UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dipartimento di Ingegneria e Architettura

Impianti fotovoltaici

Elettrotecnica

A.A. 2024 - 2025

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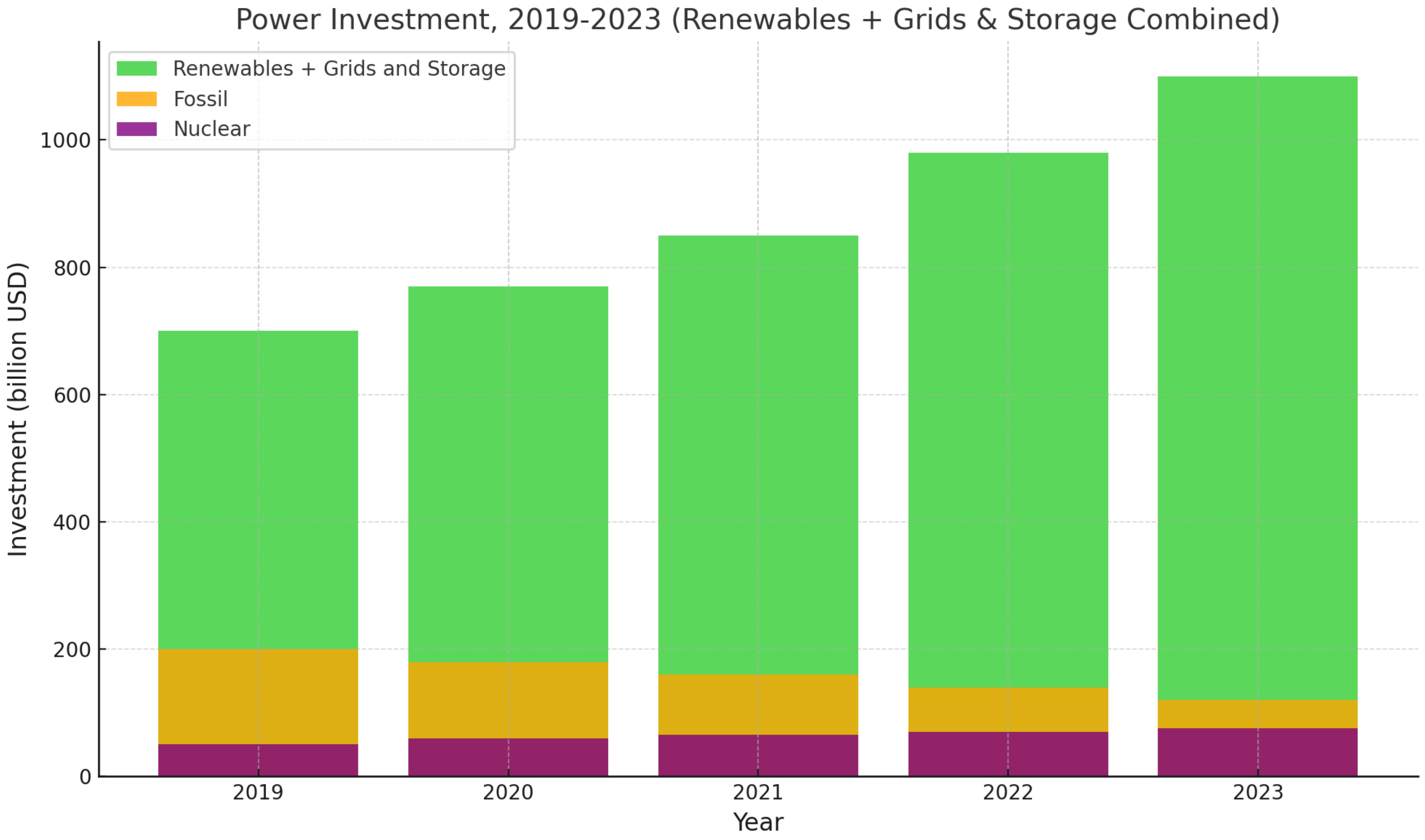
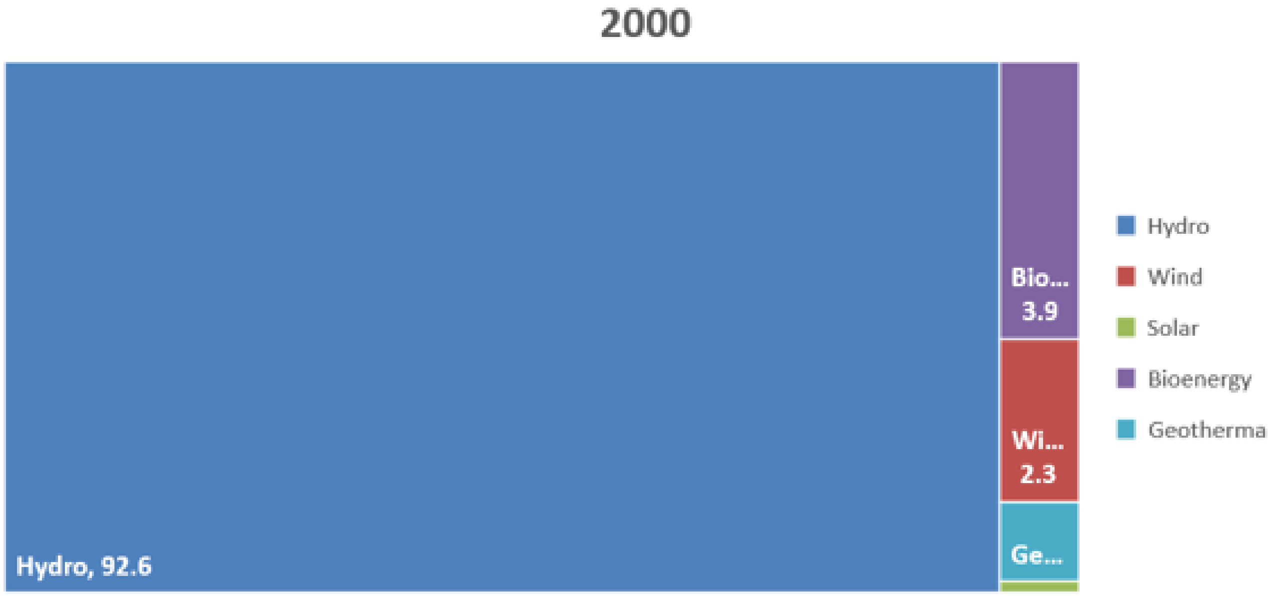
GLOBAL POWER INVESTMENTS

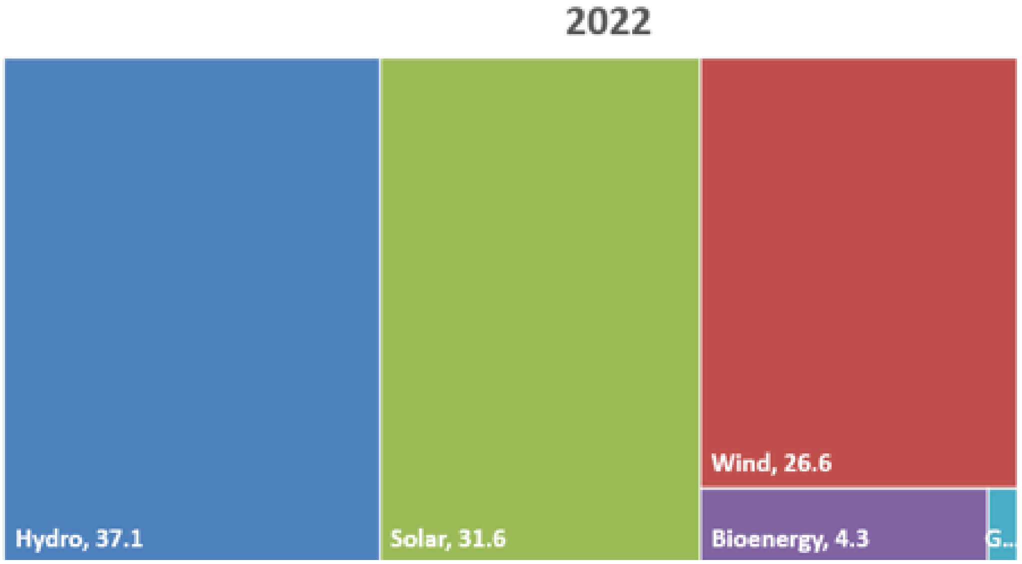


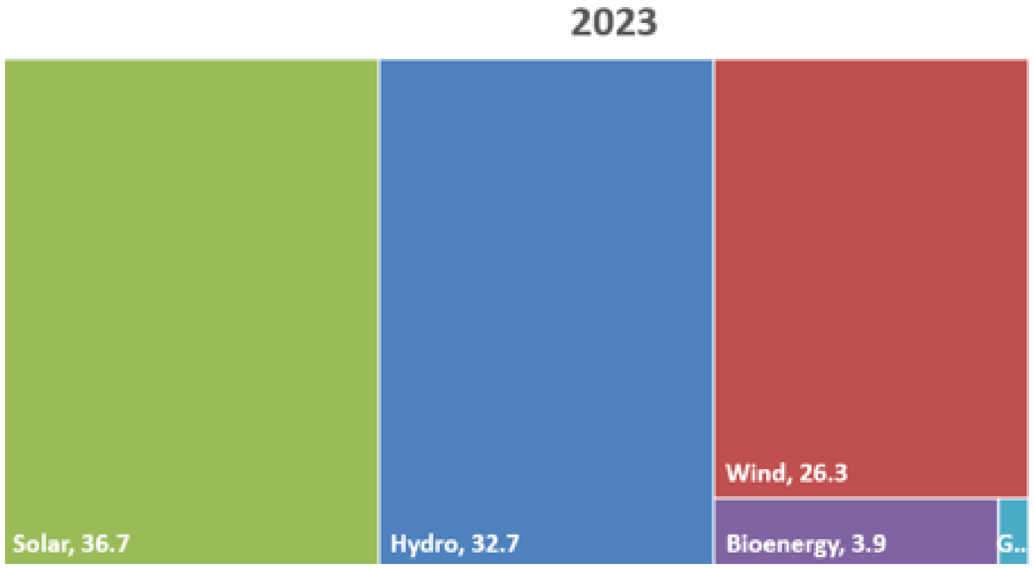
THE ROLE OF PHOTOVOLTAICS

TECHNOLOGY	2022 [GW]	2021 [GW]	Variation [%]
Photovoltaics	1055	866	21.8
Wind	899	826	8.8
Biomass, solid biofuels and waste	277	262	5.7
Gas	1895	1853	2.3
Hydropower	1392	1360	2.4
Coal	2142	2139	0.1
Nuclear	371	390	-4.9

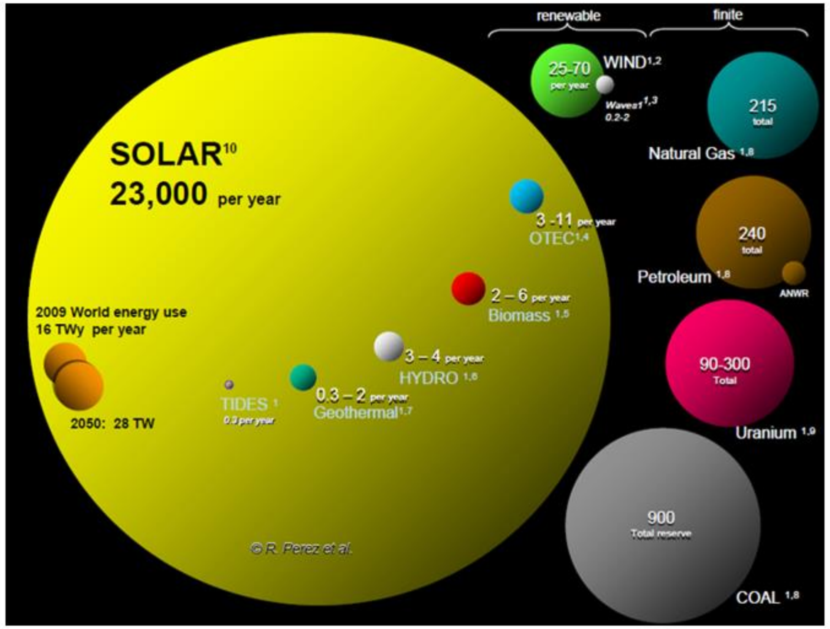
THE ROLE OF PHOTOVOLTAICS







Why photovoltaics?

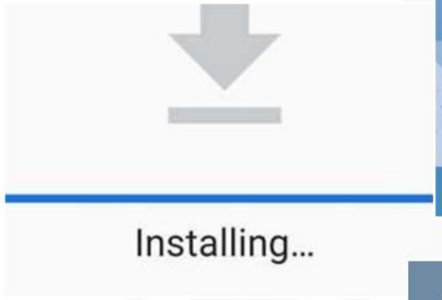


Fuel source is vast and essentially infinite

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

Low costs

Why photovoltaics?



Reliable and durable

Easy and quick installation

Why photovoltaics?

Modular technology

No moving parts, no noise (no emissions)

It isn’t true!

PV requires too much land to meet significant fraction of world needs

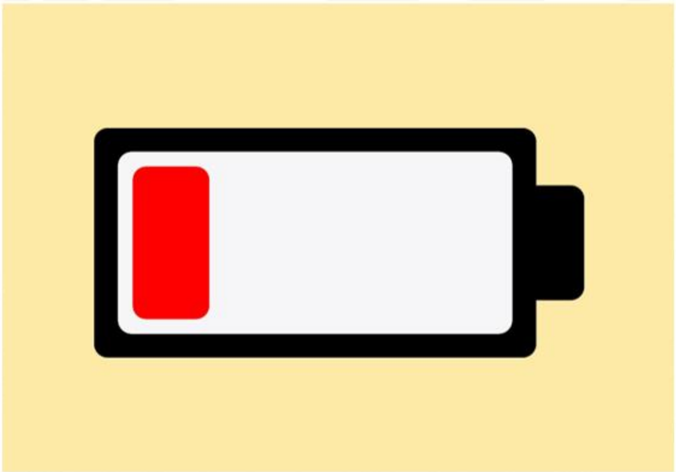
PV is polluting

PV efficiency is a problem

It isn't true!

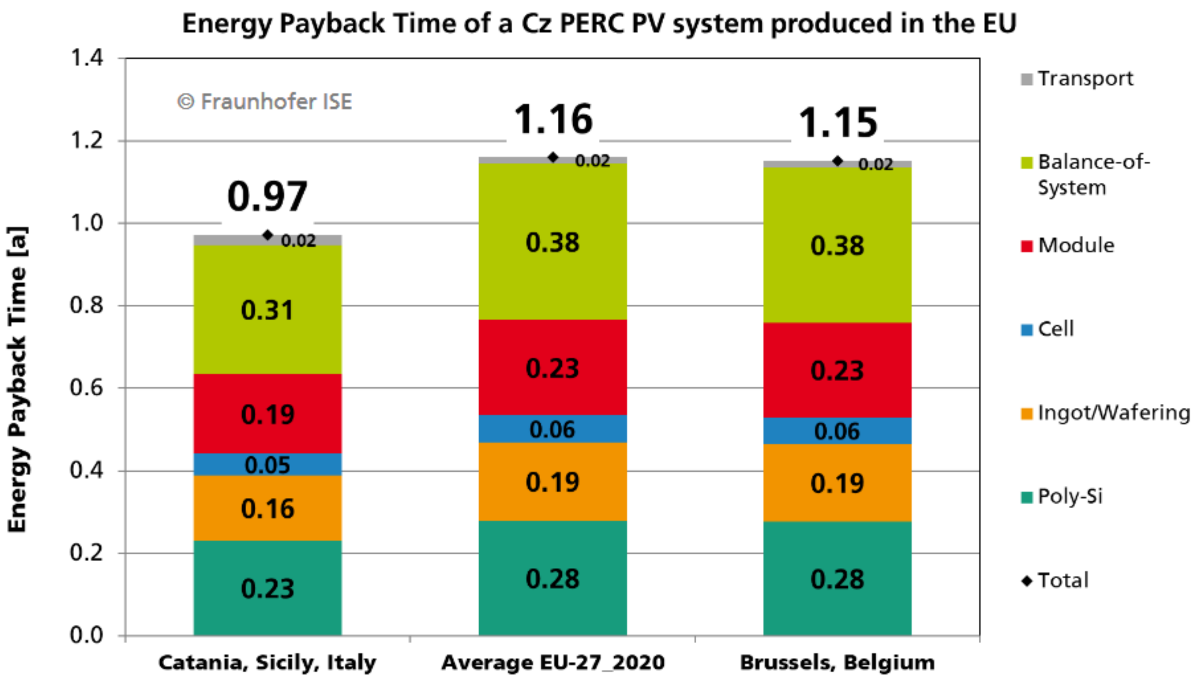
PV is a niche market

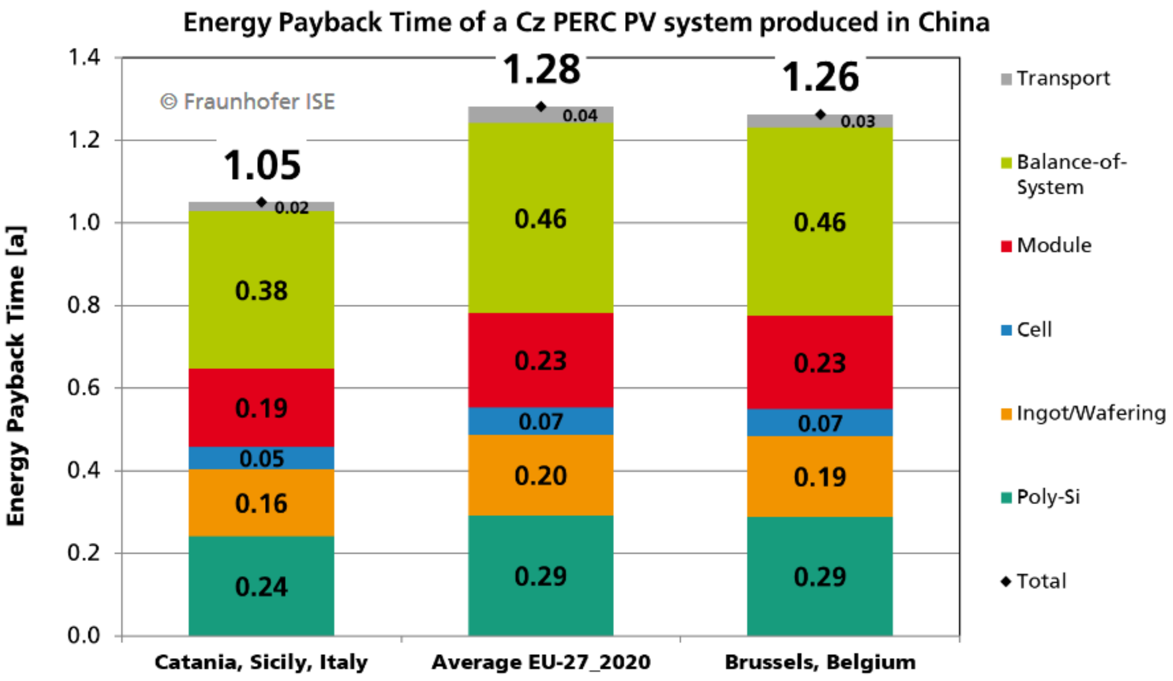
PV is too expensive



PV modules never recover the energy required to make them

PV modules energy payback time





AN «ANCIENT IDEA»

SCIENCE

FRIDAY, SEPTEMBER 27, 1912

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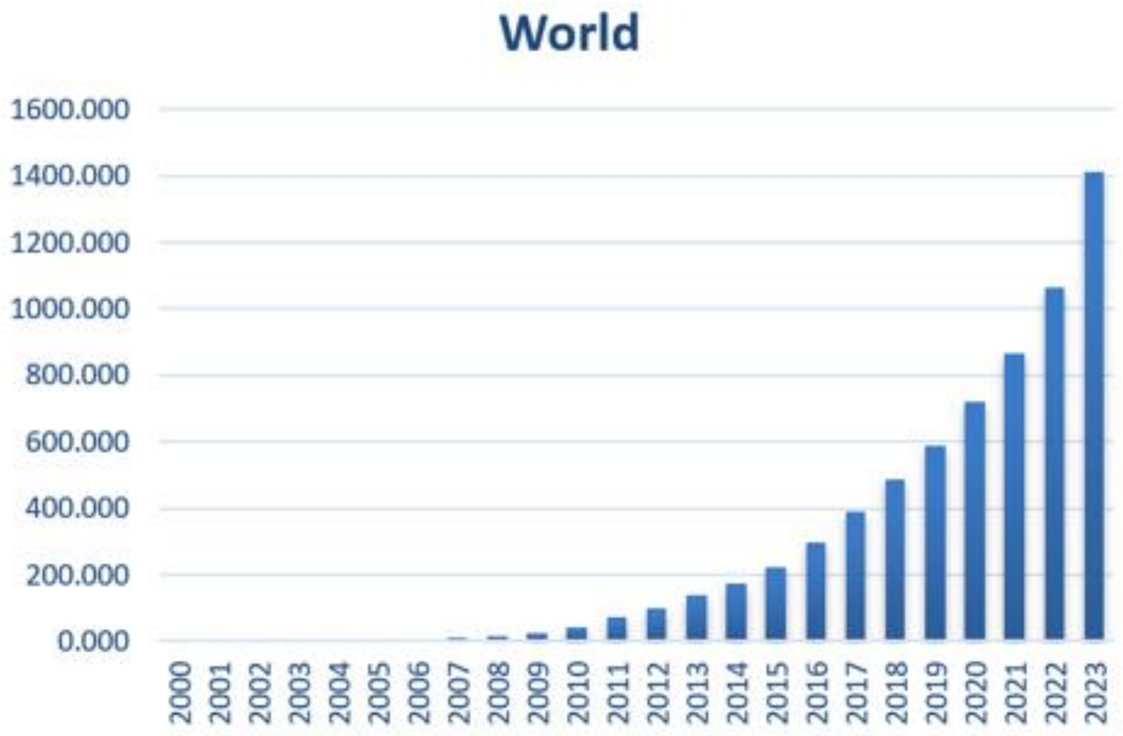
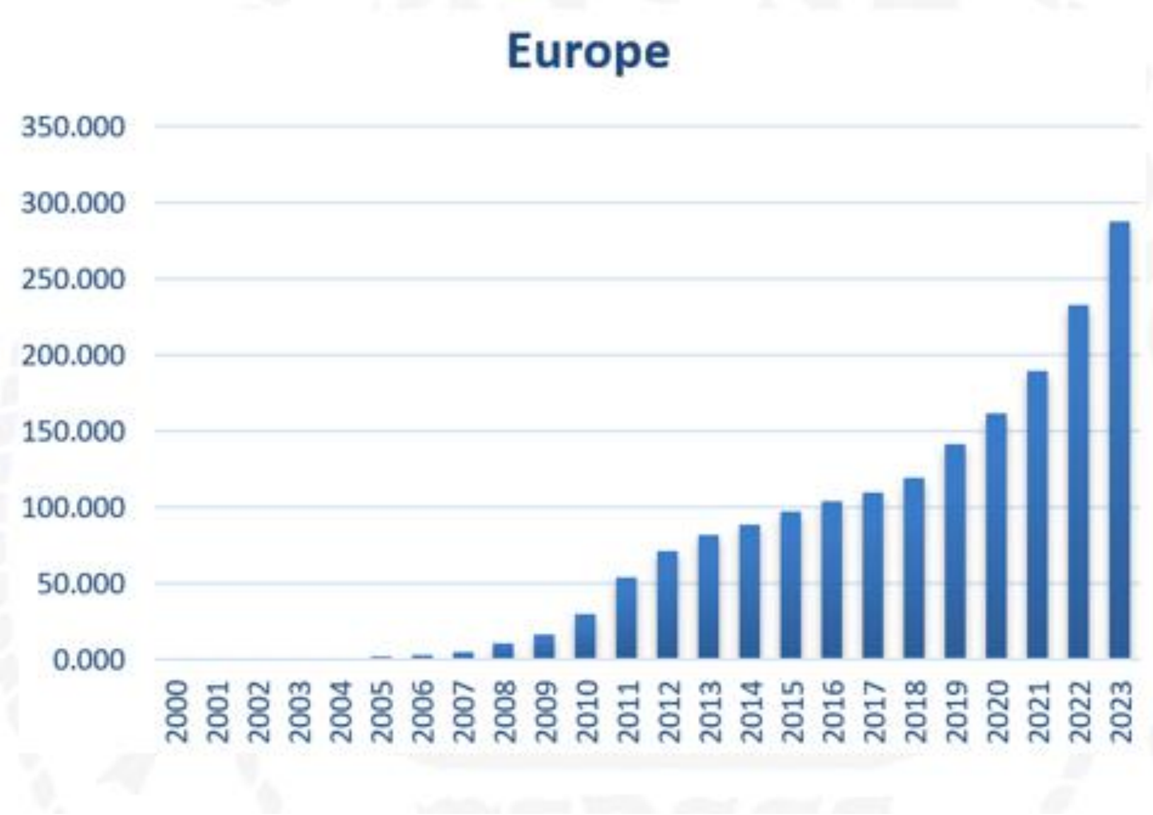
THE PHOTOCHEMISTRY OF THE FUTURE[1]

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."

Cumulative installed power [MWp]





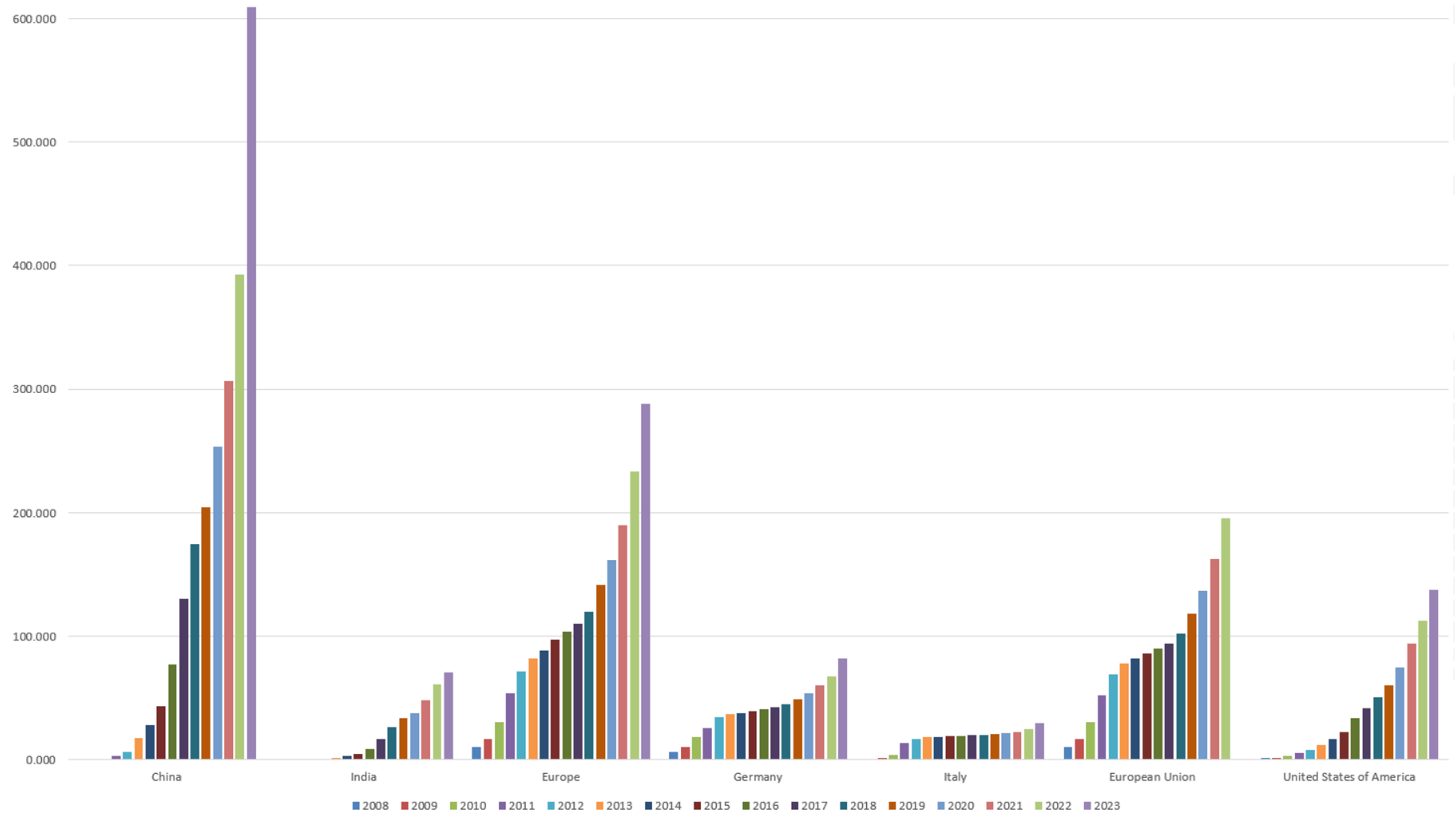

600.000
500.000
400.000
300.000
200.000
100.000
0.000
China
India
Europe
Germany
Italy
European Union
United States of America
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

Tabella 10 - Obiettivi di crescita della potenza da fonte rinnovabile al 2030 (MW) [Fonte: RSE, GSE]

	2020	2021	2025	2030
Idrica*	19.106	19.172	19.172	19.172
Geotermica	817	817	954	1.000
Eolica	10.907	11.290	17.314	28.140
- di cui off shore	0	0	300	2.100
Bioenergie	4.106	4.106	3.777	3.052
Solare	21.650	22.594	44.848	79.921
- di cui a concentrazione	0	0	300	873
Totale	**56.586**	**57.979**	**86.065**	**131.285**

Servono 7.6GW all'anno!

2,5 GW nel 2022, 5,2 GW nel 2023, 6.8 nel 2024

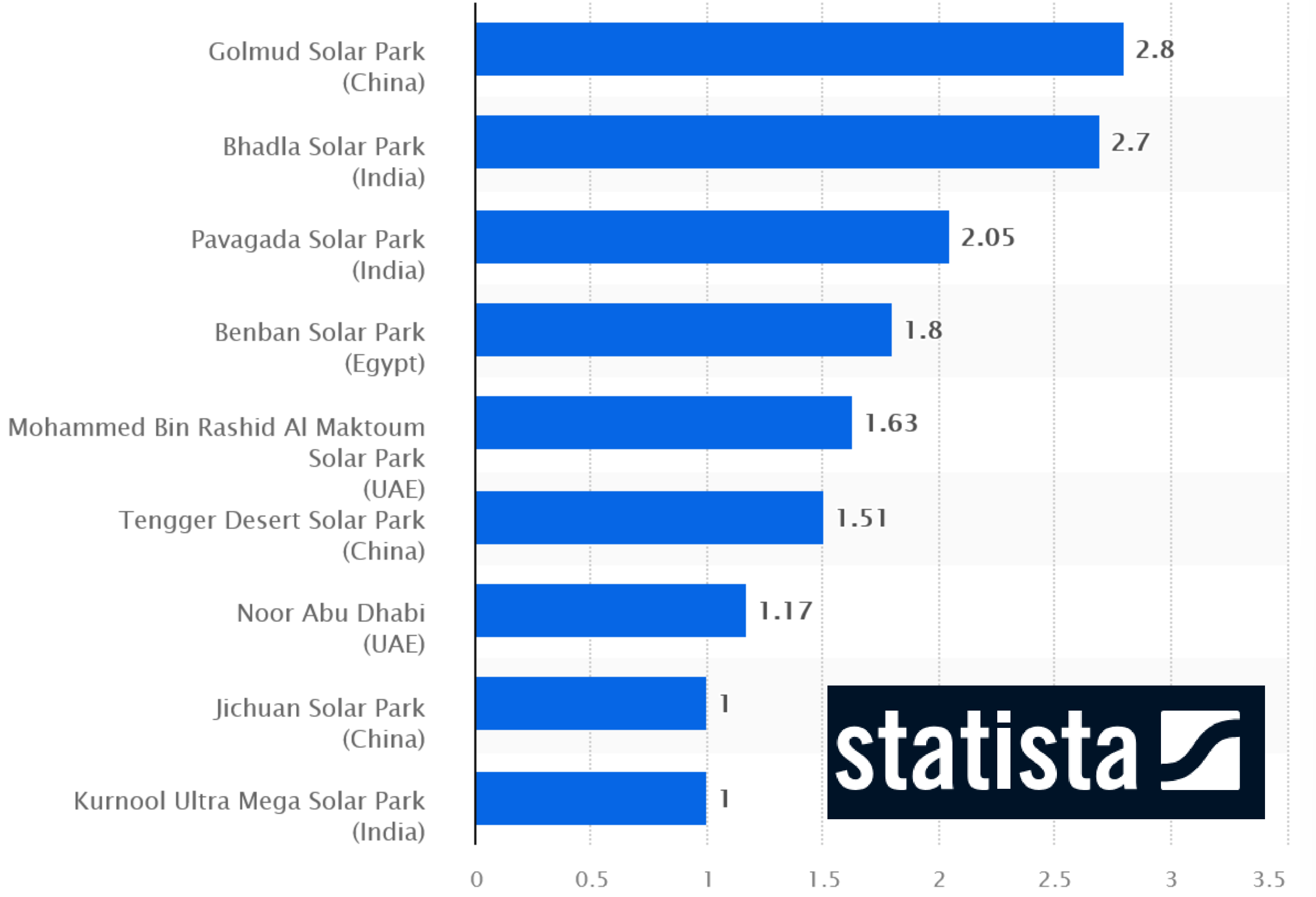
Germania (7 nel 2022, 15 nel 2023, 16.2 nel 2024!!!!)

PV POWER PER CAPITA
THE FIRST SIGN

COUNTRY	INSTALLED POWER* [GW]	POPULATION* [MILIONI]	POWER PER CAPITA	GROWTH [%]
GERMANY	59.0	83.2	802	13.1 (9.6)
ITALY	25.1	59.0	425	11.1 (4.6)
JAPAN	83.1	124.5	667	7.1 (7.9)
EUROPE	223.0	446.7	499	14.5 (16.6)
USA	111.5	330.0	338	19.1 (24.8)
CHINA	392.4	1412	278	27.3 (21.6)
INDIA	62.9	1380	46	20.5 (25.7)

*2022

GROUND-MOUNTED PV SYSTEMS



2000 – 0.02MW

2008 – 1MW

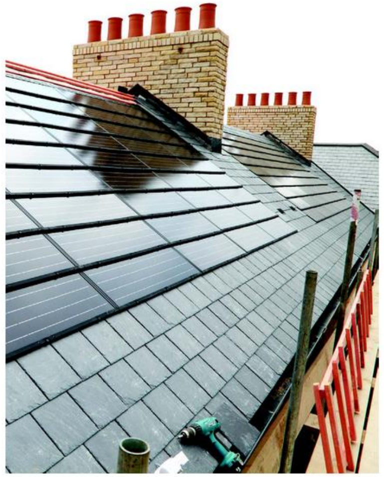
2018 – 1,365MW

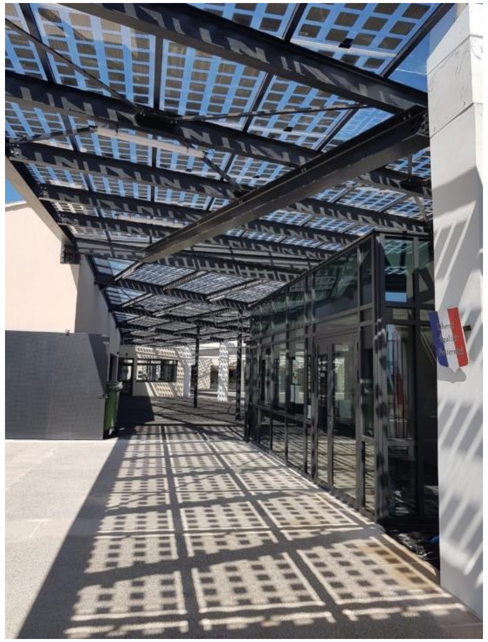
C&I ROOFTOP PV SYSTEMS

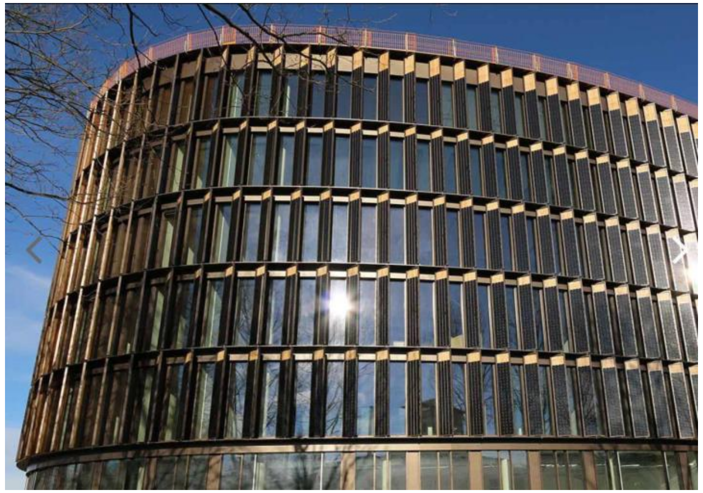
Power [1]	Location	Description [2]	On Grid
20 MW	South Korea, *Busan*	Renault, Samsung facility	2012
13 MW	Belgium, *Kallo*	Loghidden City, Katoen Natie	2010
12.5 MW	Italy, *Padova*	Interporto Padova	2010-2011
12 MW	India, *Amritsar*	RSSB-EES PV Roof System	2015
11.9 MW	France, *Maubeuge*	Renault Solar 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

RESIDENTIAL

BUILDING INTEGRATED PV (BIPV)







COMMERCIAL/INDUSTRIAL

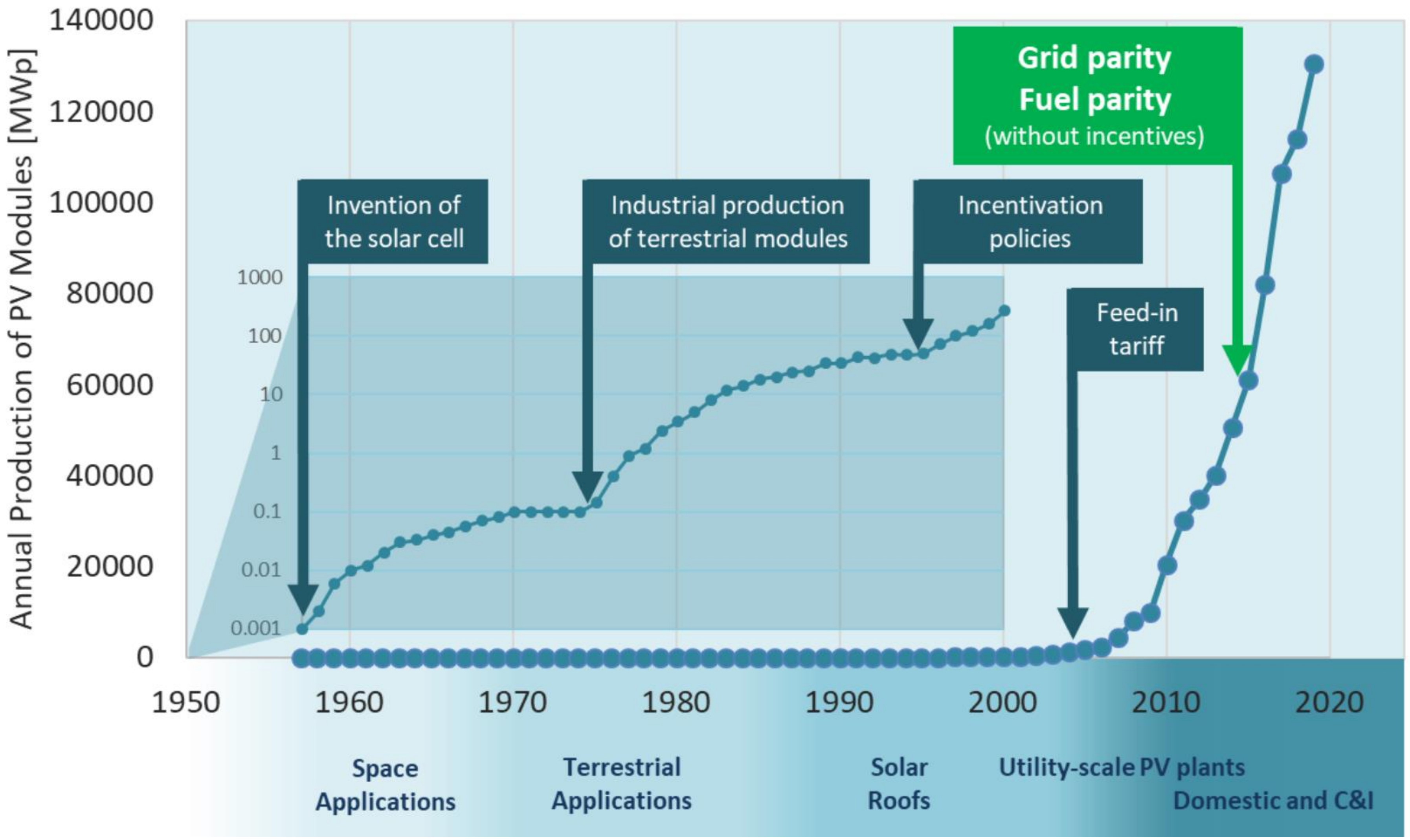
UTILITY SCALE

FLOATING AND AGRIVOLTAICS

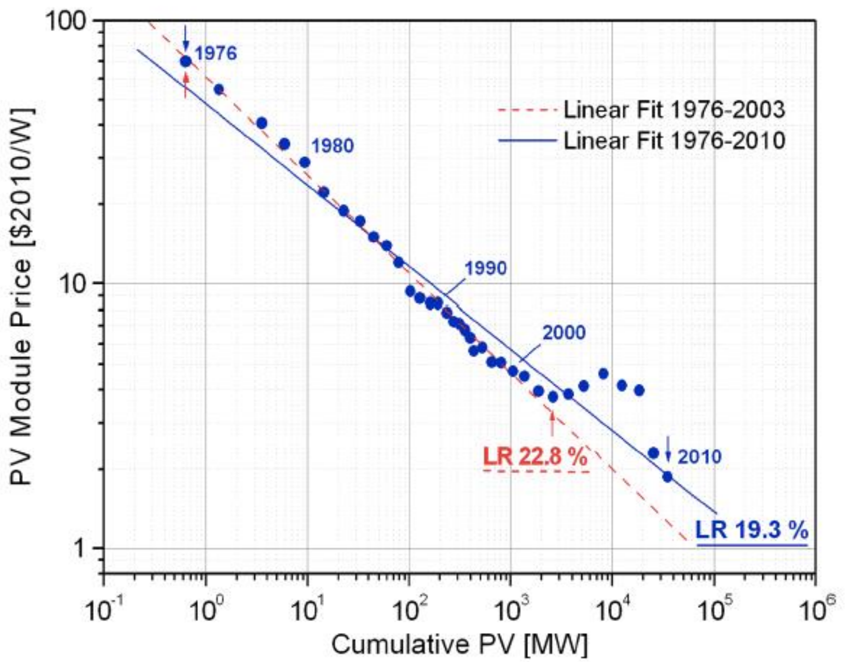
Trinasolar

KU LEUVEN

HISTORY OF PHOTOVOLTAICS



HISTORY OF PHOTOVOLTAICS

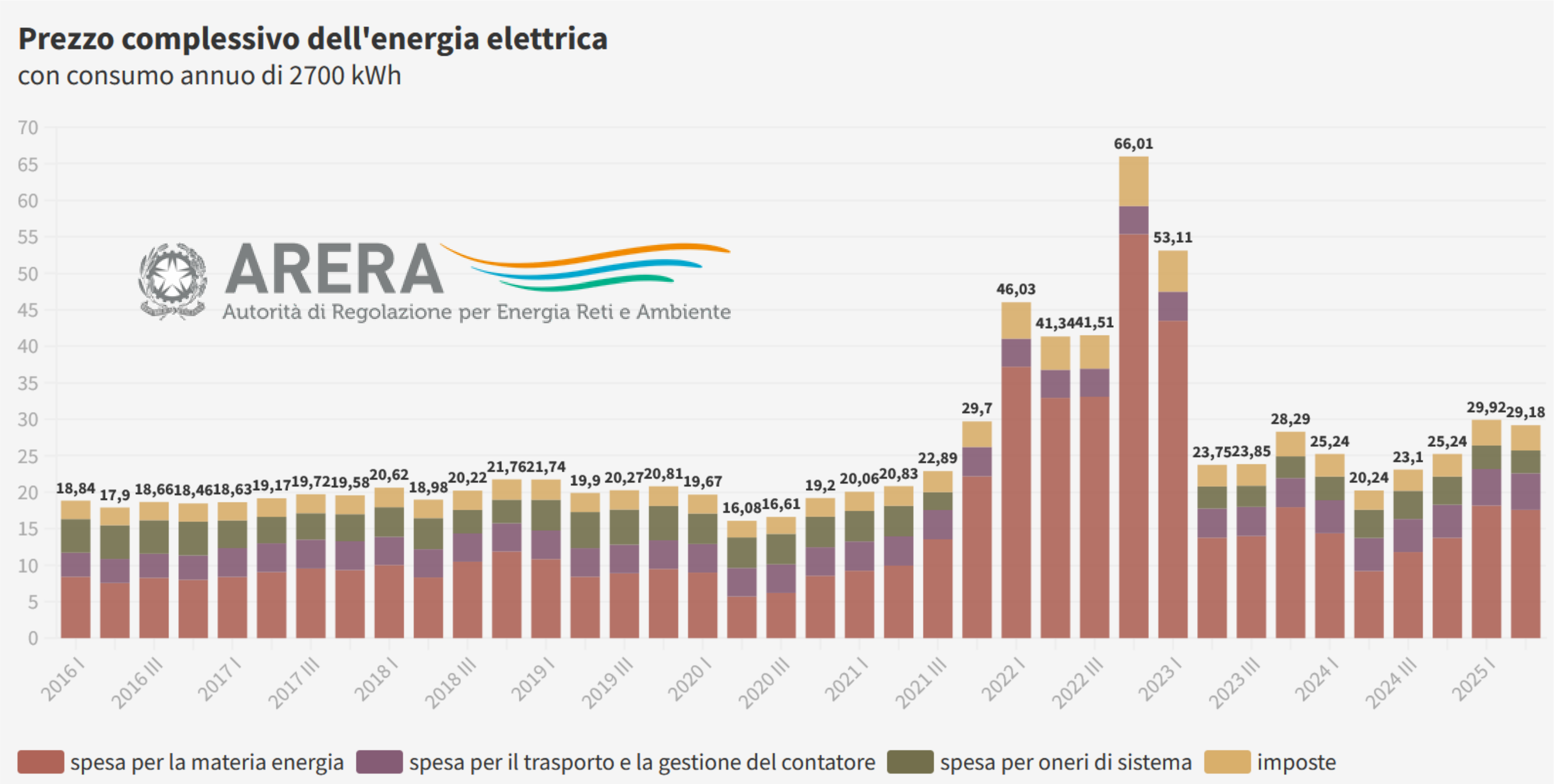


1955, 1975, 1995, ... 2015 marks a fundamental milestone in the history of PV: THE **GRID PARITY** and the **FUEL PARITY** occurring in many countries of the world!!!

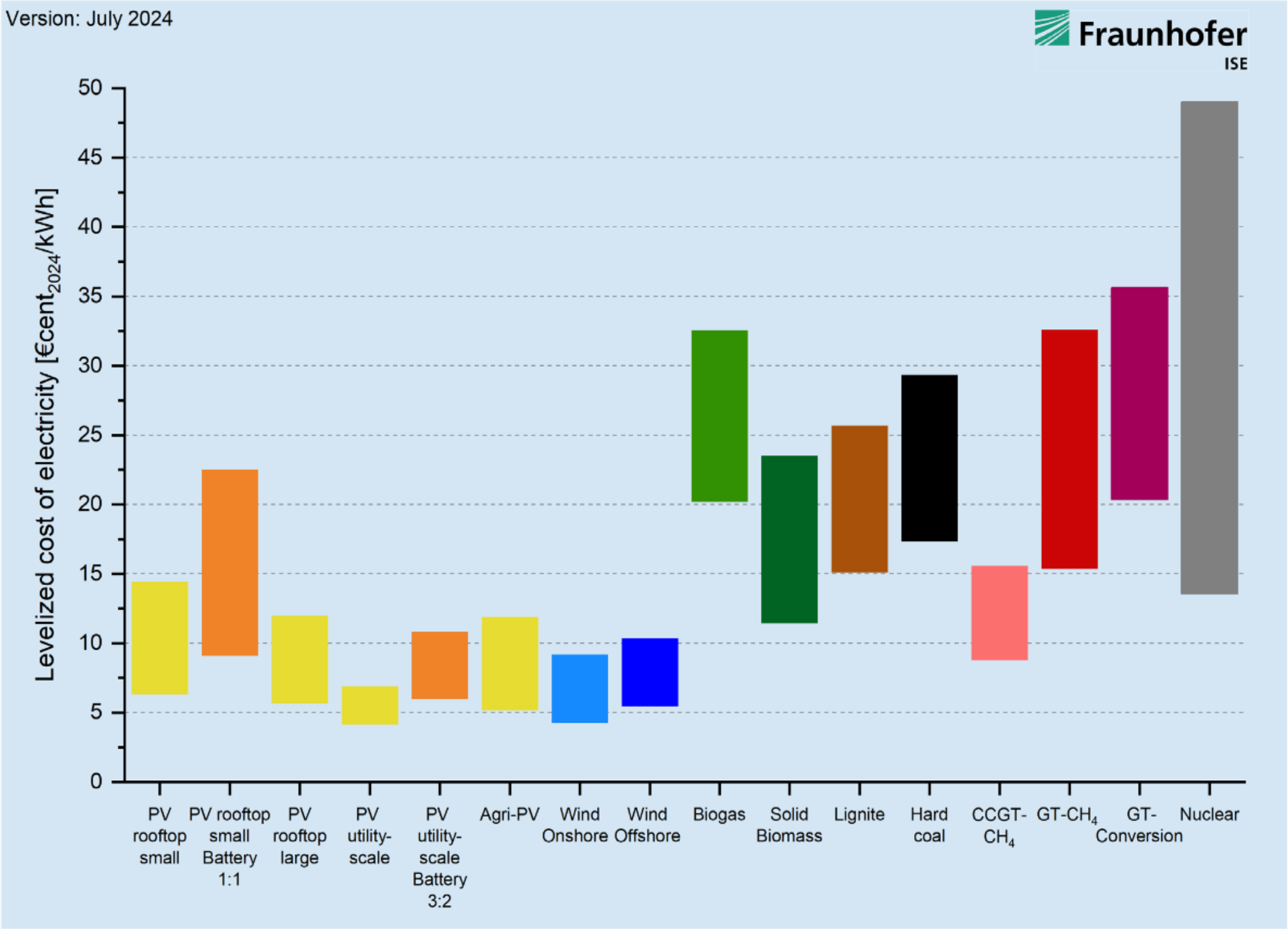
GRID AND FUEL PARITIES
THE SECOND SIGN

- The grid-parity occurs when the generation cost from PV (5 - 11 eurocent) is lower than the price the end consumer pays for the electricity (16 - 60 eurocent)
- The fuel-parity occurs when the cost of electricity from PV (3 - 5 eurocent) is comparable with the one from conventional technologies (4 - 19 eurocent)

RUOLO DEL PREZZO DELL'ENERGIA ELETTRICA

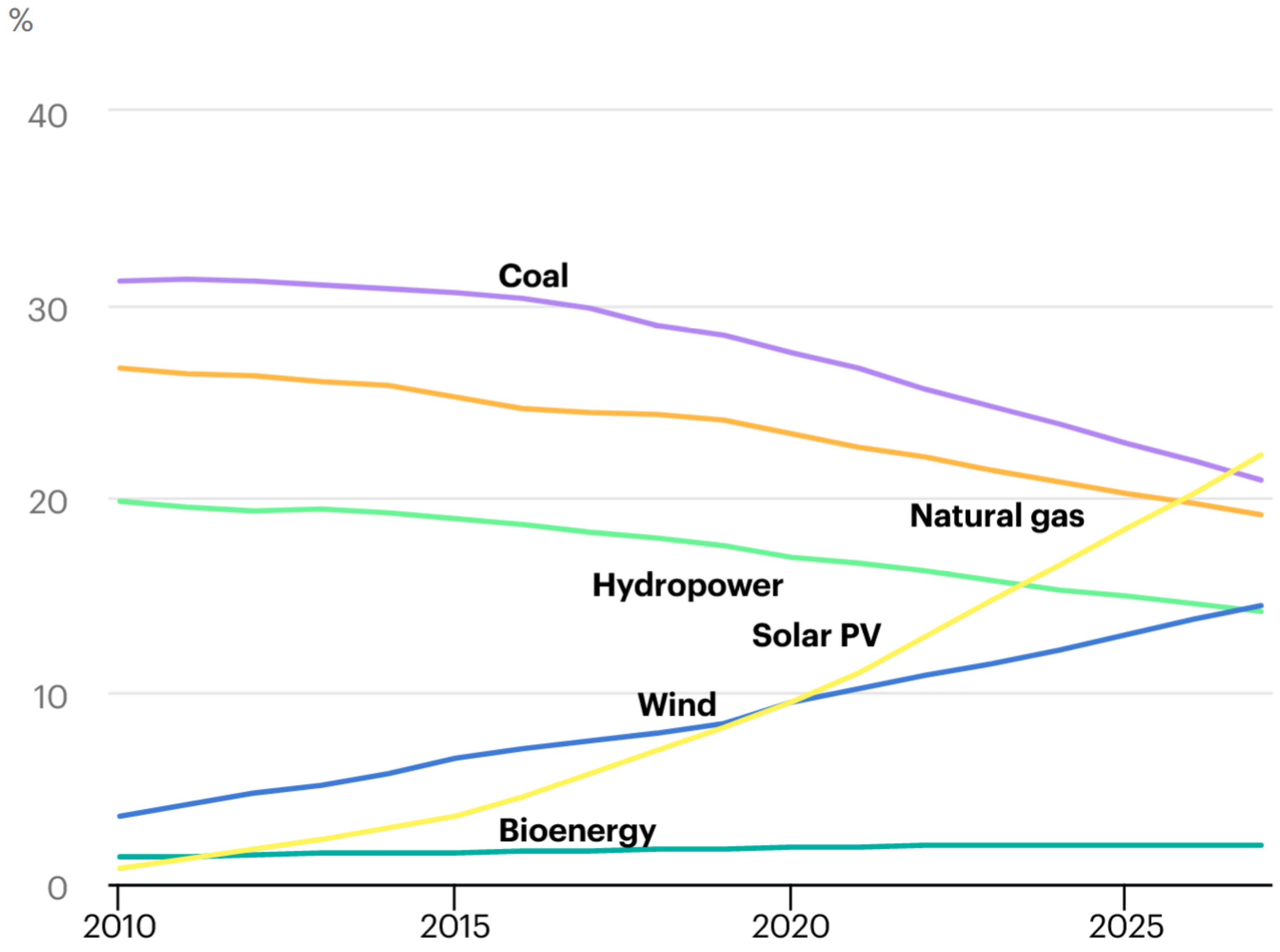


RUOLO DEL PREZZO DELL'ENERGIA ELETTRICA



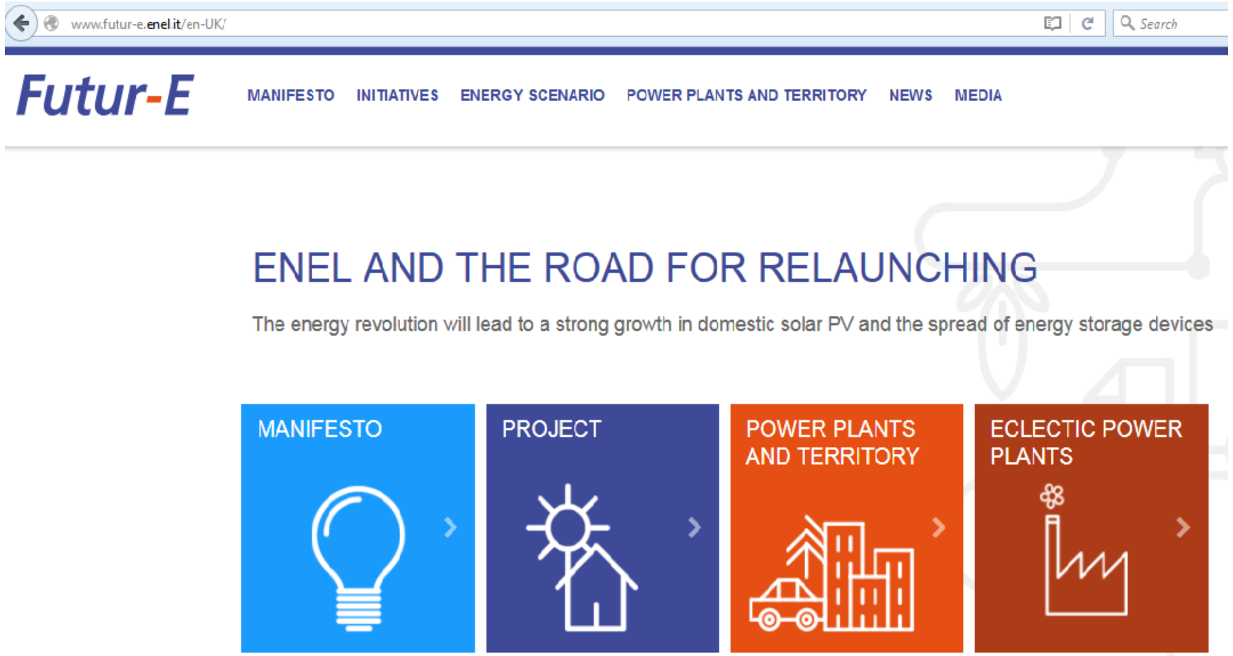
Solar is now 'cheapest electricity in history', confirms IEA

THE ROLE OF PHOTOVOLTAICS

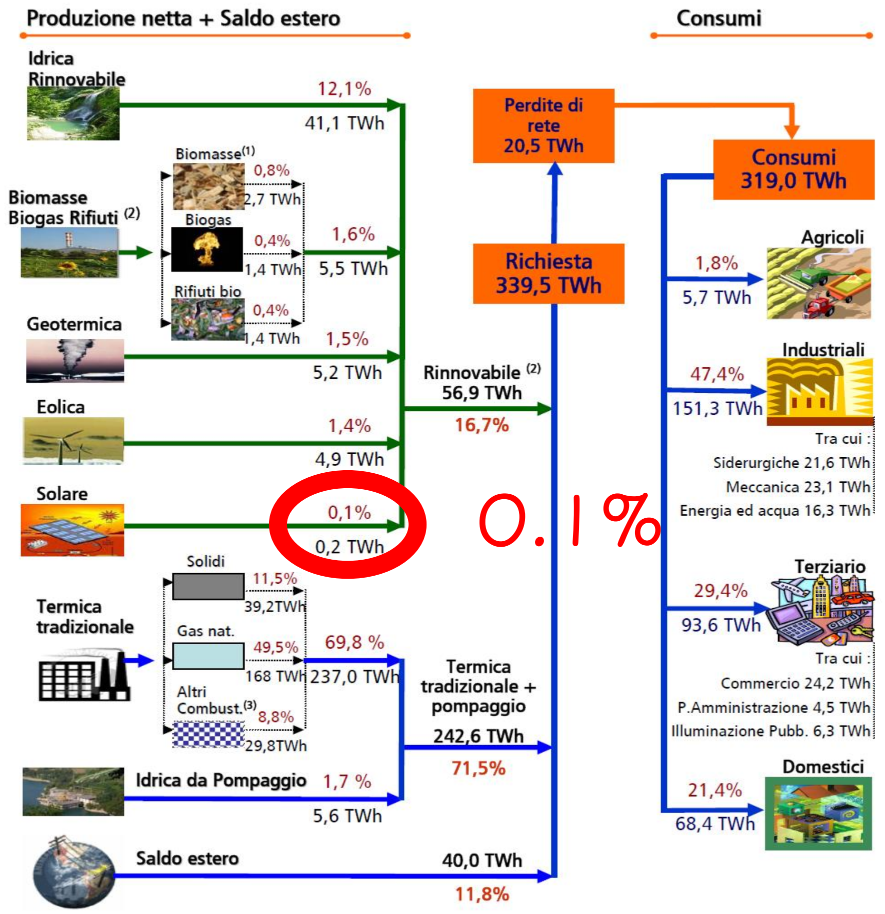


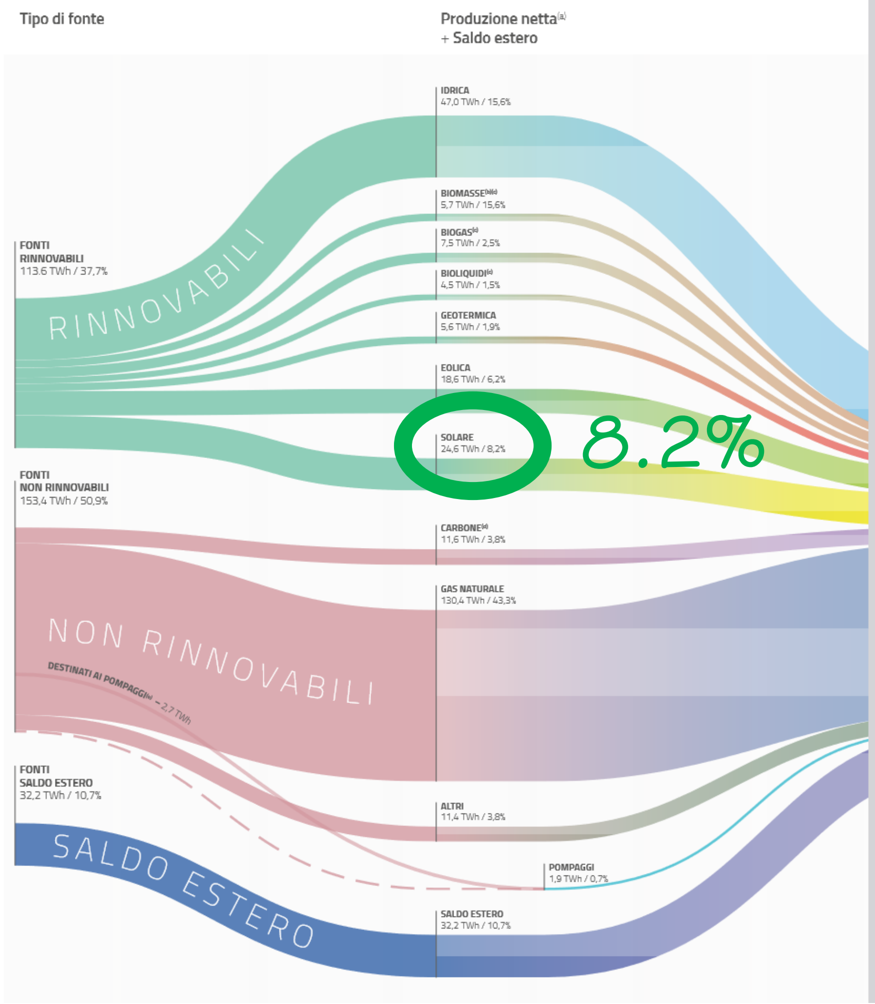
THE ROLE OF DSOs

THE THIRD SIGN

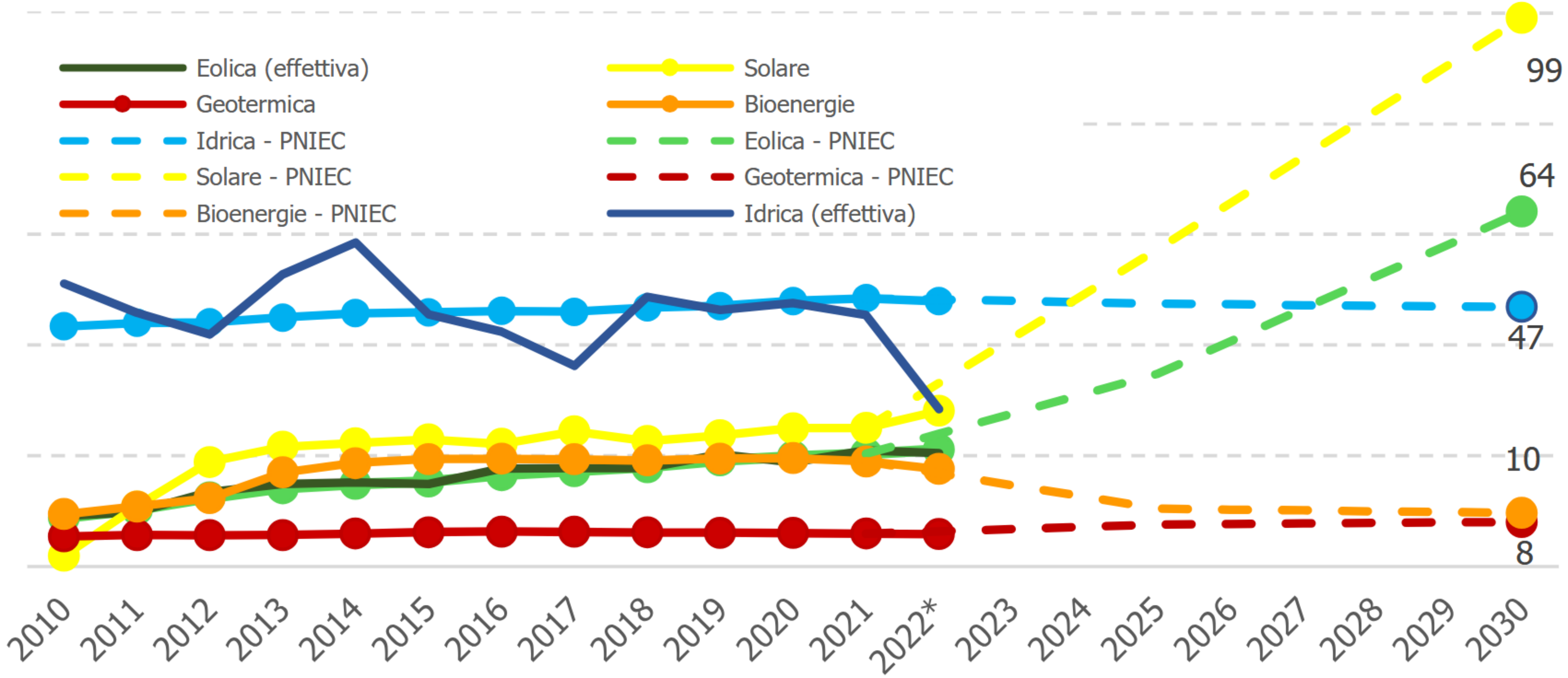


POWER SUPPLY CHAIN
ITALY 2003 - 2020





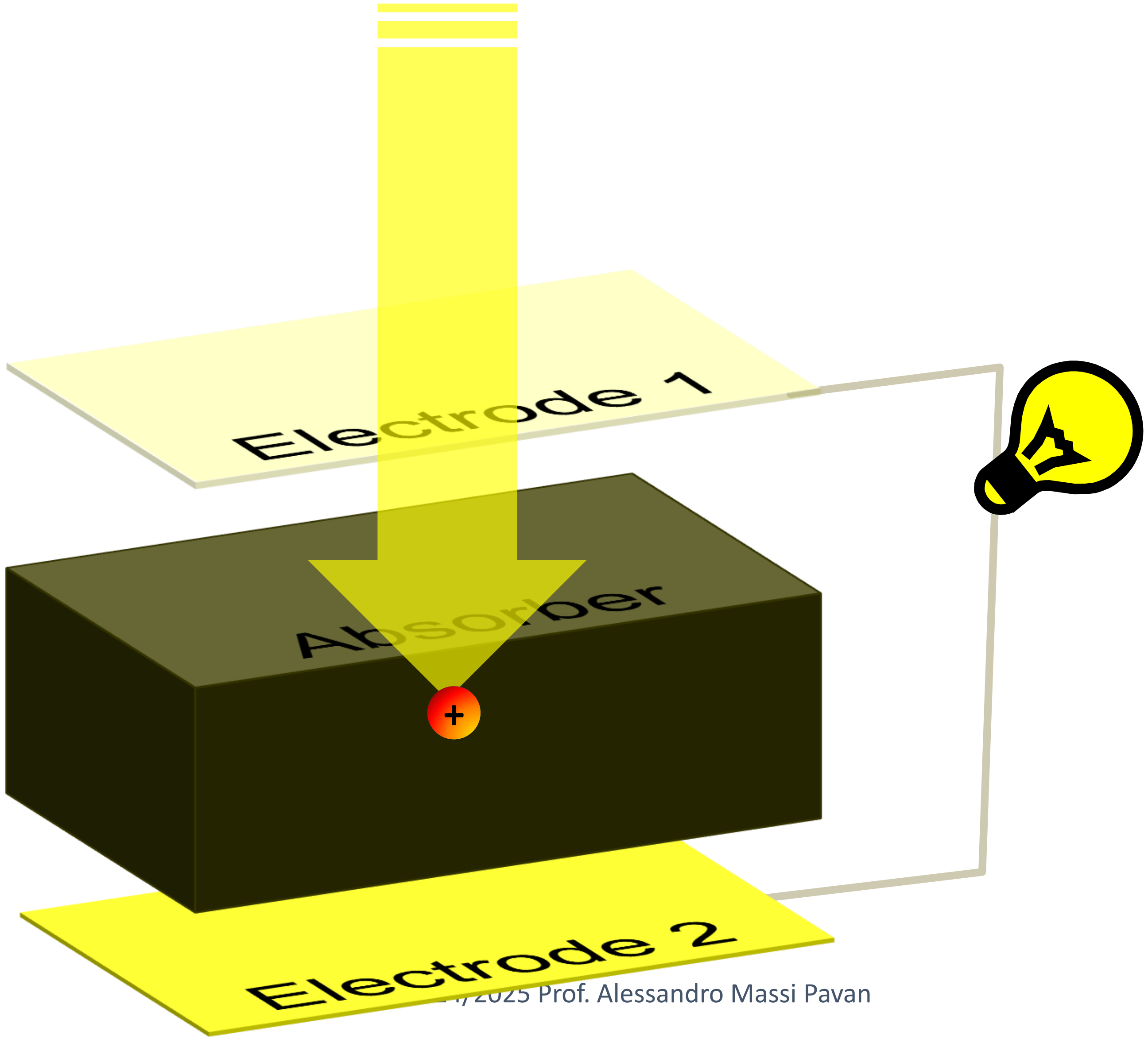
Produzione elettrica da FER per fonte: dato rilevato e traiettoria PNIEC [TWh]



GSE Gestore Servizi Energetici

“It is the greatest of all mistakes to do nothing because you can only do little“

BASIC SOLAR CELL CONCEPT



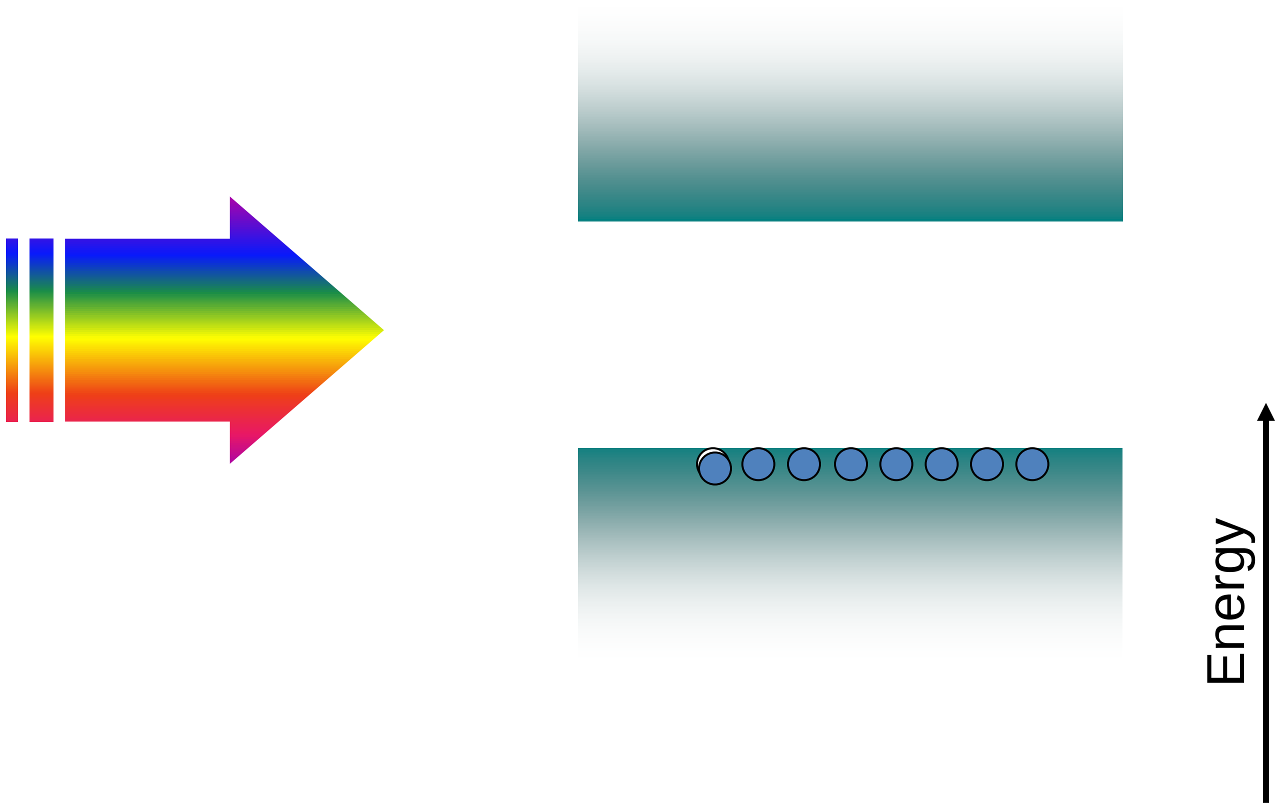
PHOTOVOLTAIC EFFECT

1.
Absorption of solar radiation

Creation of free carriers

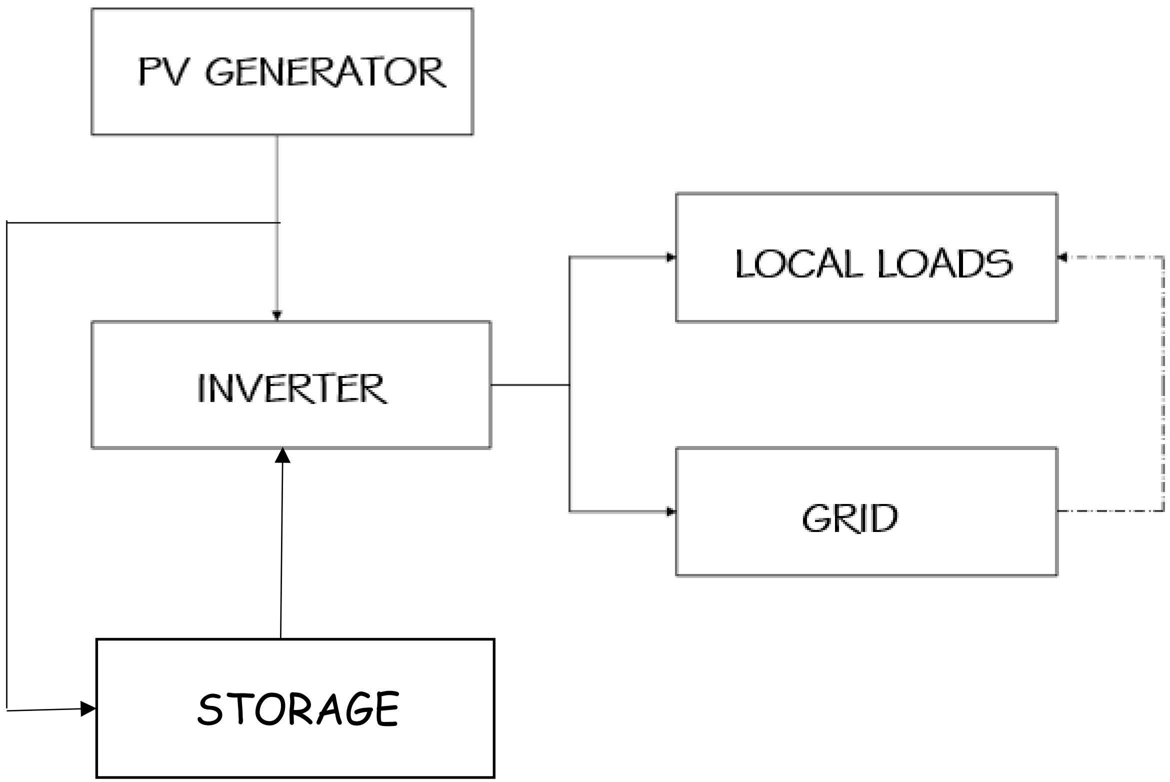
2.
Free carrier extraction

Electrical energy



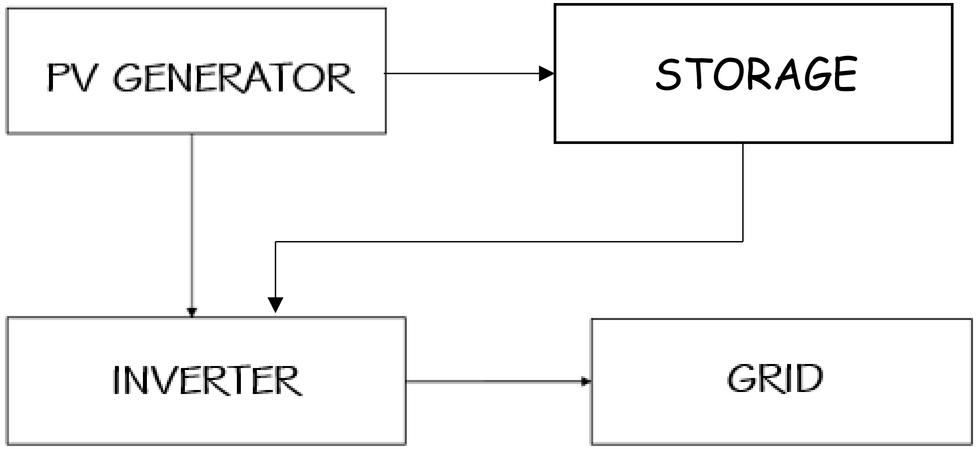
GRID-CONNECTED PV PLANTS

DISTRIBUTED



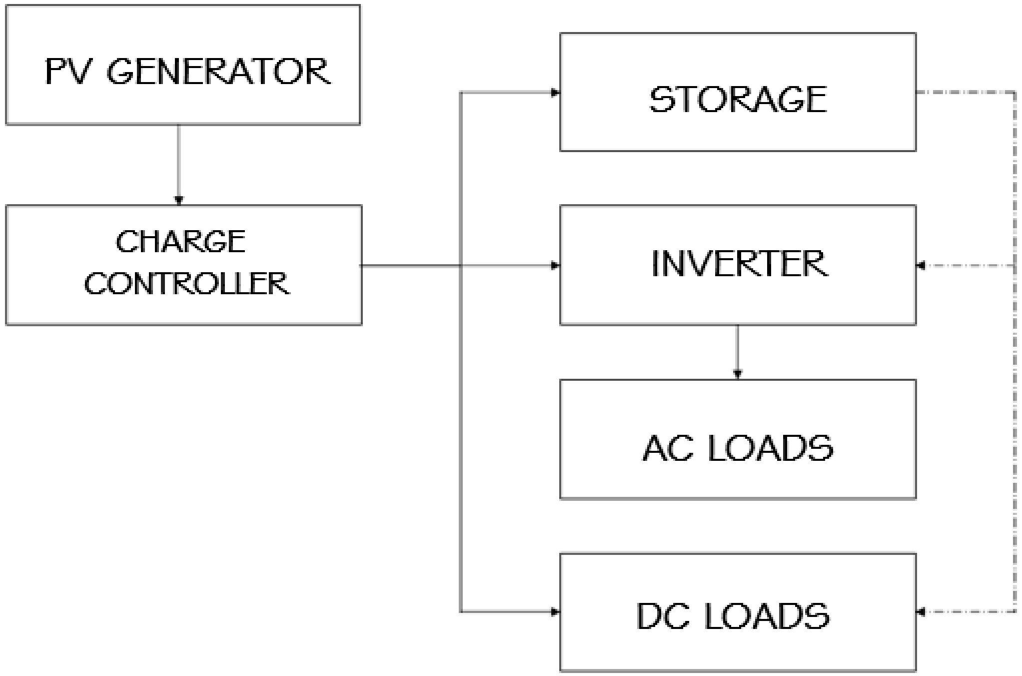
GRID-CONNECTED PV PLANTS

CENTRALIZED



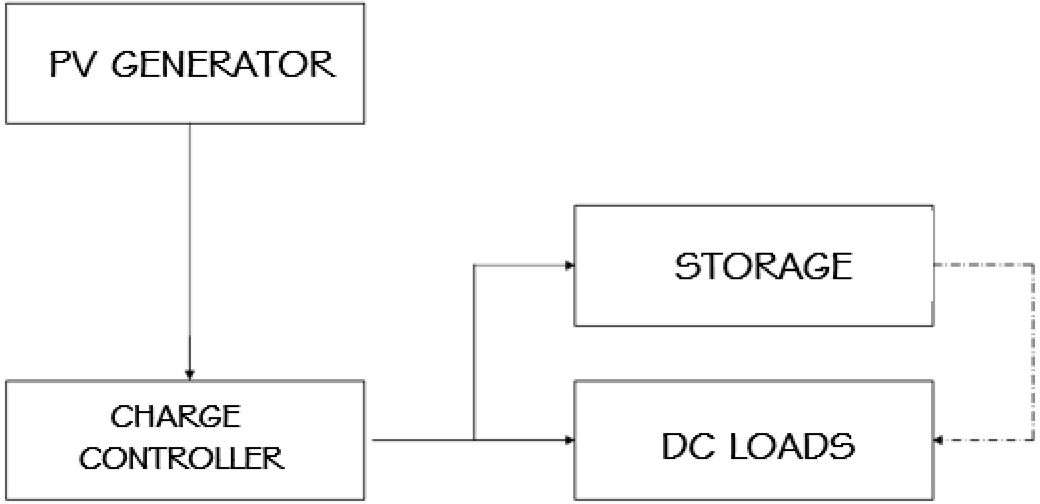
OFF-GRID PV PLANTS

RESIDENTIAL

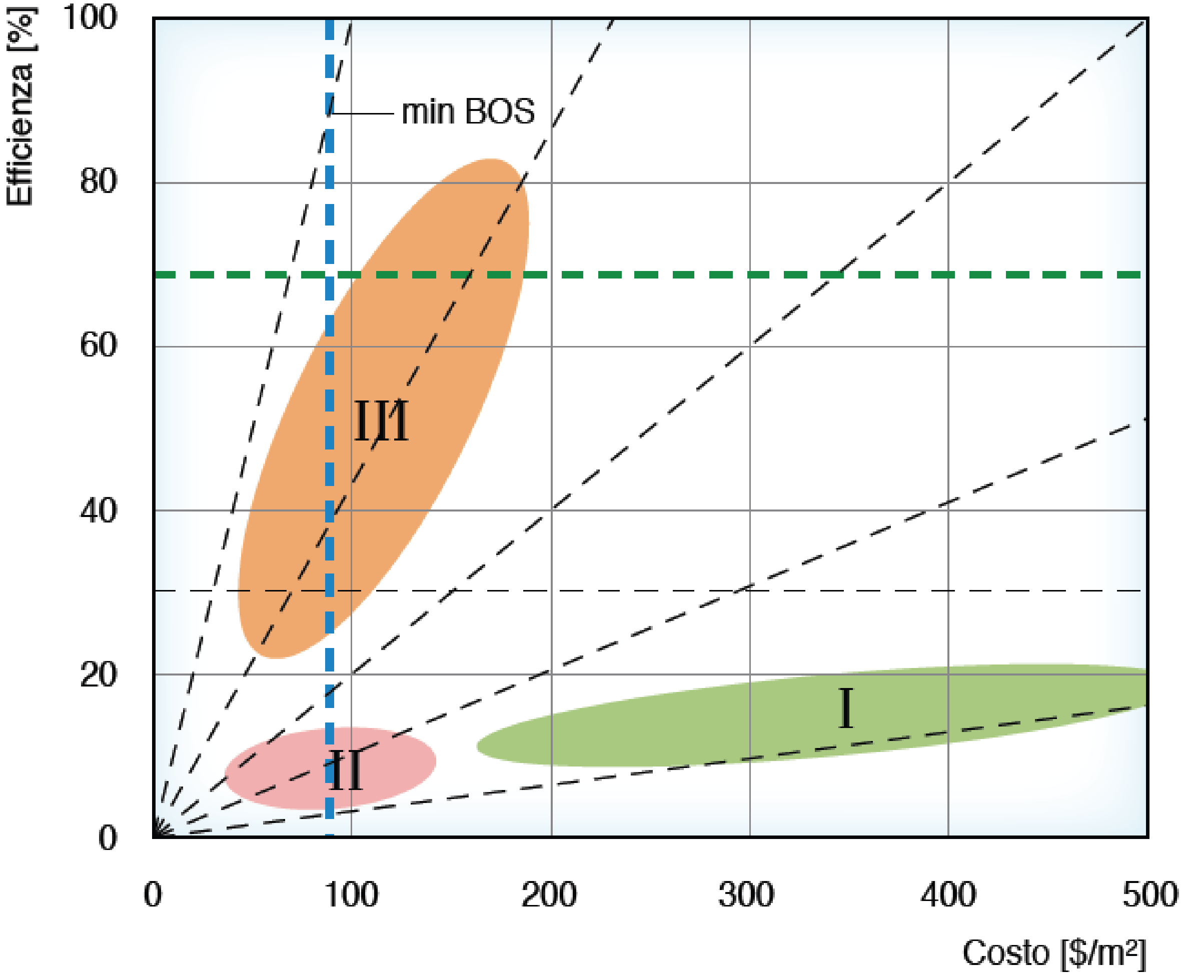


OFF-GRID PV PLANTS

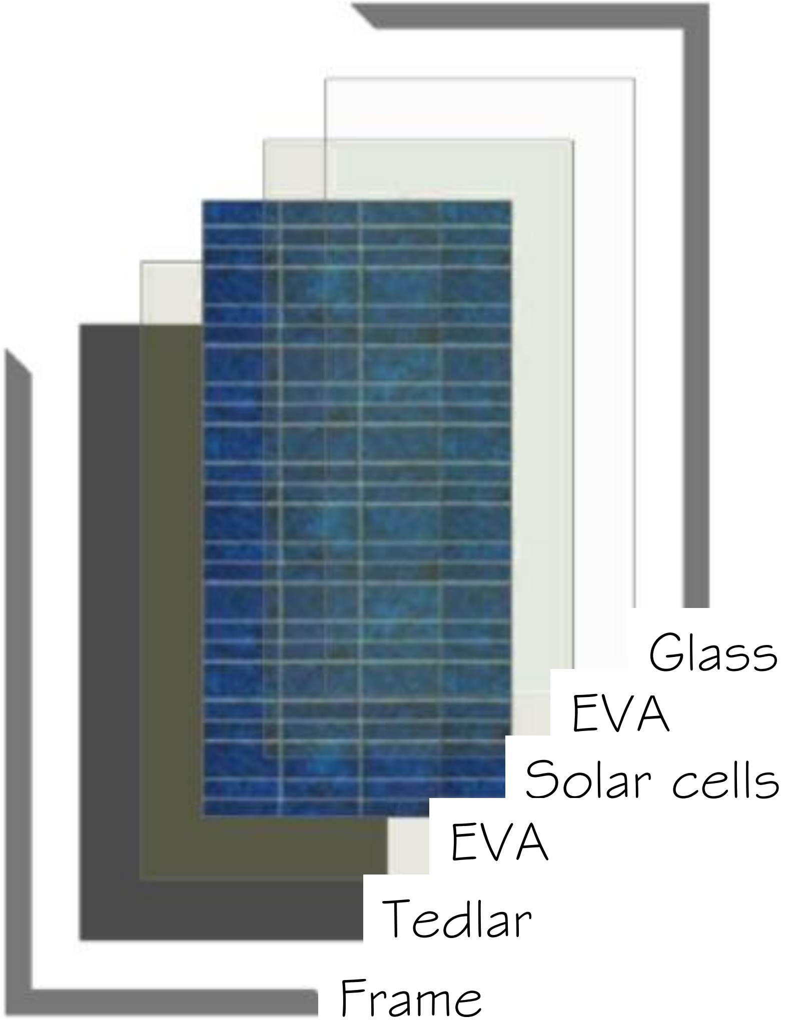
INDUSTRIAL



GENERATIONS OF PV MODULES



FIRST GENERATION PV MODULES



poly -Si

mono -Si

ELECTRICAL PARAMETERS

STANDARD TEST CONDITIONS (STC)
Irradiance 1.000W/m^2 - Cell Temperature 25°C - Air Mass 1.5

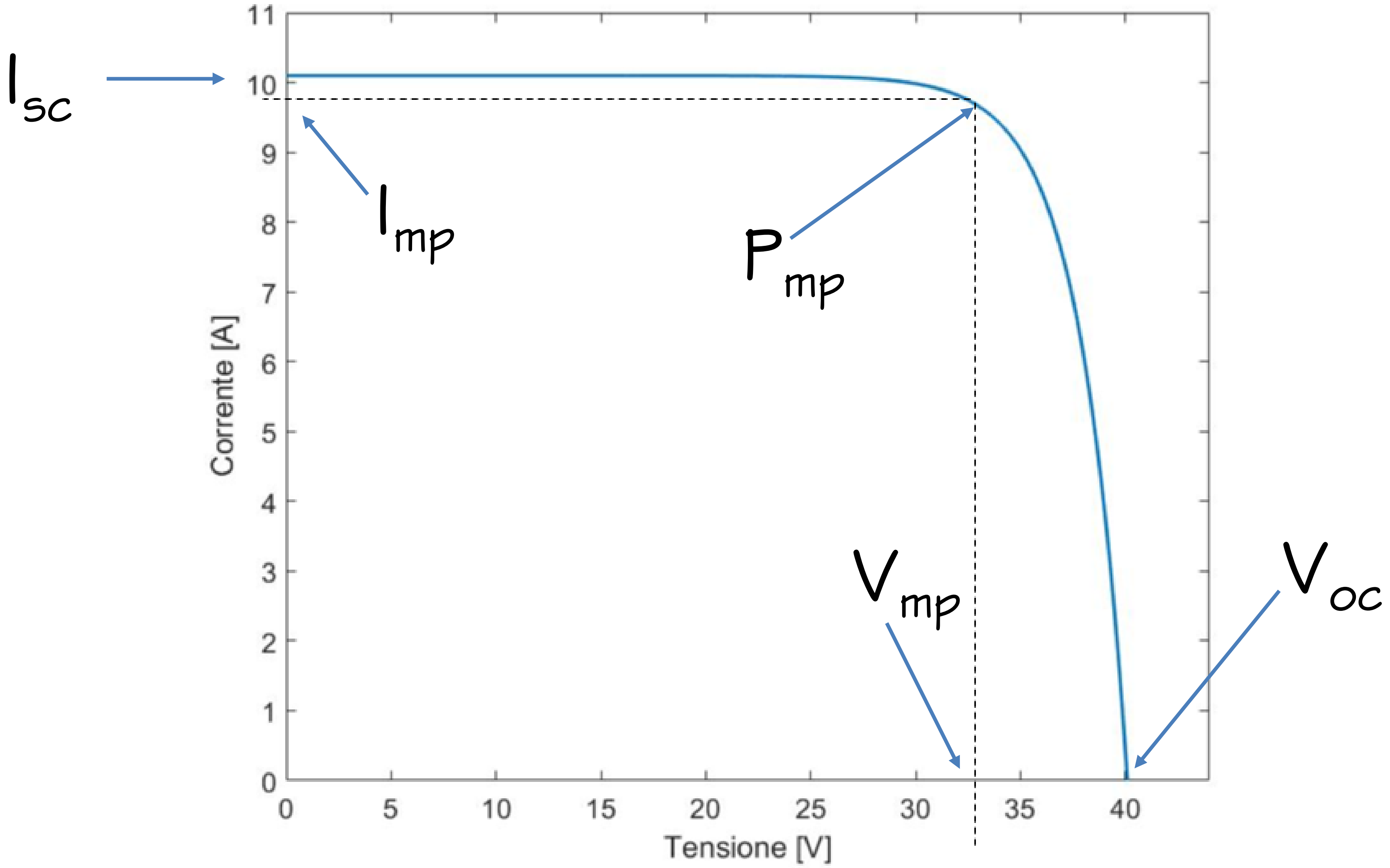
PV MODULE Q.CELLS – Q.PEAK DUO-G5 320	
Nominal Power - P_{mp} [Wp]	320 + [0-5]
Short circuit current - I_{sc} [A]	10,1
Open circuit voltage – V_{oc} [V]	40,1
Current at MPP – I_{mp} [A]	9,6
Voltage at MPP – V_{mp} [V]	33,3
Temperature coefficient of I_{sc} – z [%/K]	+0.04%/K
Temperature coefficient of V_{oc} – w [%/K]	-0.28%/K
Temperature coefficient of P_{mp} – P [%/K]	-0.37%/K
Size [mm*mm]	1685*1000
Degradation rate [%/year]	0.6
Nominal Operating Cell Temperature – T_{NOCT} [°C]	43±3

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

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

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

I-V CHARACTERISTIC

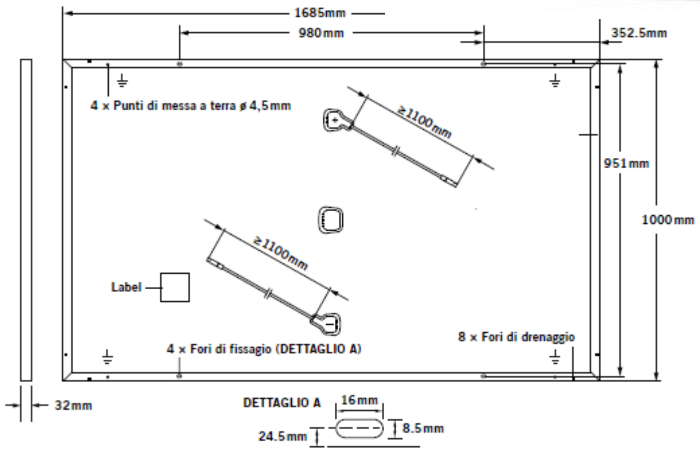


FIRST GENERATION PV MODULE

Q CELLS

SPECIFICHE MECCANICHE

Dimensioni	1685 mm × 1000 mm × 32 mm (cornice inclusa)
Peso	18,7 kg
Lato frontale	3,2 mm millimetri di vetro temprato con tecnologia anti-riflesso
Lato posteriore	Pellicola composita
Cornice	Lega di alluminio anodizzato nero
Cella	6 × 20 semicella monocristallina Q.ANTUM
Scatola di giunzione	70-85 mm × 50-70 mm × 13-21 mm Protezione IP67, con 3 diodi di bypass
Cavo	Cavo solare 4 mm^2 ; (+) ≥ 1100 mm, (–) ≥ 1100 mm
Connettore	Multi-Contact MC4, IP68



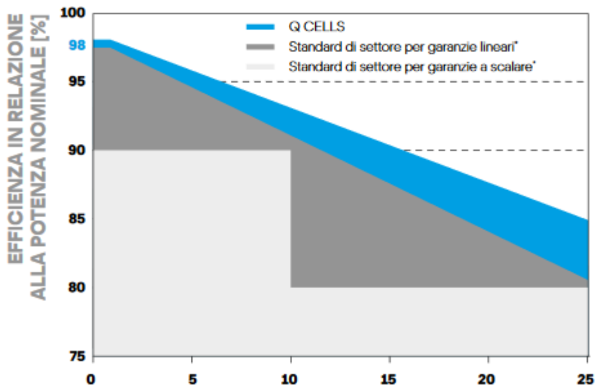
SPECIFICHE ELETTRICHE

CLASSI DI PRESTAZIONE				315	320	325	330
PRESTAZIONE MINIMA IN CONDIZIONI DI PROVA STANDARD, STC[1] (CAPACITÀ DI TOLLERANZA +5 W / –0 W)							
Minimo	Prestazioni a MPP[1]	P_{MPP}	[W]	315	320	325	330
	Corrente di cortocircuito[1]	I_{SC}	[A]	10,04	10,09	10,14	10,20
	Tensione a vuoto[1]	V_{OC}	[V]	39,87	40,13	40,40	40,66
	Corrente nel MPP	I_{MPP}	[A]	9,55	9,60	9,66	9,71
	Tensione nel MPP	V_{MPP}	[V]	32,98	33,32	33,65	33,98
	Efficienza[1]	η	[%]	≥ 18,7	≥ 19,0	≥ 19,3	≥ 19,6

FIRST GENERATION PV MODULE

Q CELLS

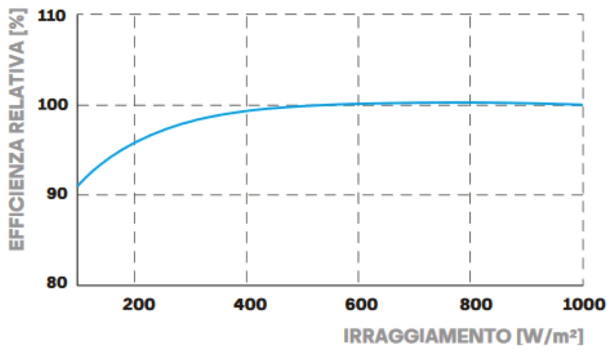
Q CELLS GARANZIA SULLA POTENZA



*Valutazione delle 10 aziende del settore FV con la maggior capacità produttiva nel 2014 (aggiornato a: settembre 2014)

Potenza nominale pari ad almeno 98 % nel corso del primo anno. Degrado annuo non superiore a 0,54 %. Potenza nominale pari ad almeno 93,1 % dopo 10 anni. Potenza nominale pari ad almeno 85 % dopo 25 anni.
Le garanzie sul prodotto e sulla potenza possono variare secondo il paese di installazione. Garanzie integrali conformi ai termini approvati dall'organizzazione commerciale Q CELLS dei rispettivi Paesi.

PRESTAZIONI IN CASO DI BASSA IRRAGGIAMENTO

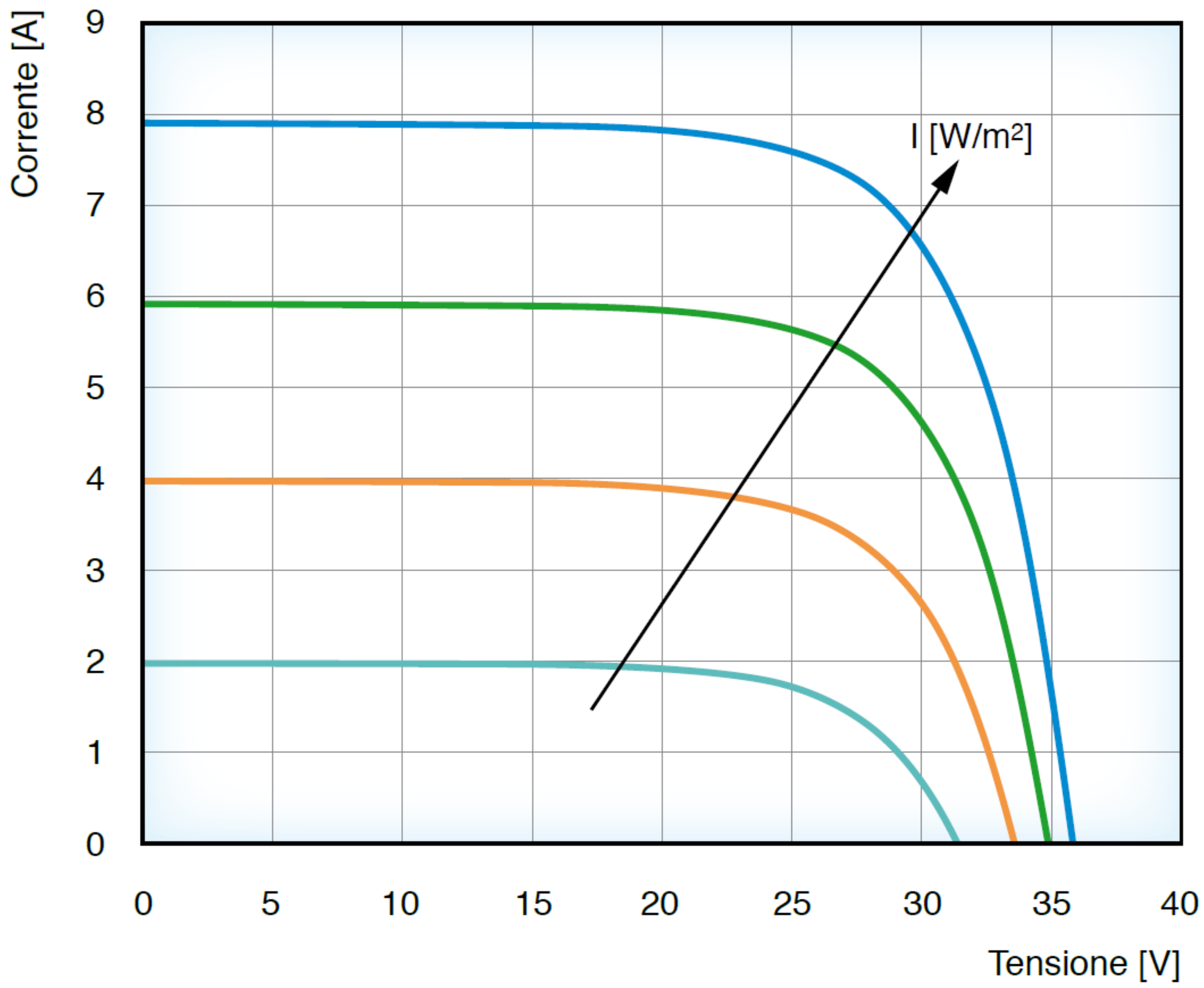


Tipica prestazione dei moduli a condizioni di irradiamento basse rispetto alle condizioni STC (25 °C, 1000 W/m²).

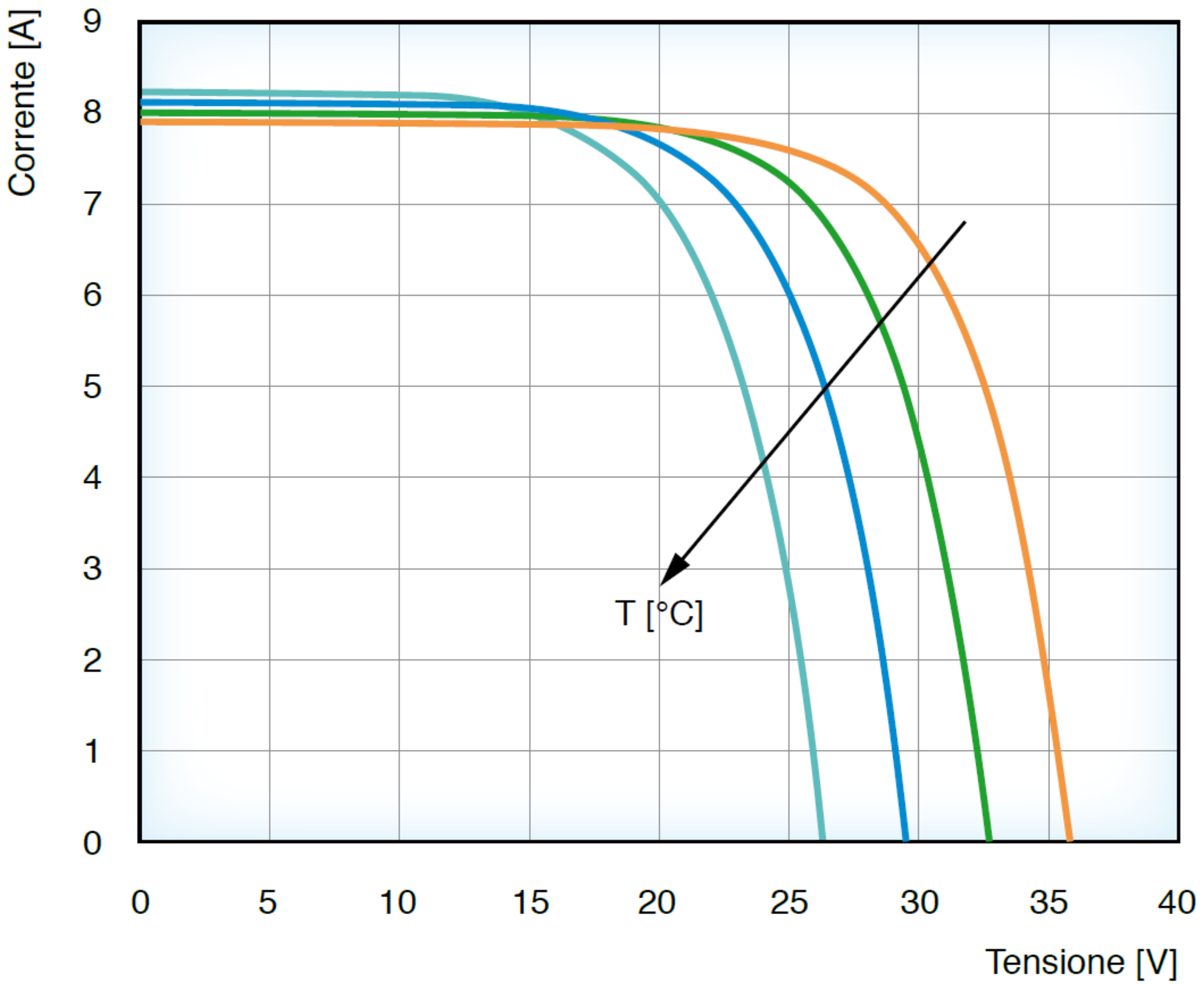
COEFFICIENTI DI TEMPERATURA IN CONDIZIONI STANDARD

Coefficienti di temperatura di I_{SC}	α	[%/K]	+0,04	Coefficienti di temperatura di V_{OC}	β	[%/K]	−0,27
Coefficienti di temperatura di P_{MPP}	γ	[%/K]	−0,36	Normal Module Operating Temperature	NMOT	[°C]	43±3

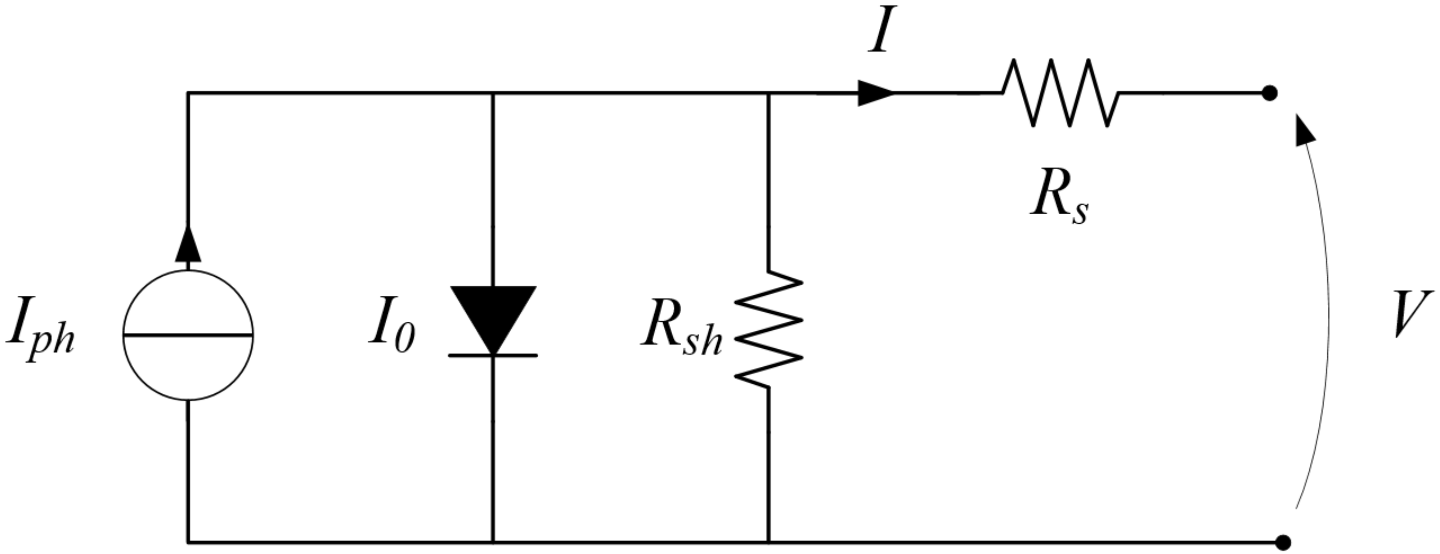
DEPENDANCE ON SOLAR IRRADIANCE



DEPENDANCE ON CELL TEMPERATURE



MODELLING PHOTOVOLTAIC DEVICES



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

I_{ph} [A] – photo generated current
I_0 [A] – dark saturation current
V_t [V] – thermal voltage

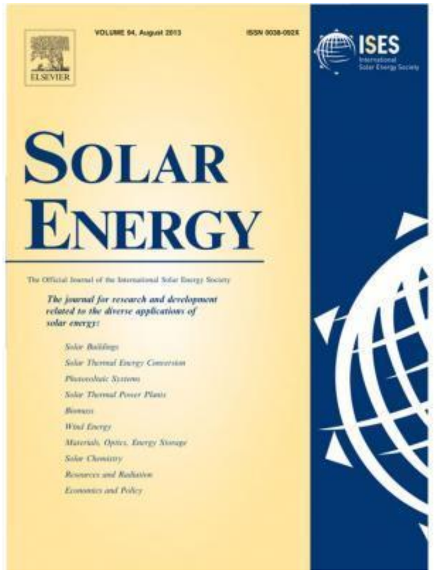
R_s [Ω] – series resistance
R_{sh} [Ω] – shunt resistance
n [ ] – ideality factor

EMPIRICAL MODEL

It is simple, explicit and based on the parameters that can be always found in a pv module datasheet

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

Solar Energy 155 (2017) 647–653



I [p.u.] – per unit current referred to I_{sc}

I_L [p.u.] – per unit irradiance referred to 1,000W/m^2

m [ ] – exponential factor

V [p.u.] – per unit voltage referred to V_{oc}

w [1/°C] – voltage/temperature coefficient

T_c [°C] – cell temperature

INVERTER

String inverter

3 kVA

30 x 30 x 12 cm

5,5 kg

Centralized Inverter

100 kVA

80 x 80 x 160 cm

420 kg

Utility scale inverter

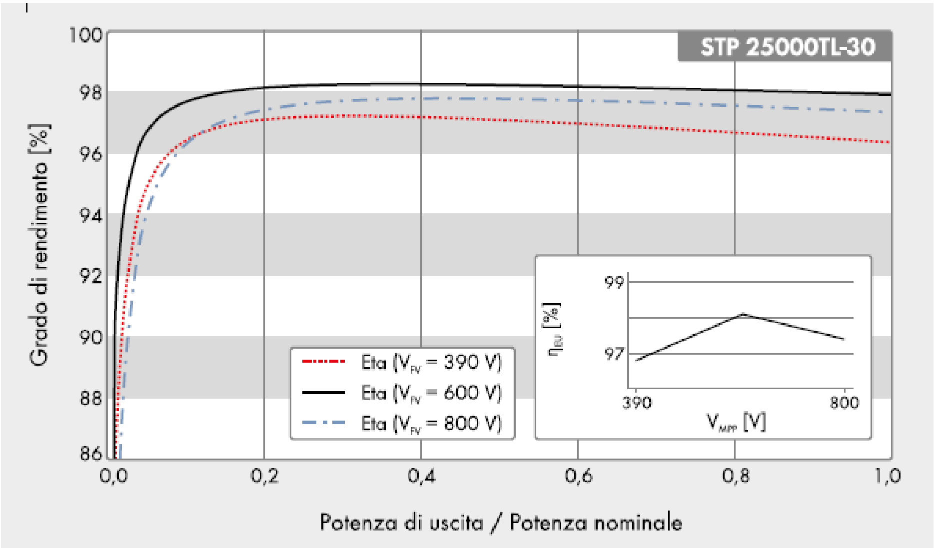
2200 kVA

2,7 x 2,3 x 1,6 m

3,400 kg

ELECTRICAL PARAMETERS

Input (DC)		
Max. DC power (@ cos φ = 1)	3200 W	3880 W
Max. input voltage	750 V	750 V
MPP voltage range / rated input voltage	175 V ... 500 V / 400 V	175 V ... 500 V / 400 V
Min. input voltage / initial input voltage	125 V / 150 V	125 V / 150 V
Max. input current input A / input B	15 A / 15 A	15 A / 15 A
Max. input current per string input A / input B	15 A / 15 A	15 A / 15 A
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2	2 / A:2; B:2
Output (AC)		
Rated power (@ 230 V, 50 Hz)	3000 W	3680 W
Max. apparent AC power	3000 VA	3680 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V – 280 V	220 V, 230 V, 240 V / 180 V – 280 V
AC power frequency / range	50 Hz, 60 Hz / -5 Hz ... +5 Hz	50 Hz, 60 Hz / -5 Hz ... +5 Hz
Rated power frequency / rated grid voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	16 A	16 A
Power factor at rated power	1	1
Displacement power factor, adjustable	0.8 overexcited ... 0.8 underexcited	0.8 overexcited ... 0.8 underexcited
Feed-in phases / connection phases	1 / 1	1 / 1
Efficiency		
Max. efficiency / European weighted efficiency	97 % / 96 %	97 % / 96.3 %



SMA SUNNY BOY 3000TL

PHOTOVOLTAIC GENERATOR

Blocking diode
(optional, in stand alone systems only)

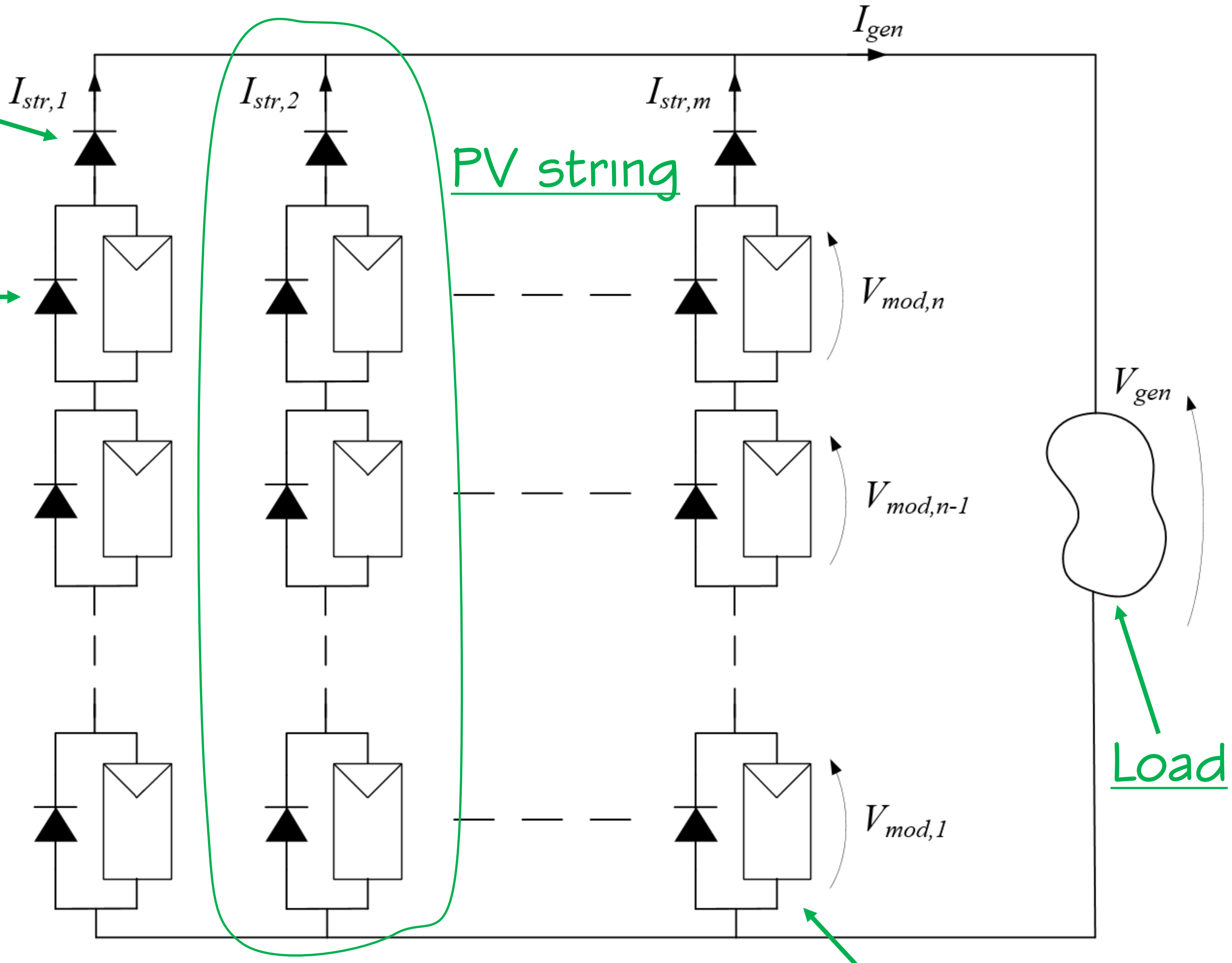
Bypass diode
(more than one inside the PV module)

$$I_{str,i} = I^{*}_{mod}$$

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

$$V_{str} = \sum_{j=1}^{n} V_{mod,j} \quad *$$

$$V_{gen} = V_{str}$$



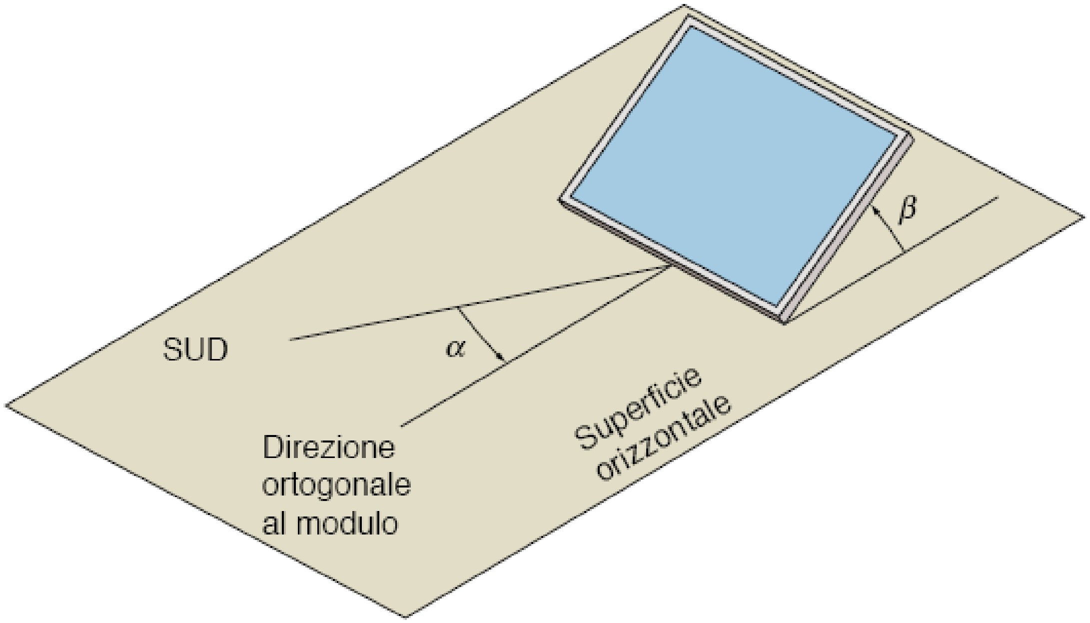
YIELD OF A PV SYSTEM

The yield of a photovoltaic system mainly depends on

- **Photovoltaic generator**: pv technology, nominal power
- **Geometry**: location, horizon and shading profile, mounting options
- **System losses**: soiling, temperature effect, mismatch, Joule effect, inverter

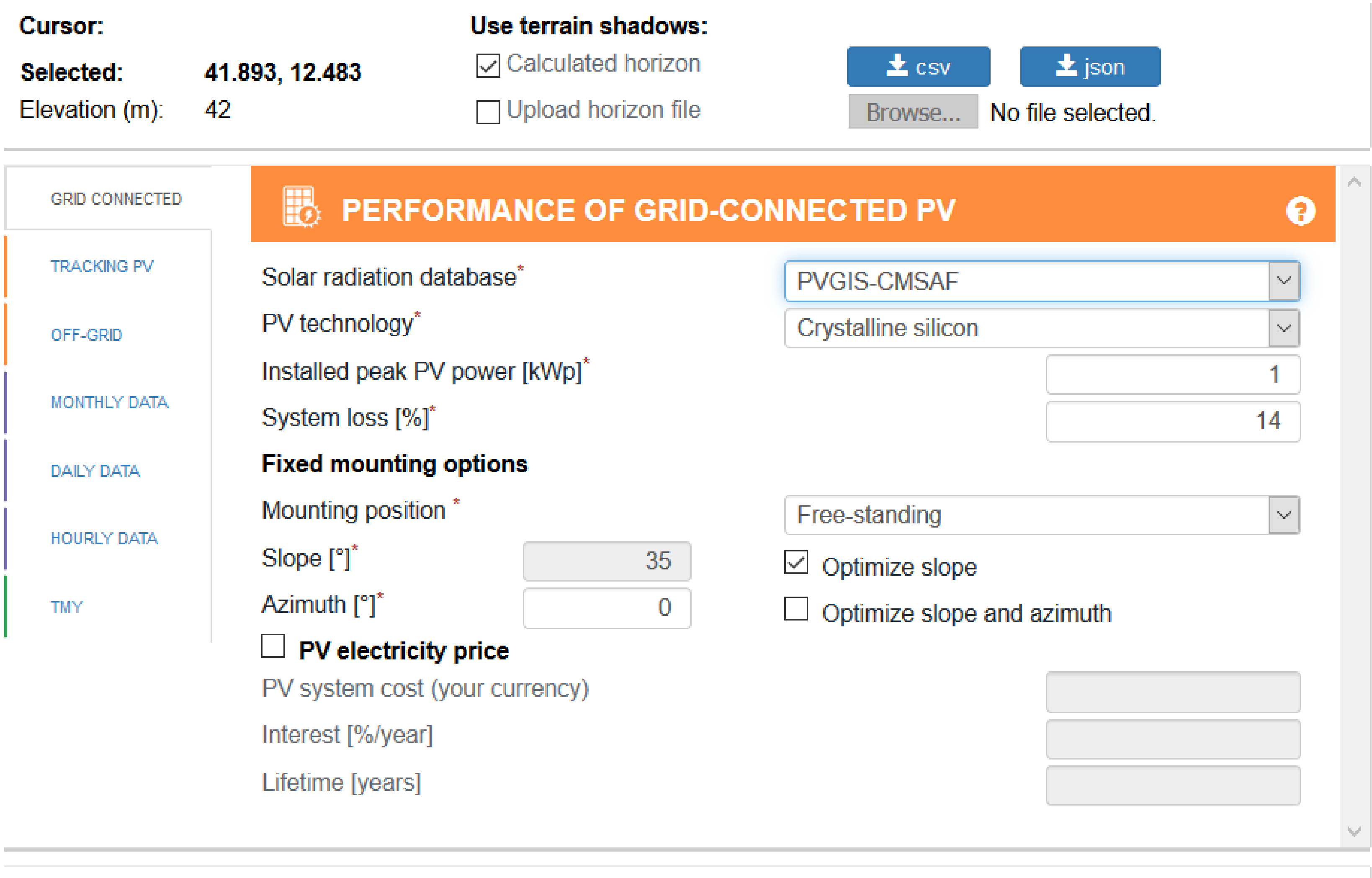
MOUNTING OPTIONS

- Type of system: fixed/tracking, free standing/BIPV
- Tilt Angle ß [0° – 90°] - slope of PV modules
- Azimuth Angle **α** [-180° – 180°] - orientation of PV modules



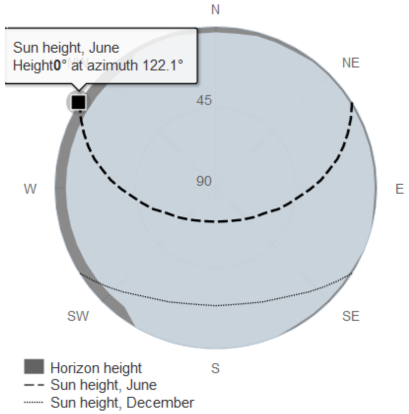
PV PERFORMANCE TOOL

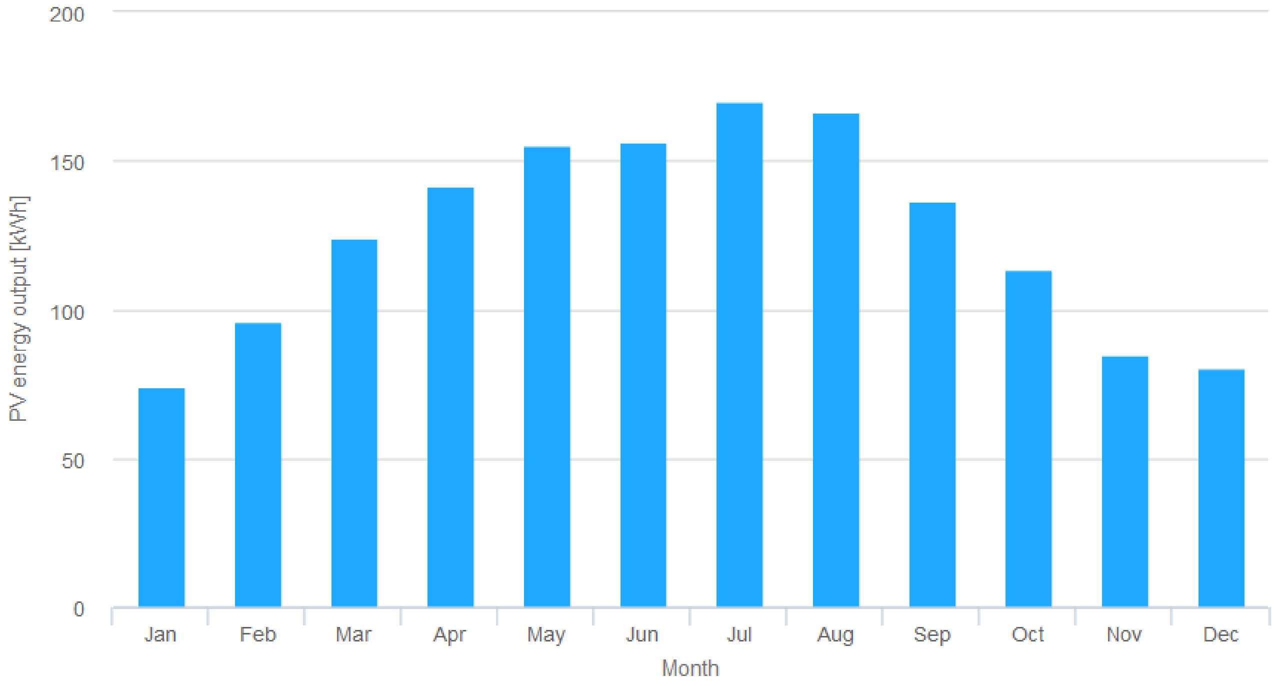
https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP



1 kWp PV SYSTEM IN ROME

Simulation outputs:	
Slope angle [°]:	35 (opt)
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	1498.69
Yearly in-plane irradiation [kWh/m^2]:	1917.28
Year to year variability [kWh]:	57.63





LEVELIZED COST OF ENERGY

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

- VO&MC [€/year]: variable operation and maintenance costs
- OCS [€]: overnight capital cost
- CRF [ ]: capital recovery factor
- FO&MC [€/year]: 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

$$CRF = \frac{WACC \times (WACC + 1)^N}{(WACC + 1)^N - 1}$$

$$WACC = \frac{E}{E + D} \times K_e + \frac{D}{E + D} \times K_d$$

LCOE PHOTOVOLTAICS

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

- OCS [€]: overnight capital cost
- CRF [ ]: capital recovery factor
- FO&MC [€/year]: fixed operation and maintenance costs
- E_0 [kWh/year]: yield of the plant over the first year of operations
- N [ ]: is the number of annuities received
- d_r [%/year]: degradation rate of the PV modules

NET PRESENT VALUE

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

$$ICF_k = E_0 \times \left[1 - \frac{d_r \times (k-1)}{100}\right] \times \left[P_{uf} \times sc + P_0 \times (1-sc)\right]$$

$$OCF_k = OCS \times FO\&MC$$

- OCFk [€]: Uscite di cassa
- E_0 [kWh]: Energia prodotta al primo anno
- Puf [€/kWh]: Costo dell'energia elettrica
- P_0 [€/kWh]: contributo scambio sul posto
- sc [ ]: Autoconsumo

- OCS [€]: Costo dell'impianto
- ICFk [€]: Entrate di cassa
- g [%]: Tasso d'inflazione
- e [%]: Tasso inflazione energia
- i [%]: Tasso d'interesse

FINANCIAL METRICS

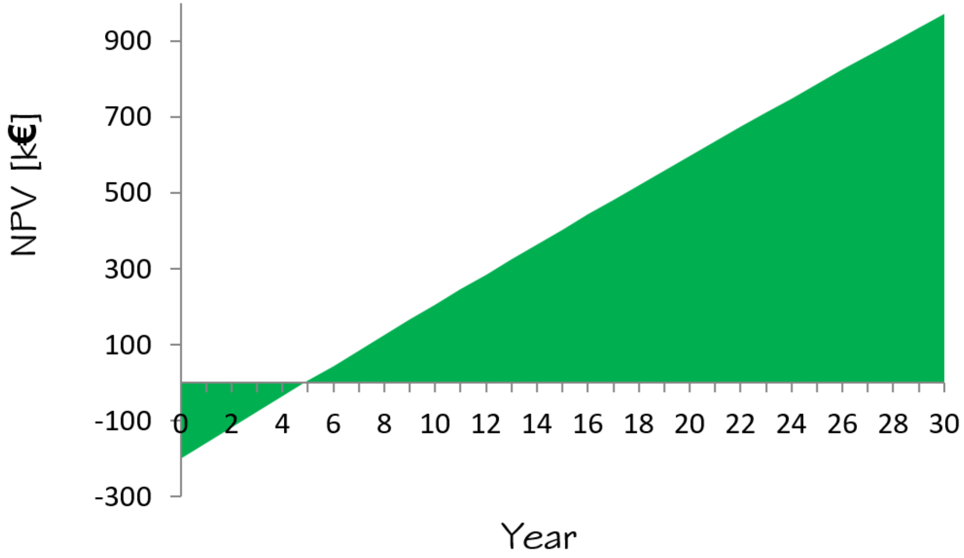
$$NPV = -ocs + \sum_{k=1}^{30} ICF_k \times \frac{(1+g)^k \times (1+e)^k}{(1+i)^k} - \sum_{k=1}^{30} OCF_k \times (1+g)^k$$

- 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

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

IMPIANTO «C&I» - ROMA

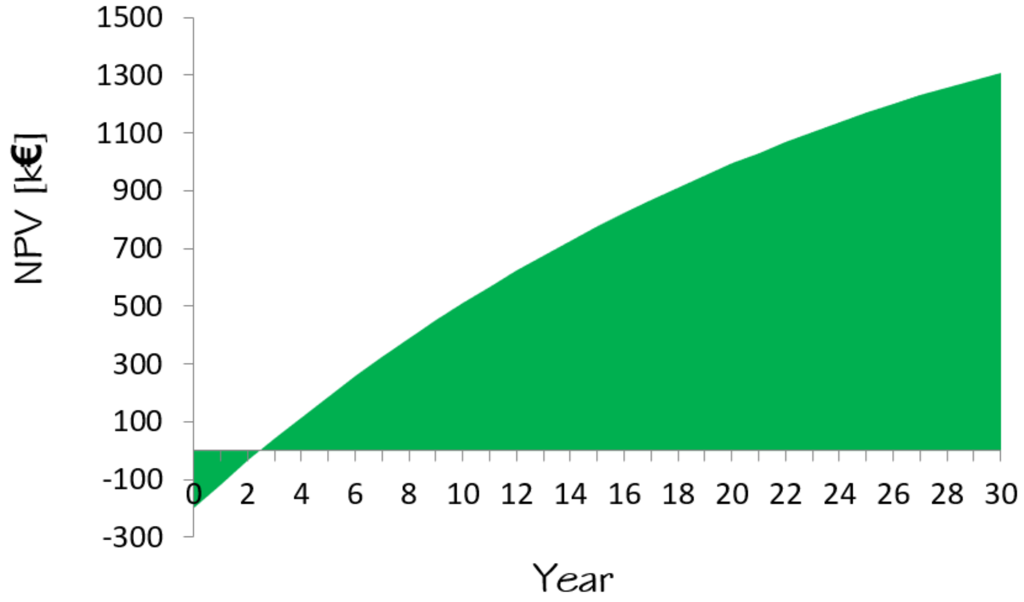
Produzione [kWh/kWp/anno]	1499
OCS [€/kWp]	1000
Potenza [kWp]	200
Prezzo energia elettrica [€/kWh]	0,15
Autoconsumo [%]	100



LCOE [€/kWh]	0,046
PBT [anni]	<5
IRR [%]	19,5

IMPIANTO «C&I» - ROMA

Produzione [kWh/kWp/anno]	1499
OCS [€/kWp]	1000
Potenza [kWp]	200
Prezzo energia elettrica [€/kWh]	0,30
Autoconsumo [%]	100



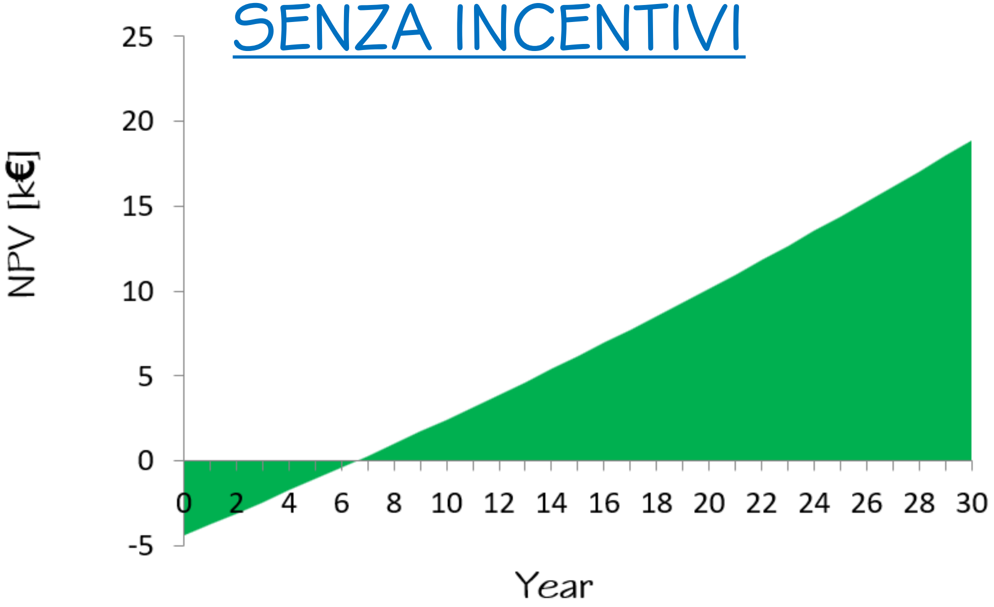
LCOE [€/kWh]	0,046
PBT [anni]	2.5
IRR [%]	25%

IMPIANTO «DOMESTICO» - ROMA

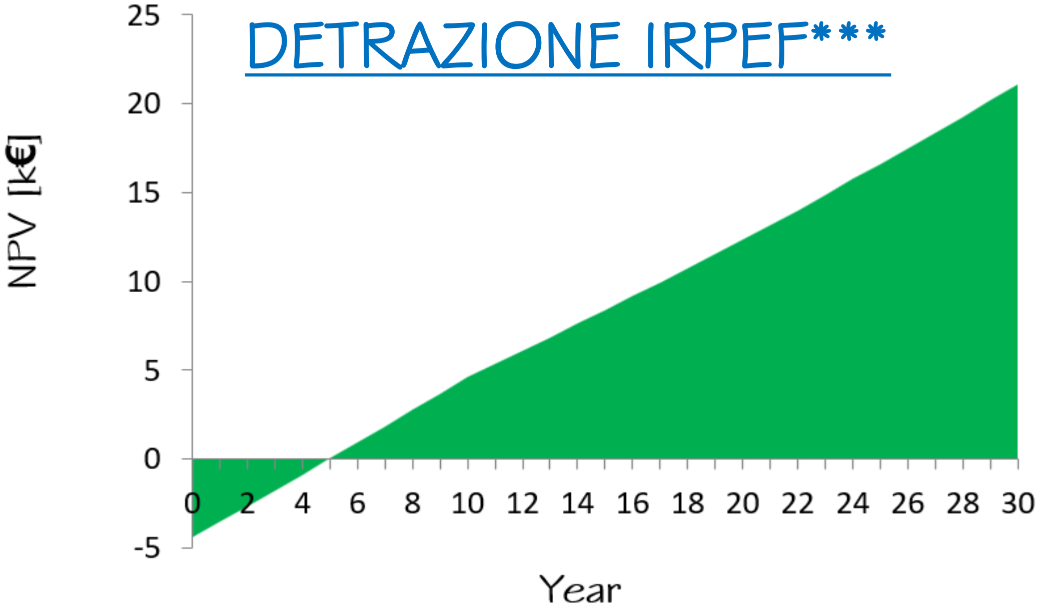
Produzione [kWh/kWp/anno]	1499
OCS [€/kWp]	2,200
Potenza [kWp]	2
Prezzo energia elettrica [€/kWh]	0.22
Autoconsumo [%]	40
Scambio sul posto medio [€/kWh]	0.20

LCOE [€/kWh]	0,05
PBT [anni]	6.5
IRR [%]	17.6
PBT*** [anni]	5
IRR*** [%]	19.3

SENZA INCENTIVI



DETRAZIONE IRPEF***



Elettrotecnica AA 2024/2025 Prof. Alessandro Massi Pavan

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APPLICATIONS ARE NOW OPEN!