	3%
Ke	2%
E	100%
Kd	/
D	/
EP	300 €/MWh
FiT	47 €/MWh
Sc	100%
E0	1,500
dr	0.6%



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%**