MIT Portugal

TÉCNICO LISBOA

Renewable Energy Resources (RER)

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PV Energy

Chapter 3

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GENERAL CONCEPTS

Use of PV

- High Power (tens of MW)
  - Utility scale PV parks
- Medium Power (tens to hundreds kW)
  - Rural electrification
  - Decentralized power production - microgeneration
- Low power (0.1-kW)
  - Watches and pocket calculators, battery chargers, road signals, parking meters, …

Medium power use of PV

- Connected to the grid
  - Inverters
- Isolated
  - Battery
  - Load Controller
  - Inverter (if needed)
- Hybrid Systems
  - Feed isolated loads together with other renewables
  - Internal combustion engine (backup)

A simple problem

- The electricity demand in Portugal is 50TWh/year
- Assume:
  - The average efficiency of the PV panels is 10%
  - The average solar irradiation in Lisbon is 1750kWh/m^2/year
  - The total area occupied by the PV installation is double of the useful area of the PV panels

- **Compute the area occupied by the PV installation needed to supply all the electrical energy consumed in Portugal**

Solution

- PV electrical output = 1750 x 10% = 175kWh/m^2
- Required useful area = 50×10^9 / 175 = $286 \times 10^6 m^2$ = approximately 300km^2
- Required total area = 2 x 300 = 600km^2 = a square with a side of 24km
  - Area of Portugal = 91,000km^2
  - Area of Alentejo = 31,000km^2

- The problem is not the area
- **The problem is that electricity cannot be stored**

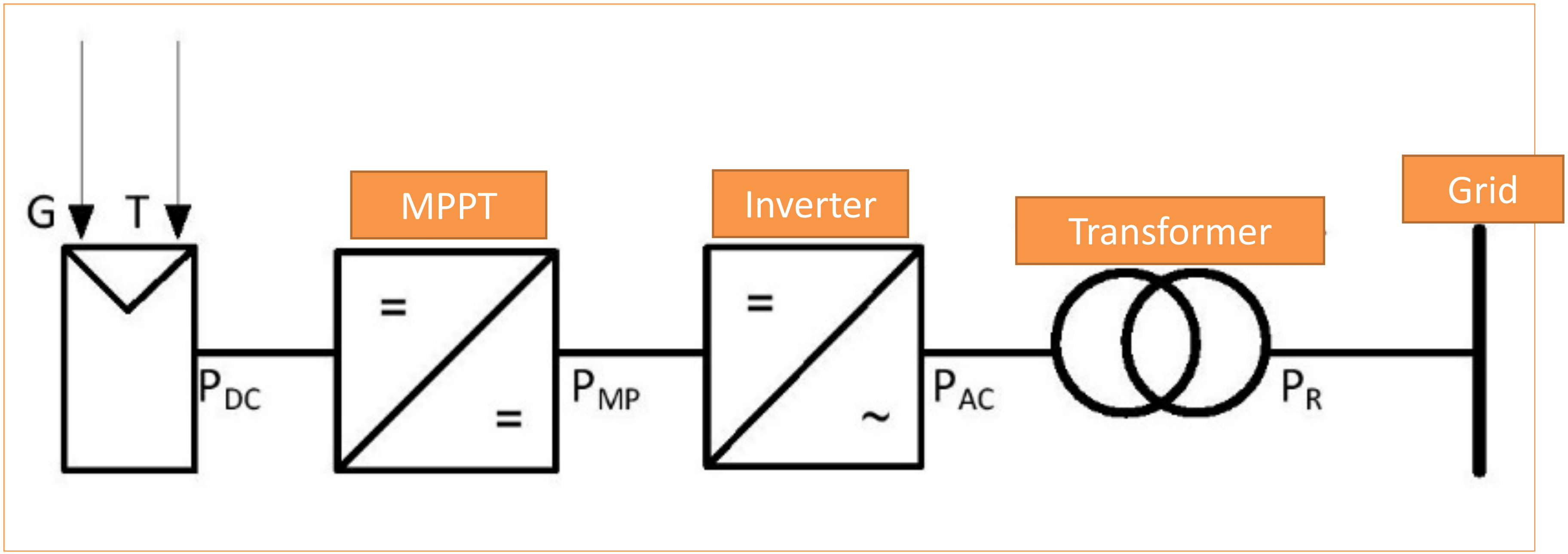
Some definitions

- Irradiance – G (W/m^2)
- Irradiation (Insolation) – H_i (Wh/m^2)
- Peak Power – $P_p = P^r_{DC}$ (W_p)
- **Standard Test Conditions – STC**
  - $G^r = 1000$ (W/m^2)
  - Cell temperature $\theta^r = 25ºC$

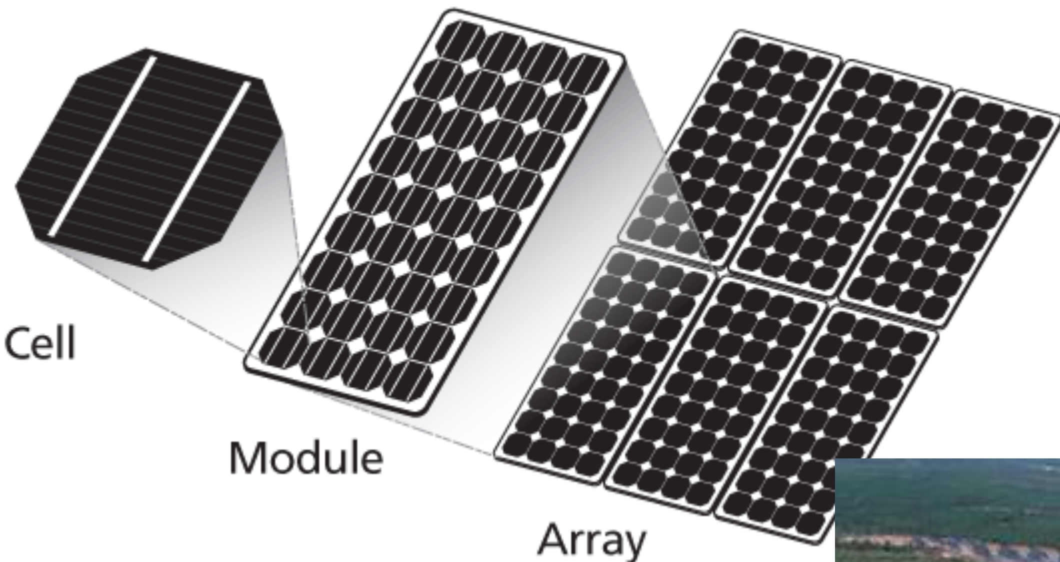
Efficiency @STC

$$\eta^r = \frac{P_p}{AG^r}$$

PV equipment



Cells, modules, arrays and parks



PHOTOVOLTAIC CELL OPERATING PRINCIPLE

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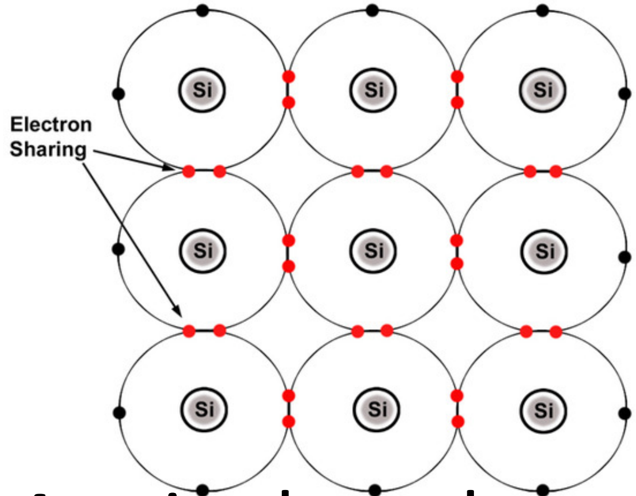


- 14p+&14e-; 4 e- in the valence band; 4 covalent bonds
- Valence band full (8e-): stable connection
- Photons with enough energy can displace the electrons e- to the conduction band and originate hole–electron pairs
- Energy gap band **1.12 eV**

An electric field is needed

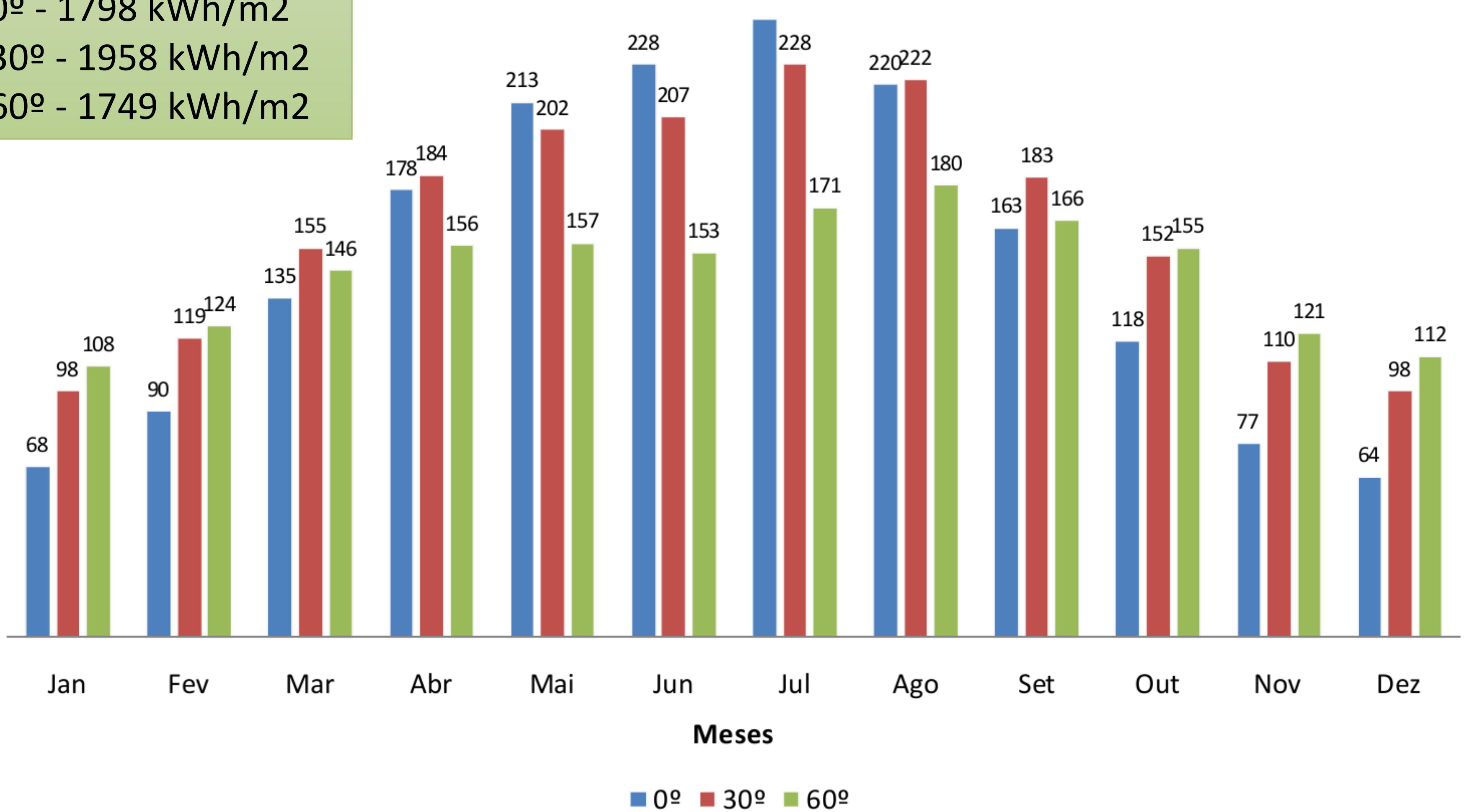
- Dope the silicon
  - Less 1e- (boron)=>Si type p (1:10,000,000)
  - More 1e- (phosphorous) => Si type n (1:1,000)
- p – n junction
  - holes will be accelerated to the + terminal
  - electrons will be accelerated to the - terminal
- DC current is produced

ENERGY PRODUCED BY A PV MODULE

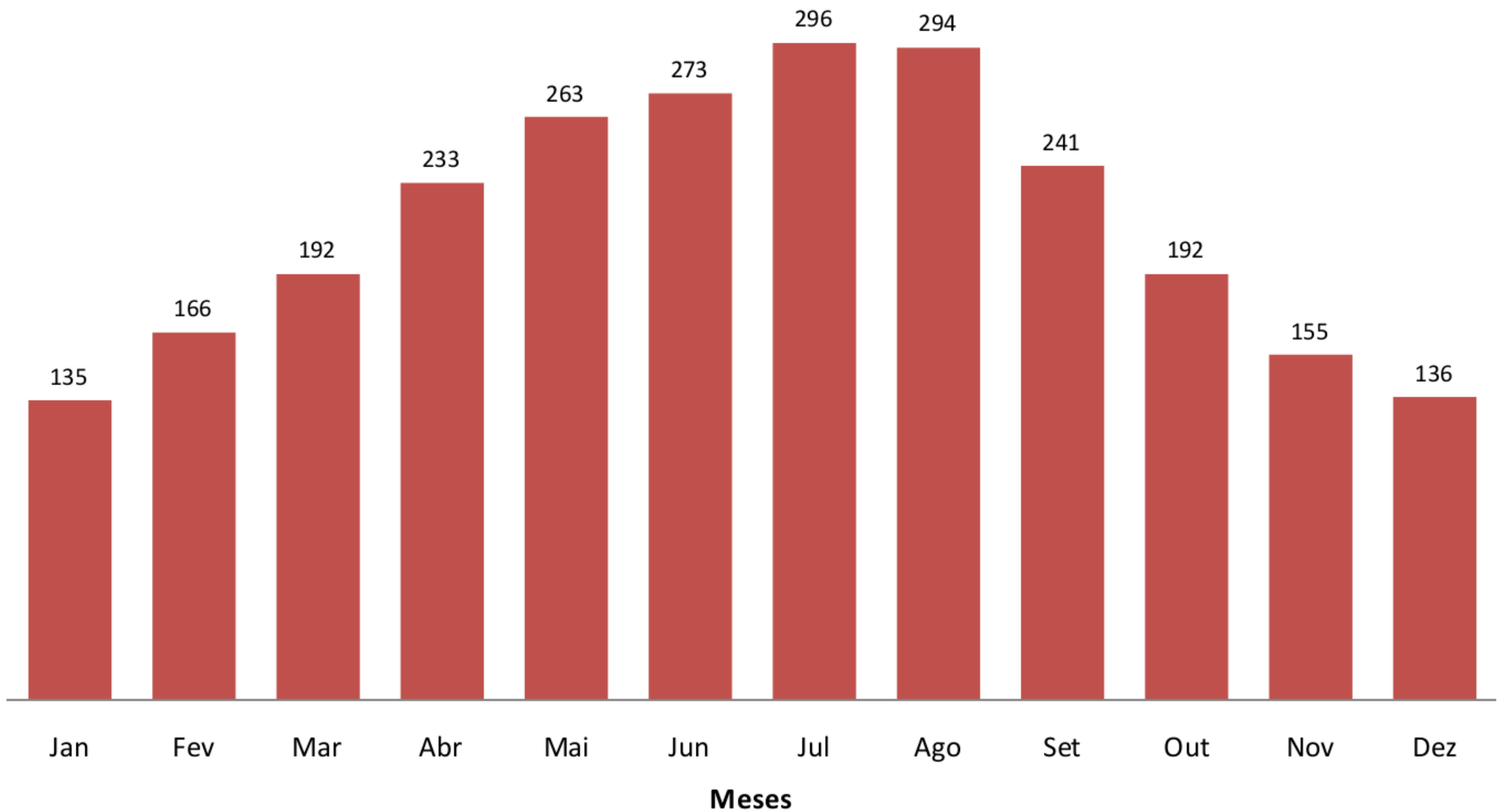
Energy delivered

Monthly irradiation (kWh/m2/month)

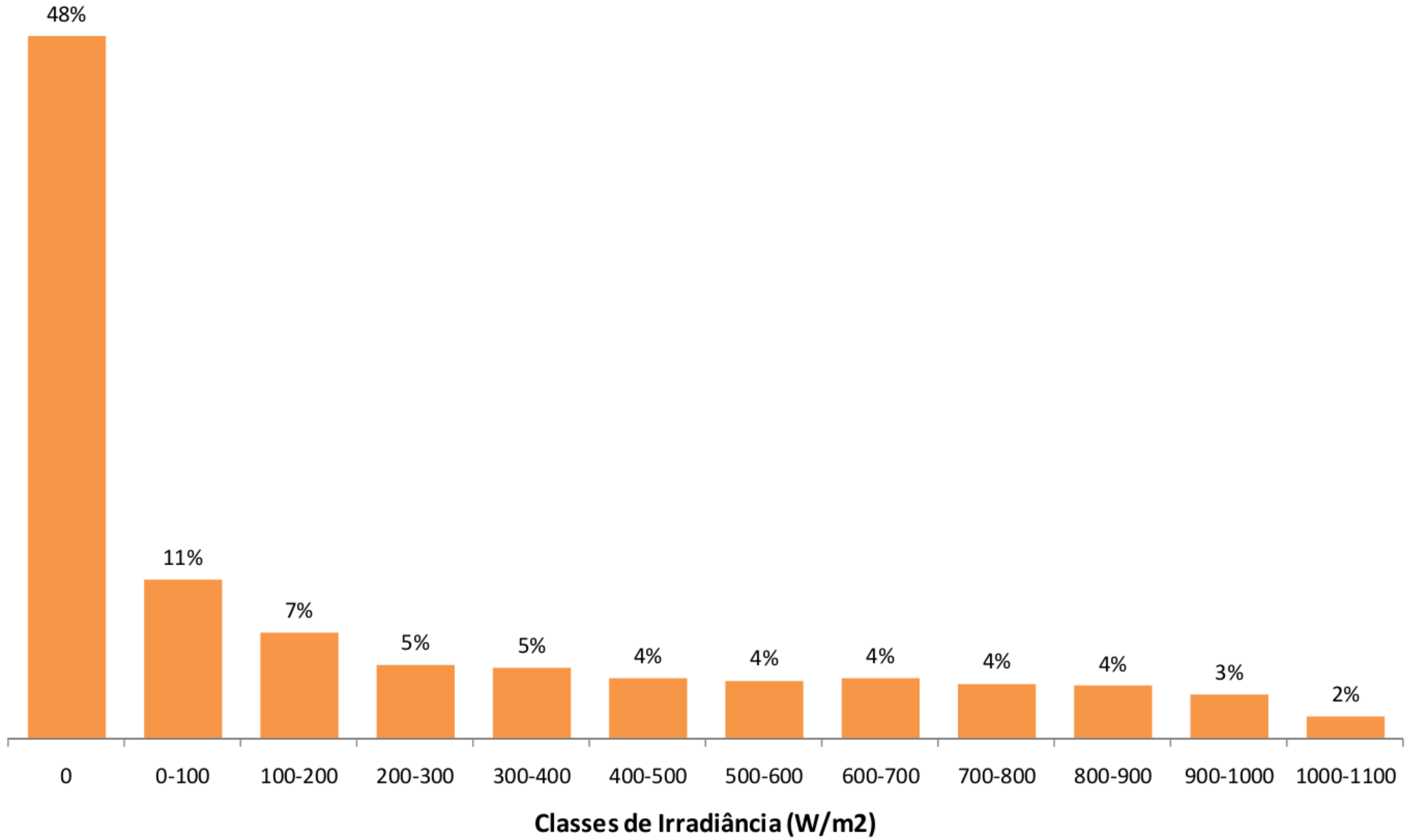
Year
0º - 1798 kWh/m2
30º - 1958 kWh/m2
60º - 1749 kWh/m2



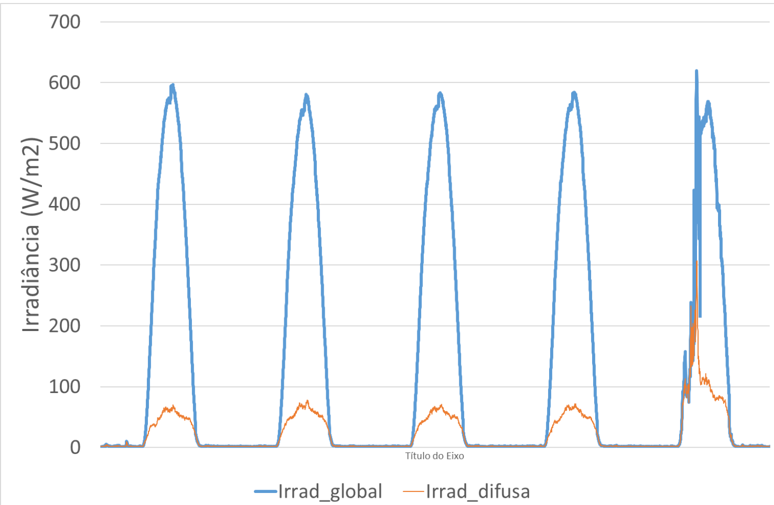
Average irradiance (W/m2)



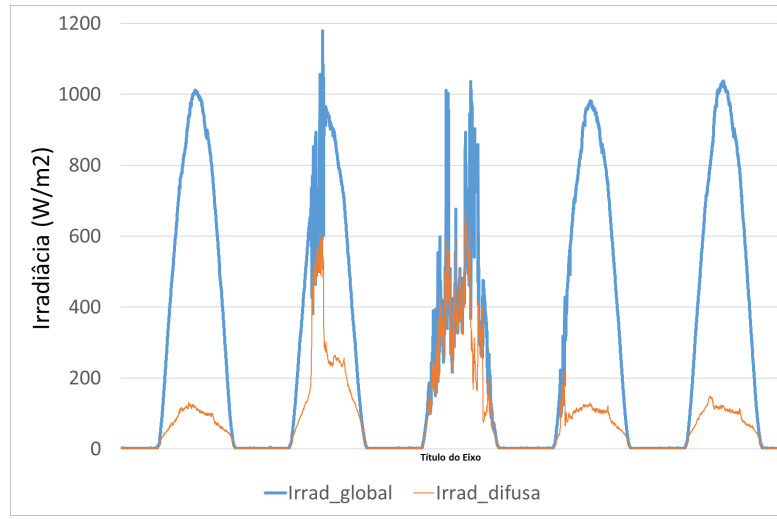
Irradiance histogram



Measured irradiance (W/m2)



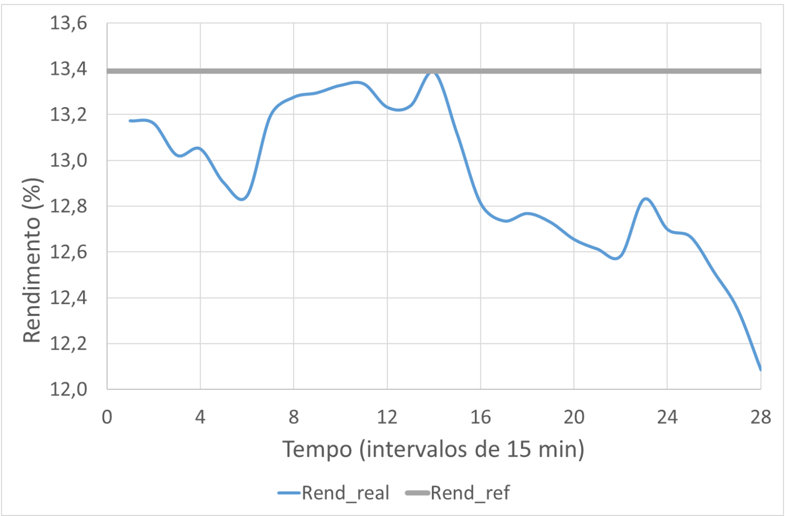
Winter



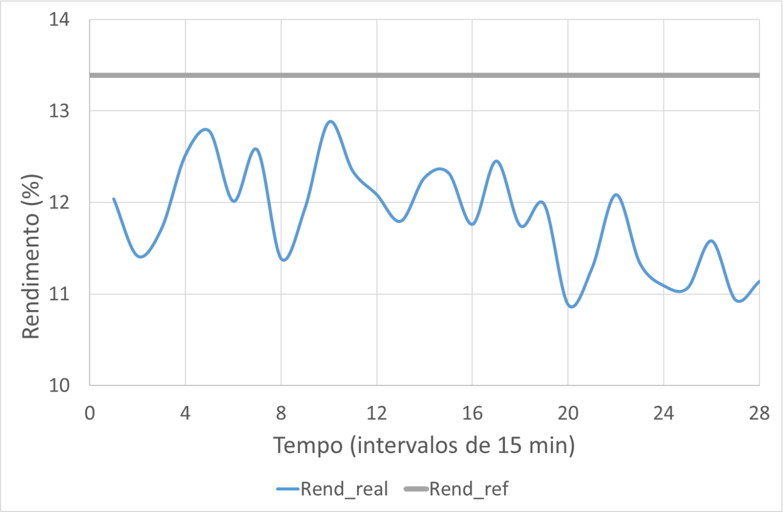
Summer

Blue – global irradiance
Orange – diffuse irradiance

Measured efficiency (%)



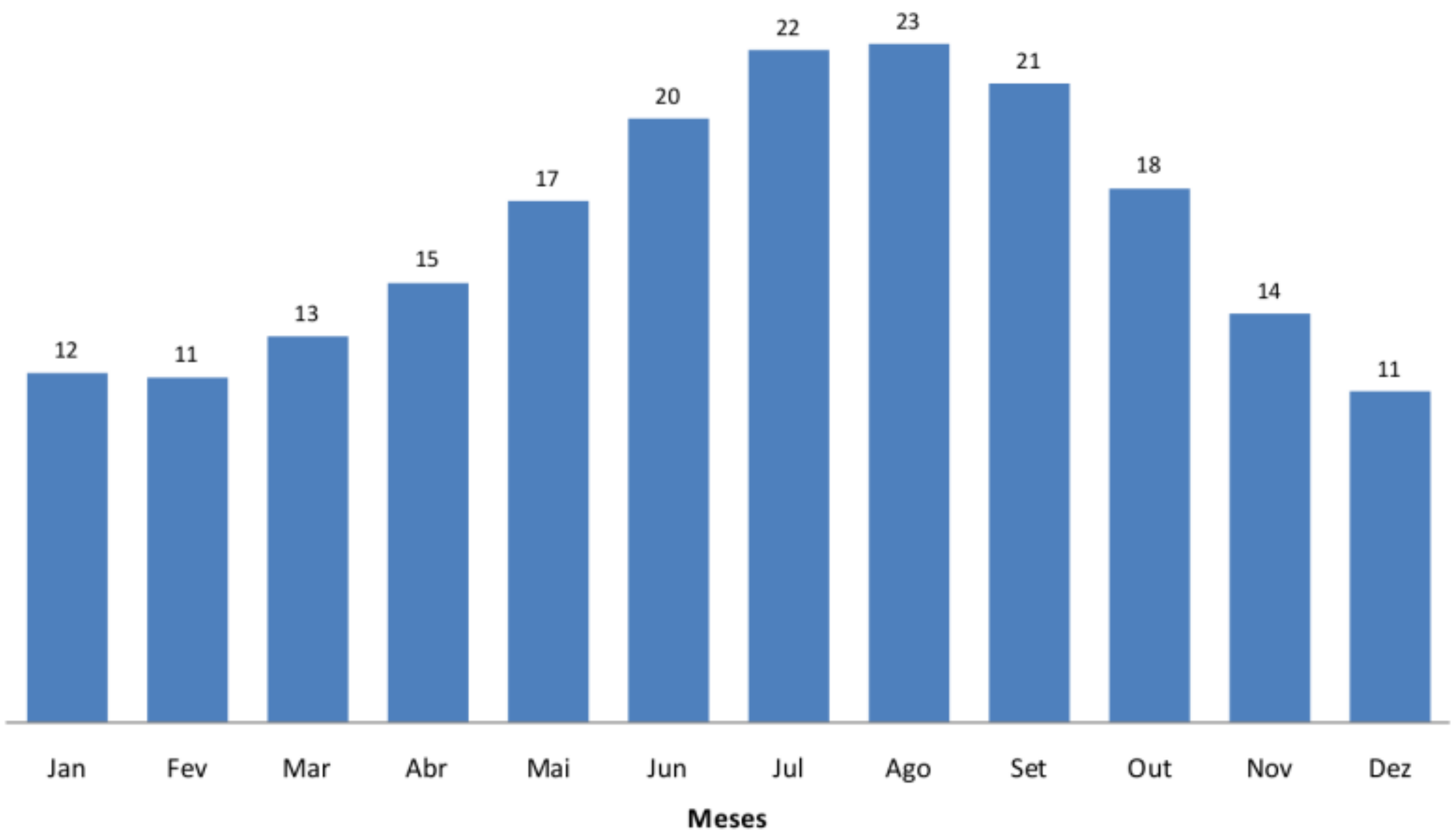
Clear sky



Cloudy day

Blue – measured efficiency
Grey – STC efficiency

Ambient temperature (ºC)



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Module temperature

$$\theta_m = \theta_a + kG$$

NOCT – **Normal Operating Cell Temperature**

Temperature of the cell when:

G = 800 W/m^2

θ_a = 20ºC (ambient temperature)

Given in the datasheet

$$\theta_m = \theta_a + \frac{G(NOCT - 20)}{800}$$

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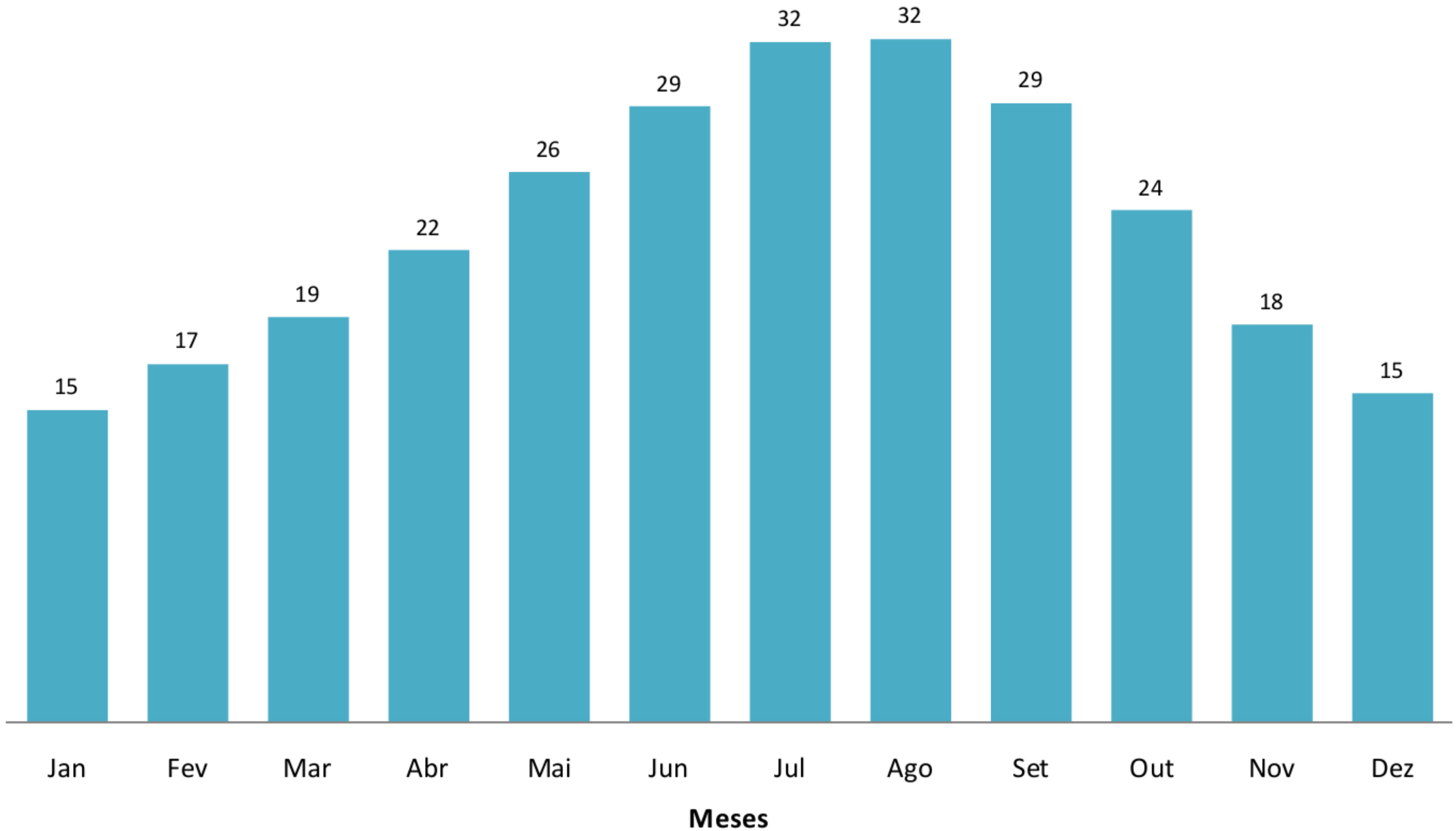
Module temperature (ºC)

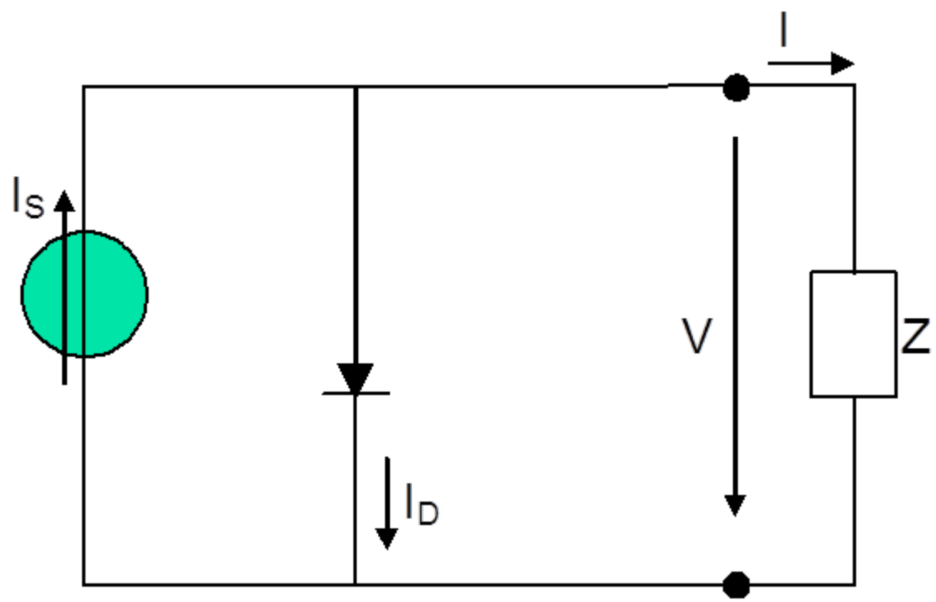


Fast estimate of DC power

$$P_{DC}(G,T) = \frac{G}{G^r} P_p \left[1 + \mu_{Pp}\left(T - T^r\right)\right]$$

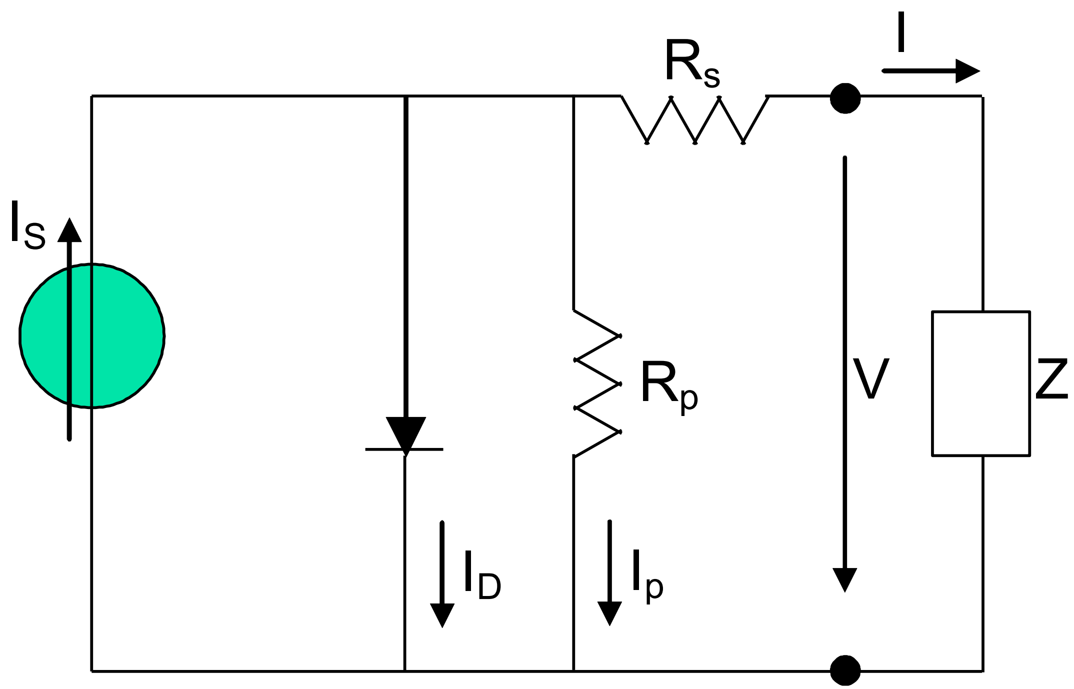
G – irradiance
Pp – peak power
µPp – peak power temperature coefficient (given in the datasheet)
T – cell temperature

Other models – 1D+3P



$$I = I_s - I_D = I_s - I_0\left(e^{\frac{V}{mV_T}} - 1\right)$$

Other models – 1D+5P



$$I = I_s - I_D - I_p = I_s - I_0\left(e^{\frac{V+R_sI}{mV_T}} - 1\right) - \frac{V+R_sI}{R_p}$$

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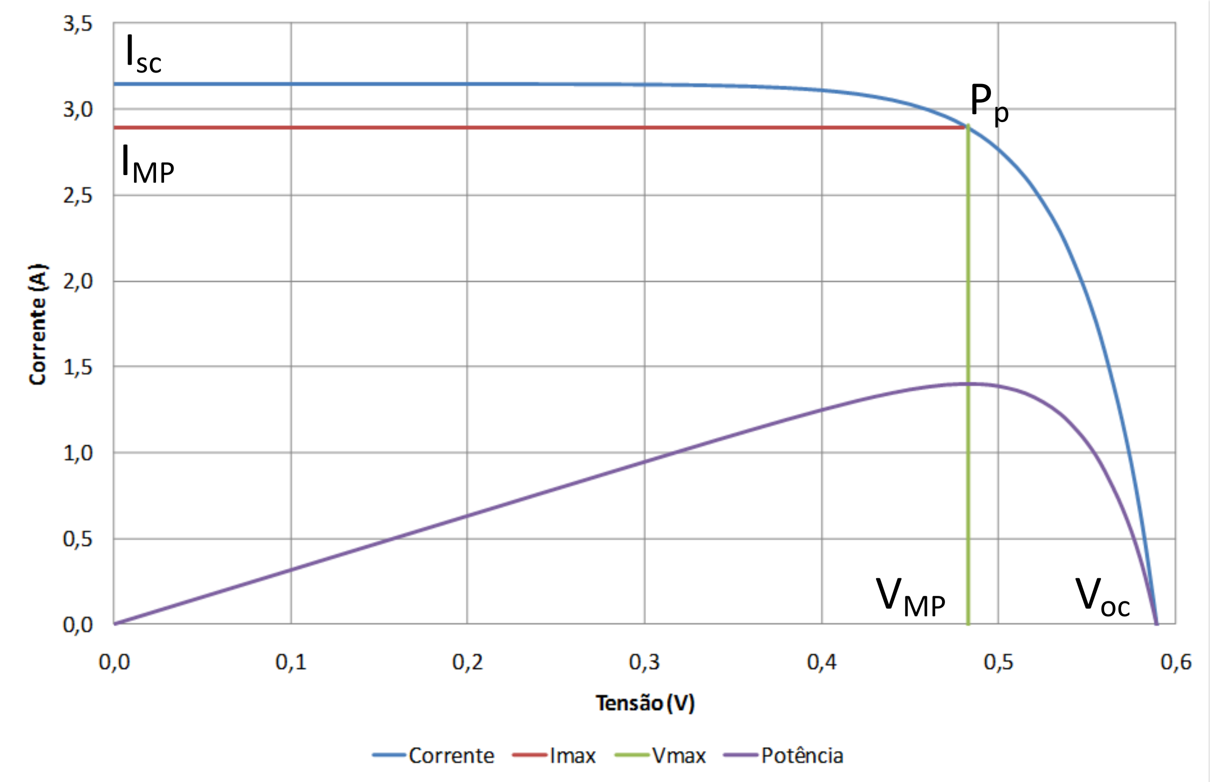
PV datasheets

Symbol	Unit	Description
$P_{MP}^{r} = P_p$	Wp	Peak power – Maximum DC power output @STC.
V_{MP}^{r}	V	Output voltage at maximum power @STC.
I_{MP}^{r}	A	Output current at maximum power @STC.
V_{oc}^{r}	V	Open circuit voltage @STC.
I_{sc}^{r}	A	Short-circuit current @STC.
NOCT	ºC	Normal Operating Cell Temperature (NOCT) – Module temperature in Normal Operating Conditions (NOC) defined as: irradiance = 800 W/m^2 and ambient temperature = 20ºC.
μ_{Isc}	%/ºC	Temperature coefficient of the short-circuit current.
μ_{Voc}	%/ºC	Temperature coefficient of open circuit voltage.
μ_{Pp}	%/ºC	Peak power temperature coefficient.
N_s		Number of cells connected in series in the module.
P_{MP}^{NOCT}	W	Maximum DC power output under NOC.
V_{MP}^{NOCT}	V	Voltage at maximum power under NOC.
I_{MP}^{NOCT}	A	Current at maximum power under NOC.
V_{oc}^{NOCT}	V	Open-circuit voltage under NOC.
I_{sc}^{NOCT}	A	Short-circuit current under NOC.

Standard Test Conditions



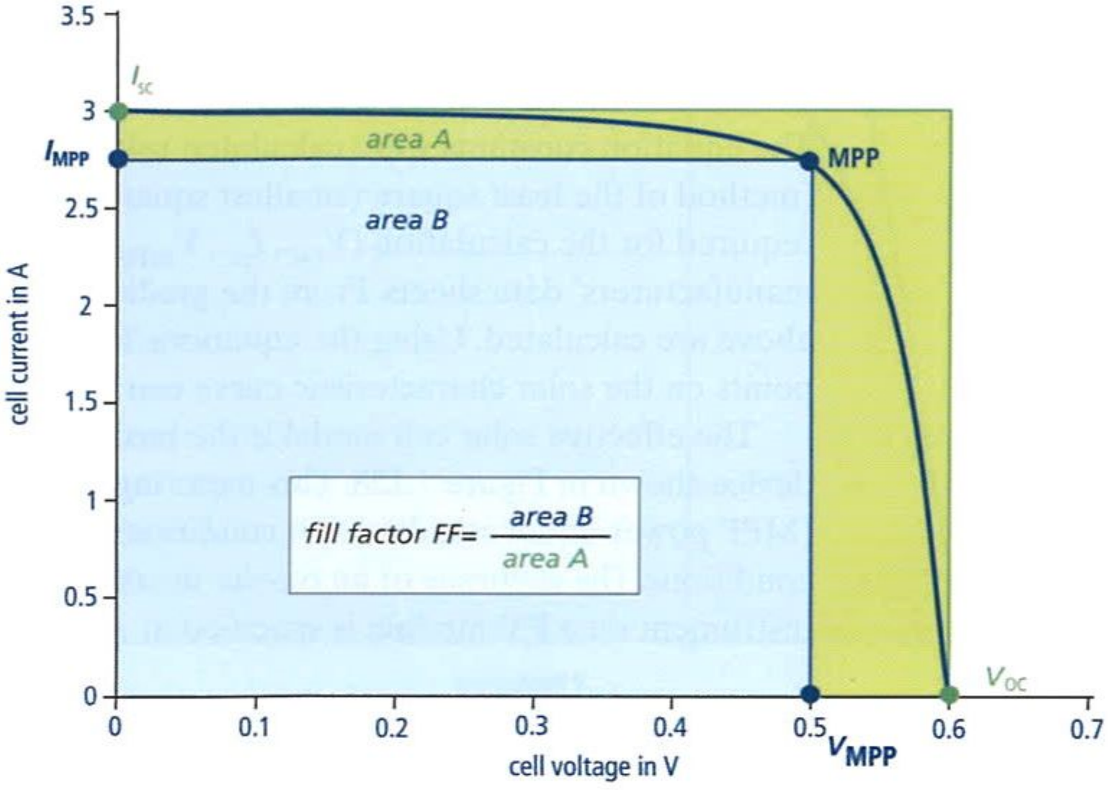
Peak Power

$$P_p = P_{DC}^r = V_{MP}^r I_{MP}^r$$

Efficiency and Fill Factor

$$\eta^r = \frac{P_{DC}^r}{AG^r}$$

$$FF = \frac{P_{DC}^r}{V_{ca}^r I_{cc}^r}$$



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Annual Energy

$$E_a = \sum_{i=1}^{n} \eta_{inv}(P_{DC_i}) P_{DC}(G,T)_i \Delta t_i$$

- P_{DC} – Depending on the desired accuracy, it can be computed with:
  - 1D+5P model
  - 1D+3P model
  - Fast Estimate
- Δt_i is the time interval
- n is the total number of time intervals
- η_{inv} is the efficiency of the power electronics, namely the inverter; in general, it depends on the DC output power level

MAXIMUM POWER POINT TRACKER (MPPT) AND INVERTER

- DC output power changes with atmospheric conditions and with the terminal voltage
- **Objective**: operation at maximum possible output power, according to the conditions of irradiance and temperature
- PV converters are equipped with a digital controller of the voltage at maximum power (**MPPT**)
- The voltage reference value as calculated by the MPPT is the input of a **DC/DC converter** that adjusts the output voltage to the input voltage of the inverter

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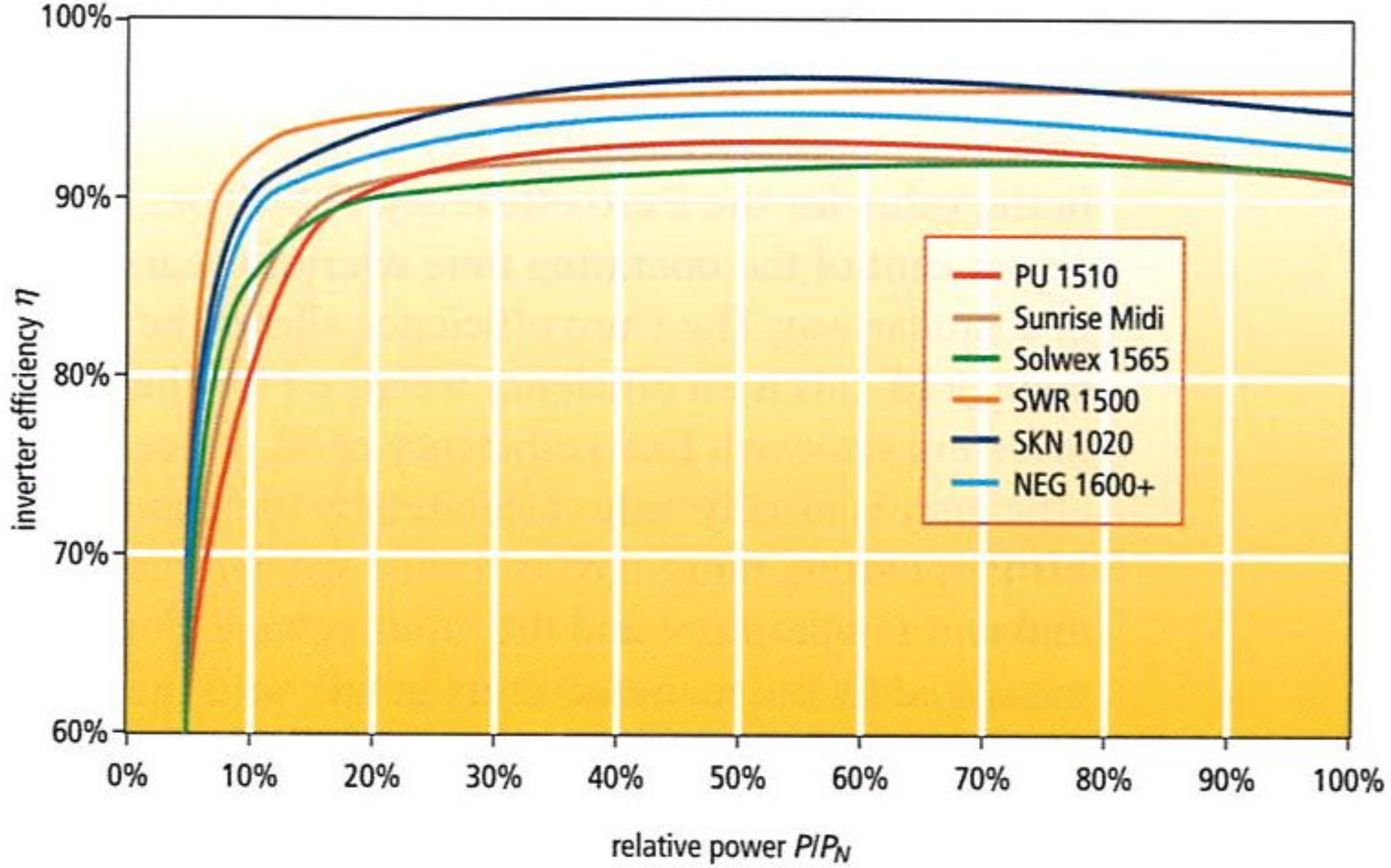

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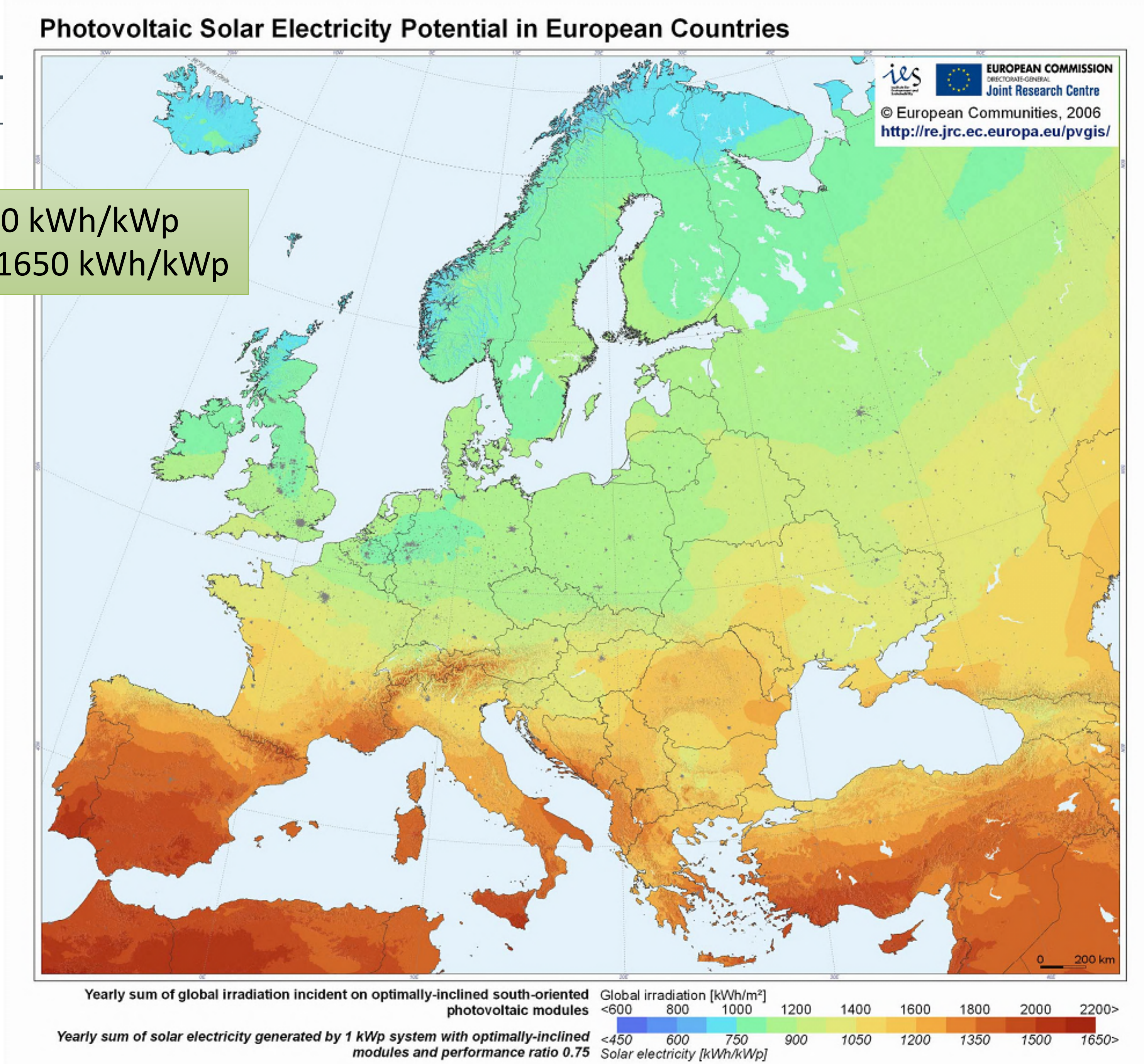
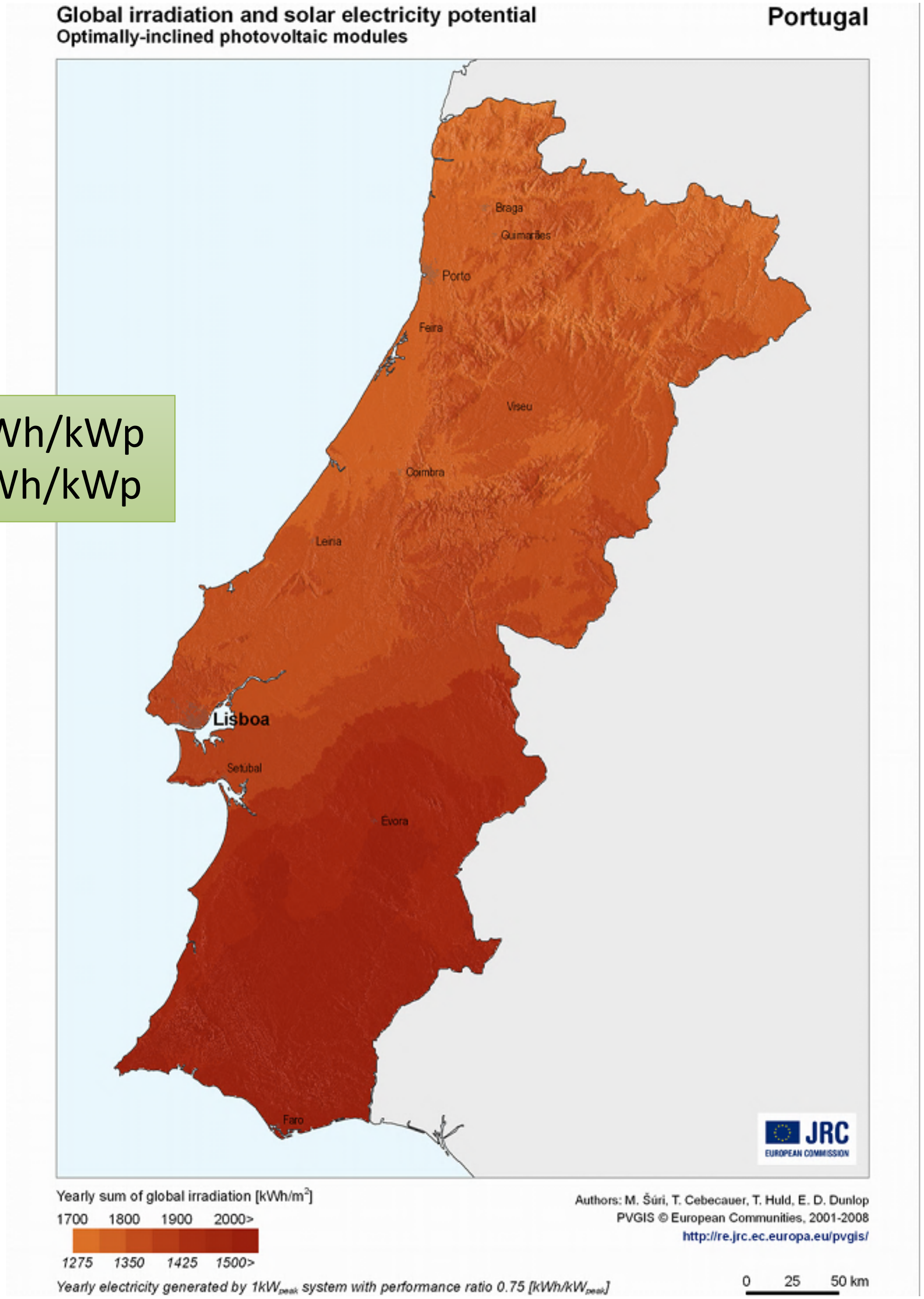
PV RESOURCE

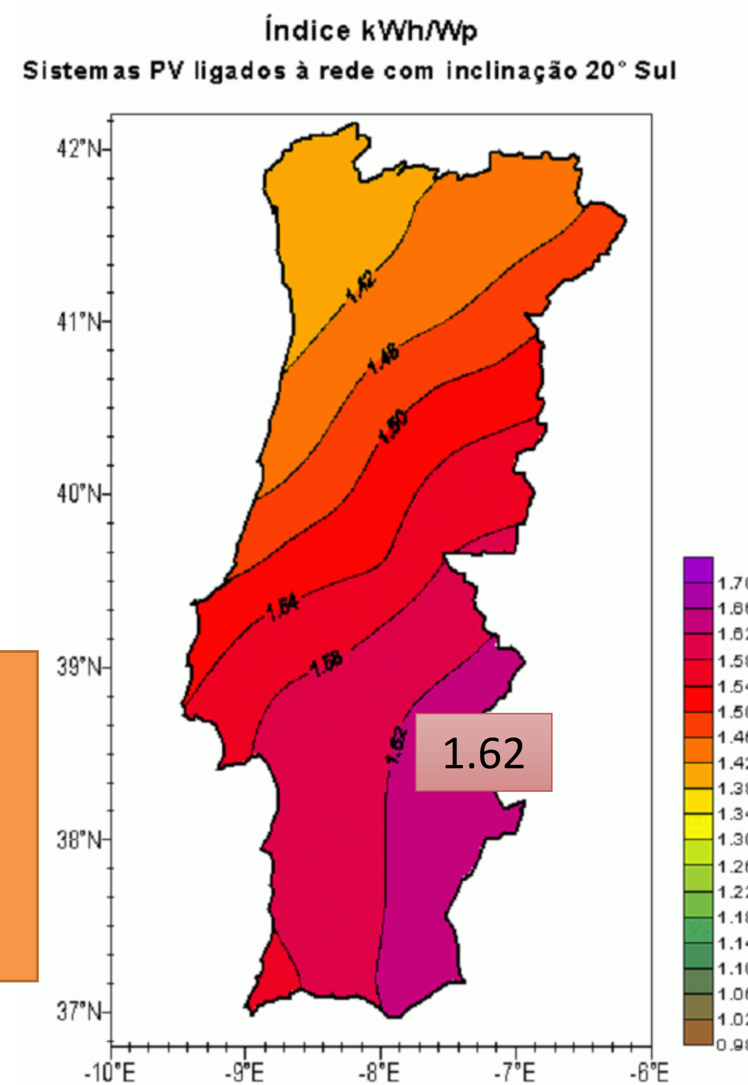
Blue: 450 kWh/kWp
Brown: 1650 kWh/kWp



Light brown: 1250 kWh/kWp
Dark Brown: 1650 kWh/kWp



Sun tracking systems



Sun tracking systems

Moura: 90 GWh ⇔ 1950 kWh/kWp

Serpa: 20 GWh ⇔ 1800 kWh/kWp

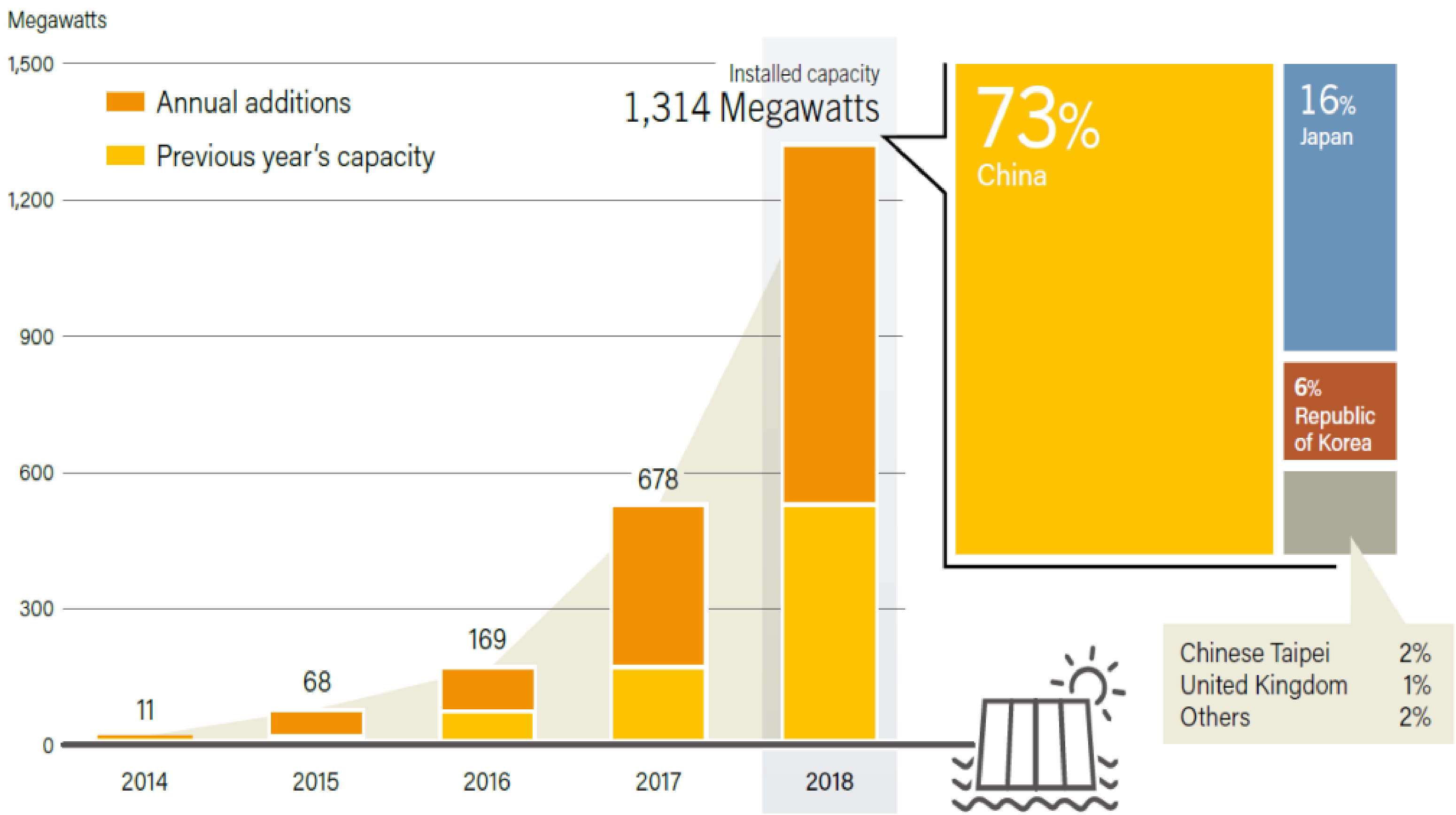
FLOATING PV

Floating PV

- Exponential increase in the number of FPV installations
  - strong interest from regions that lack available land for solar deployment
  - driven by the rapid development of large-scale projects in China

Statistics

FIGURE 29. Floating Solar PV Global Capacity and Annual Additions, 2008-2018, and Top Countries, End-2018



Source: World Bank Group, ESMAP and SERIS. See endnote 146 for this section.

Source: REN21

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Advantages

- Elimination of the need for major site preparation
- Improved output (due to the cooling effect of water and less dust on panels)
- Reduced evaporation from water reservoirs
- Use of existing electricity transmission infrastructure at hydropower sites.

Hybrid FPV

- Combining solar PV technology with hydropower stations
- World's first hybrid FPV and hydropower system installed in 2017 in Portugal (220 kW at the Alto Rabagão Dam)
- LCOE of FPV does not differ greatly from that of ground mounted
- Capital costs of FPV are still slightly higher
  - need for floats, moorings and more resilient electrical components
- These costs are balanced by a higher expected energy yield of FPV
  - conservatively estimated to be 5% higher, with gains potentially as high as 10-15% in hot climates

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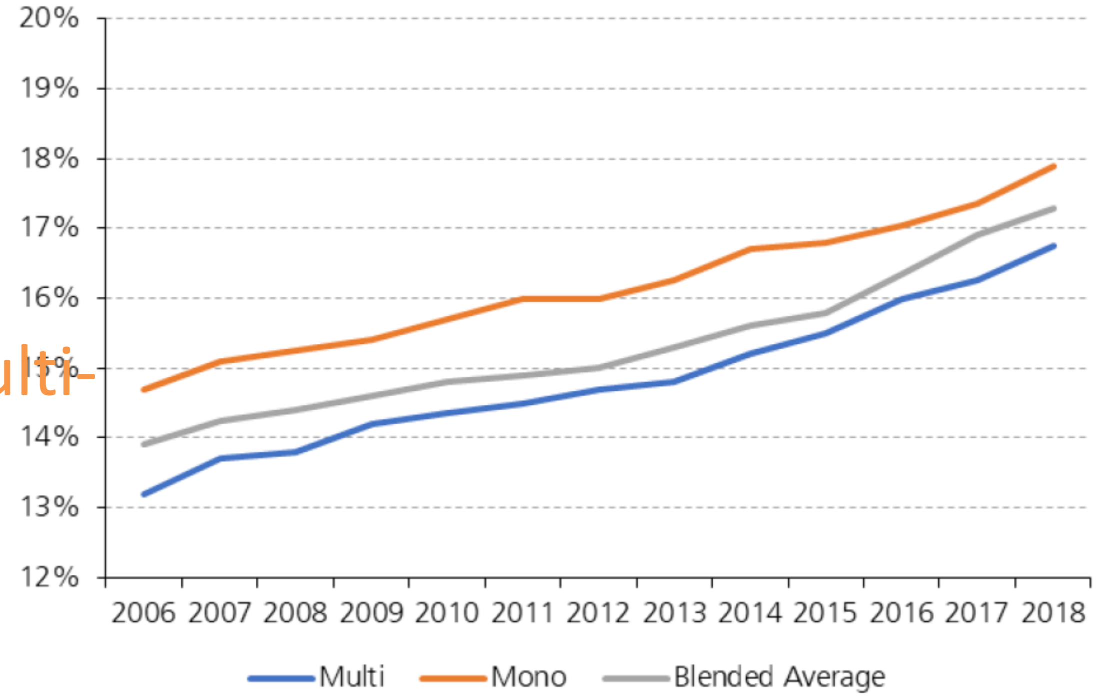
PHOTOVOLTAIC TECHNOLOGIES

1st Generation – Crystalline silicon cells

- Monocrystalline:
  best efficiency: 18%

- Polycrystalline or Multi-crystalline:
  best efficiency: 16%

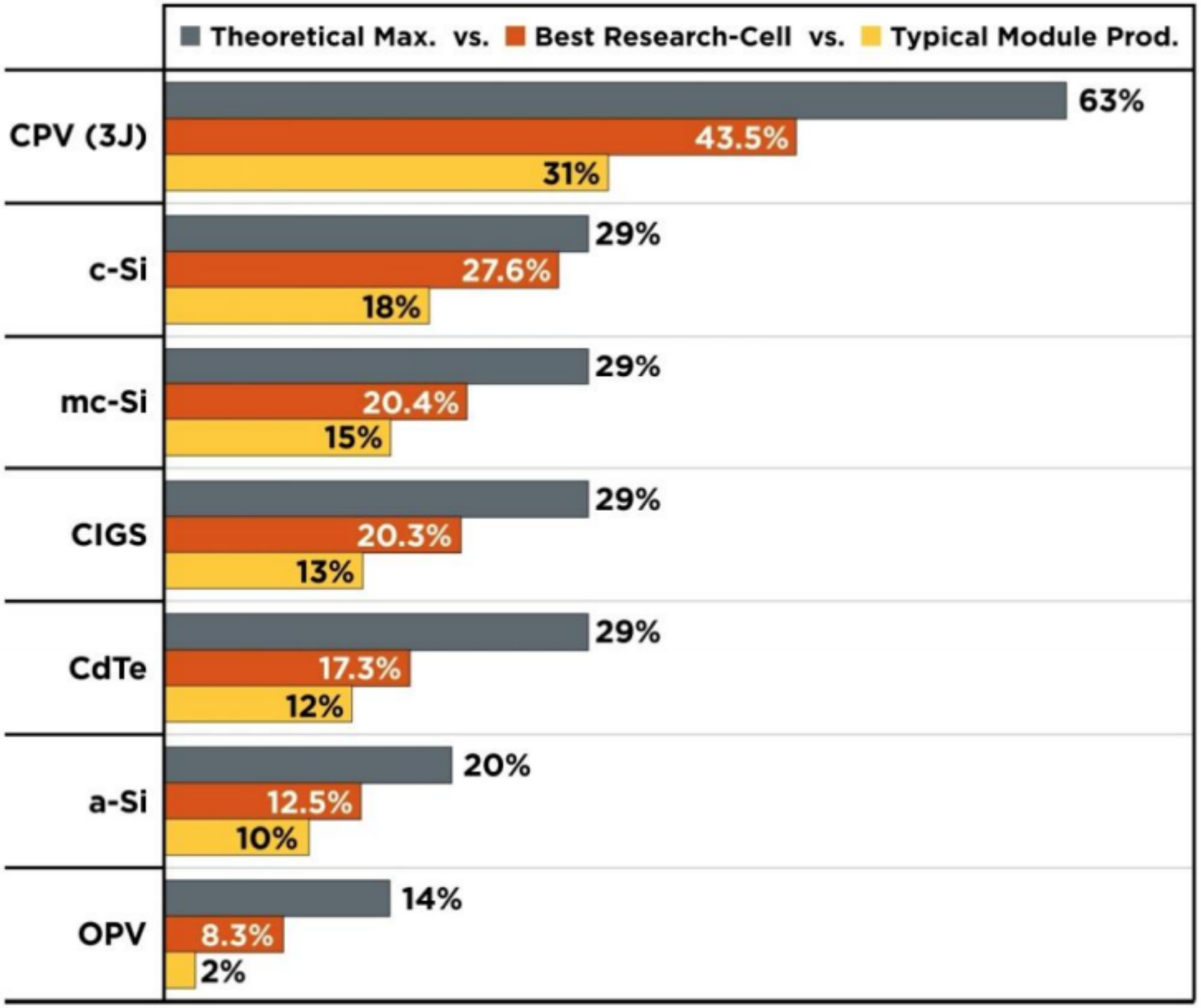


Source: Fraunhofer ISE

2nd Generation – Thin films

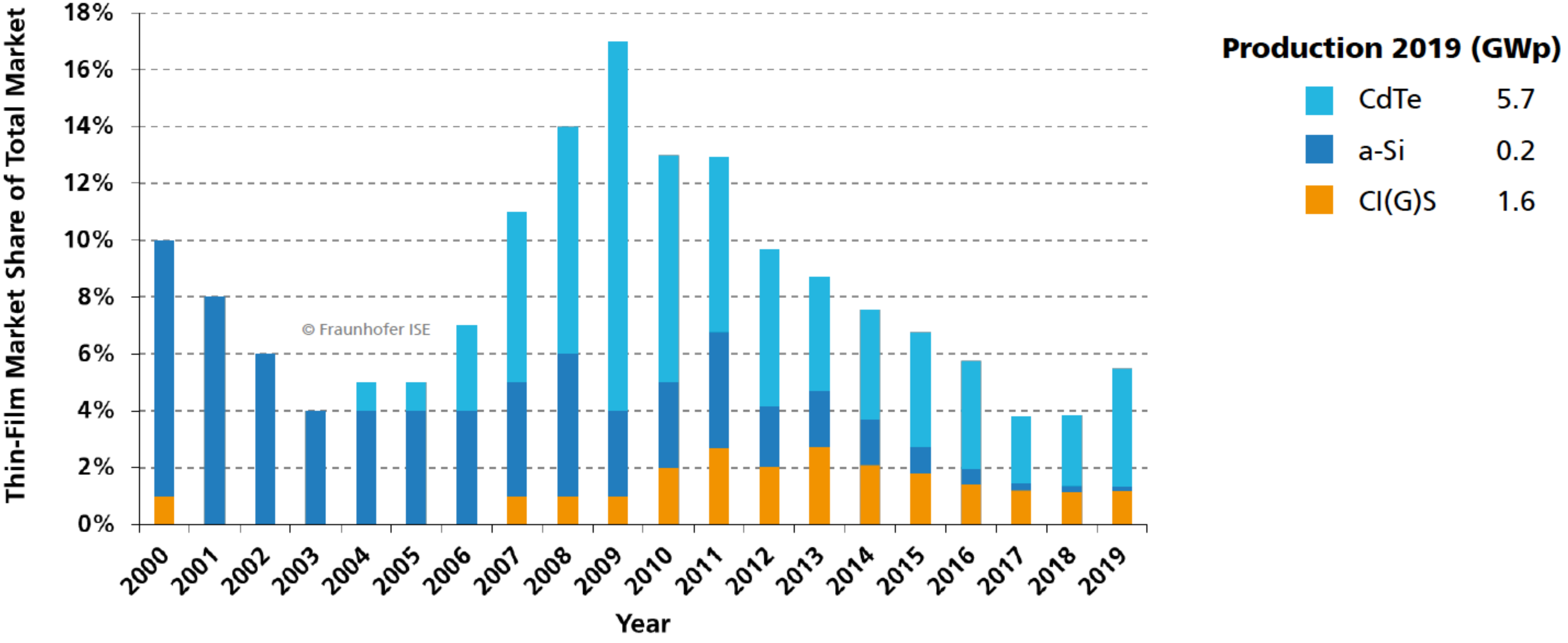
- Materials with high light absorption properties
- Lightweight solar cells that can be made on flexible substrates
- Large-scale production
- High efficiencies in Lab, but not in practice
  - Cadmium Telluride (CdTe); Cd is toxic
  - Amorphous Silicon (a-Si); less efficient
  - Copper-Indium-Gallium Selenide (CIGS); high Lab promises

Thin Film efficiency



Source: NREL

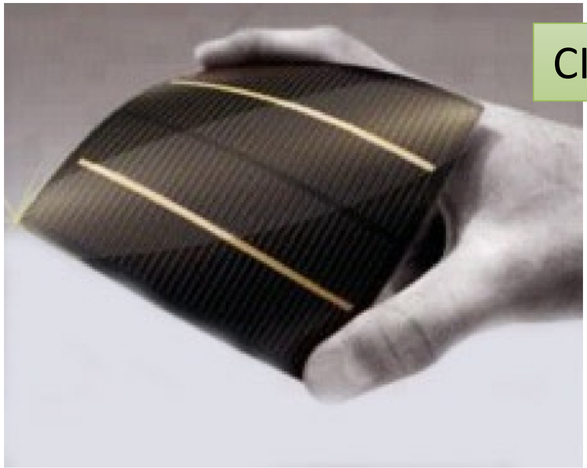
Thin Film market share



Source: Fraunhofer ISE

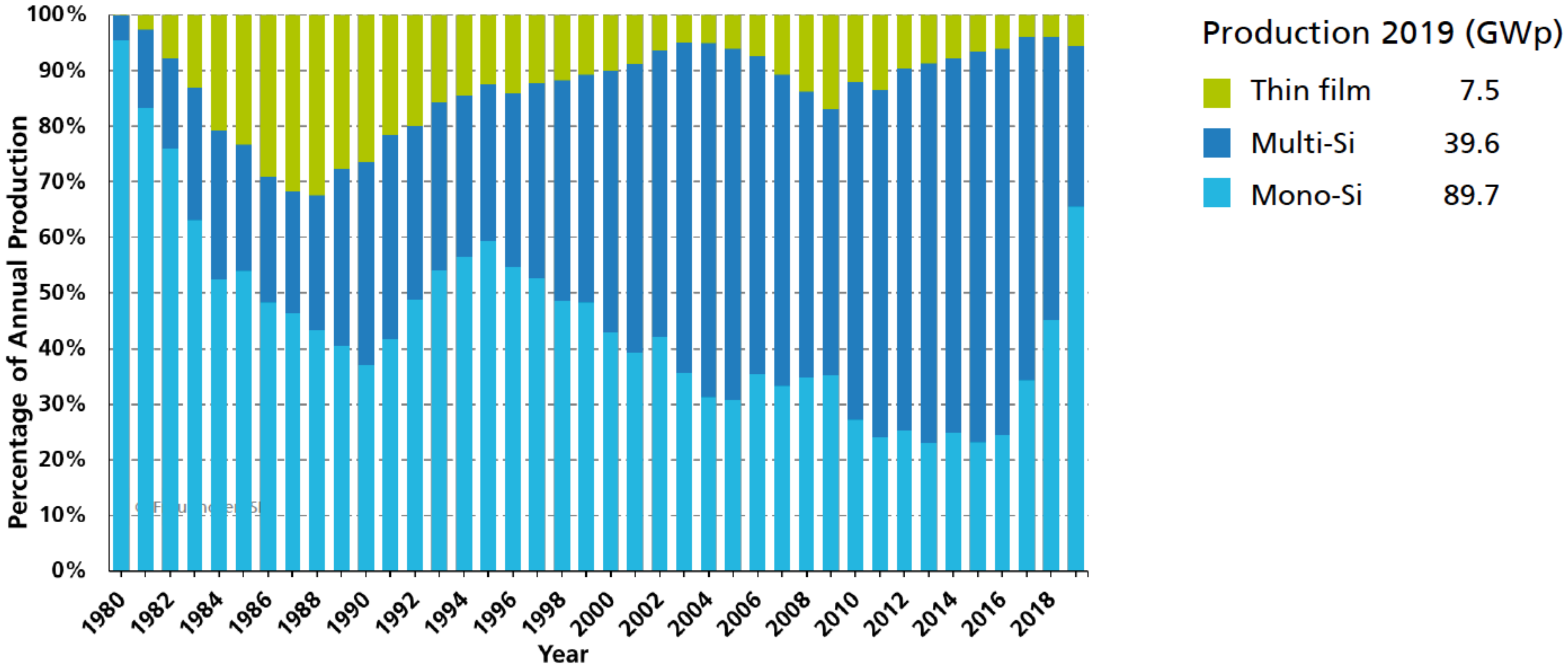
Thin films

CdTe



CIGS

PV market



Source: Fraunhofer ISE

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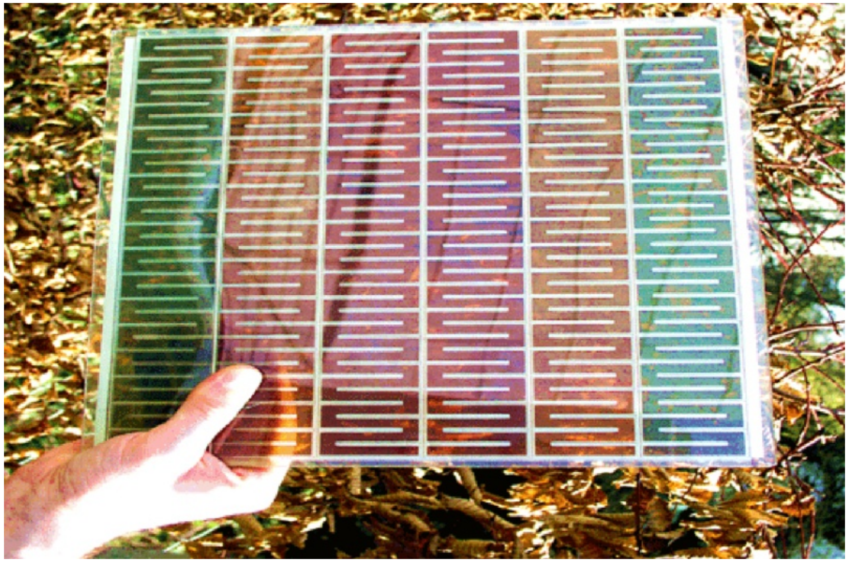
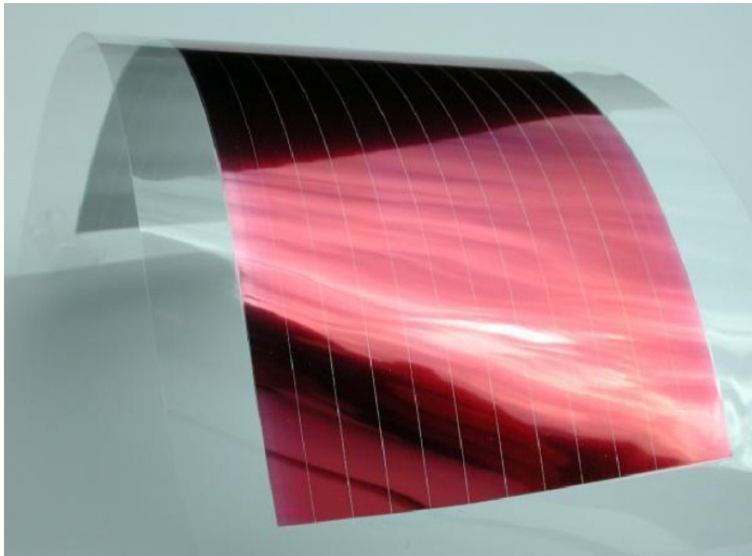
3rd Generation – Emerging technologies

- Dye–Sensitized nano crystalline cells (Gratzel cells): base material is titanium dioxide
- eff: 12% (laboratory), 5% (1st batch produced)



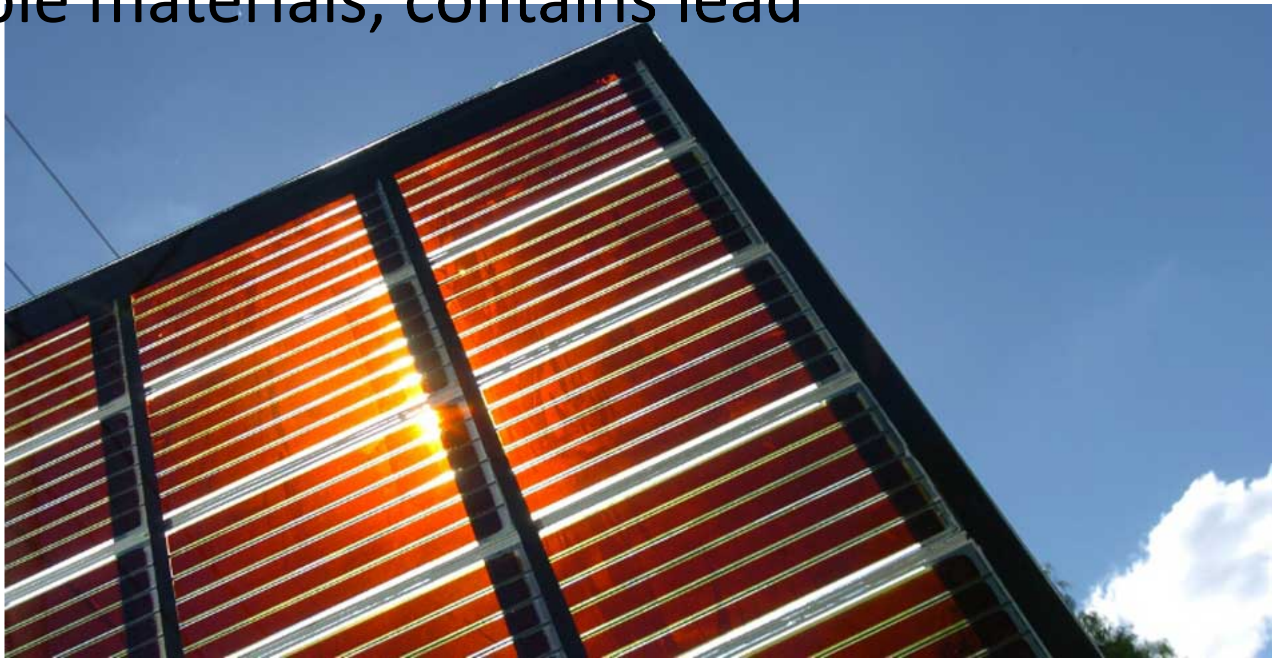
3^{rd} Generation – Emerging technologies

- Organic cells: organic pigments as donors and receivers of electrons and holes instead of a p-n junction; eff: 7% - 8%
- Less efficient (about 1/3 of a typical Si) and prone to quicker degradation



3rd Generation – Emerging technologies

- Perovskite solar cells: perovskite structured compound, hybrid organic-inorganic lead or tin halide-based
- Issues: overall cost (electrode material is gold), short lifespan, unstable materials, contains lead



3rd Generation – Emerging technologies

- Bifacial: power production on the back and front
- Advantage: Power gains between 5% and up to 30%, depending on the solar cell technology used, location, and system design

Concentration technologies

- Optical system (Fresnel lenses) to concentrate the solar radiation in multiple solar PV cells stacked one above the other (multi-junction)

- Only direct radiation (DNI – Direct Normal Irradiance) can be concentrated (factor of 500)

Concentration technologies

- Two axis sun tracker needed
  - eff: 46% (with concentrated light in the laboratory)
  - eff: 33% (open ground, not under standard test conditions)

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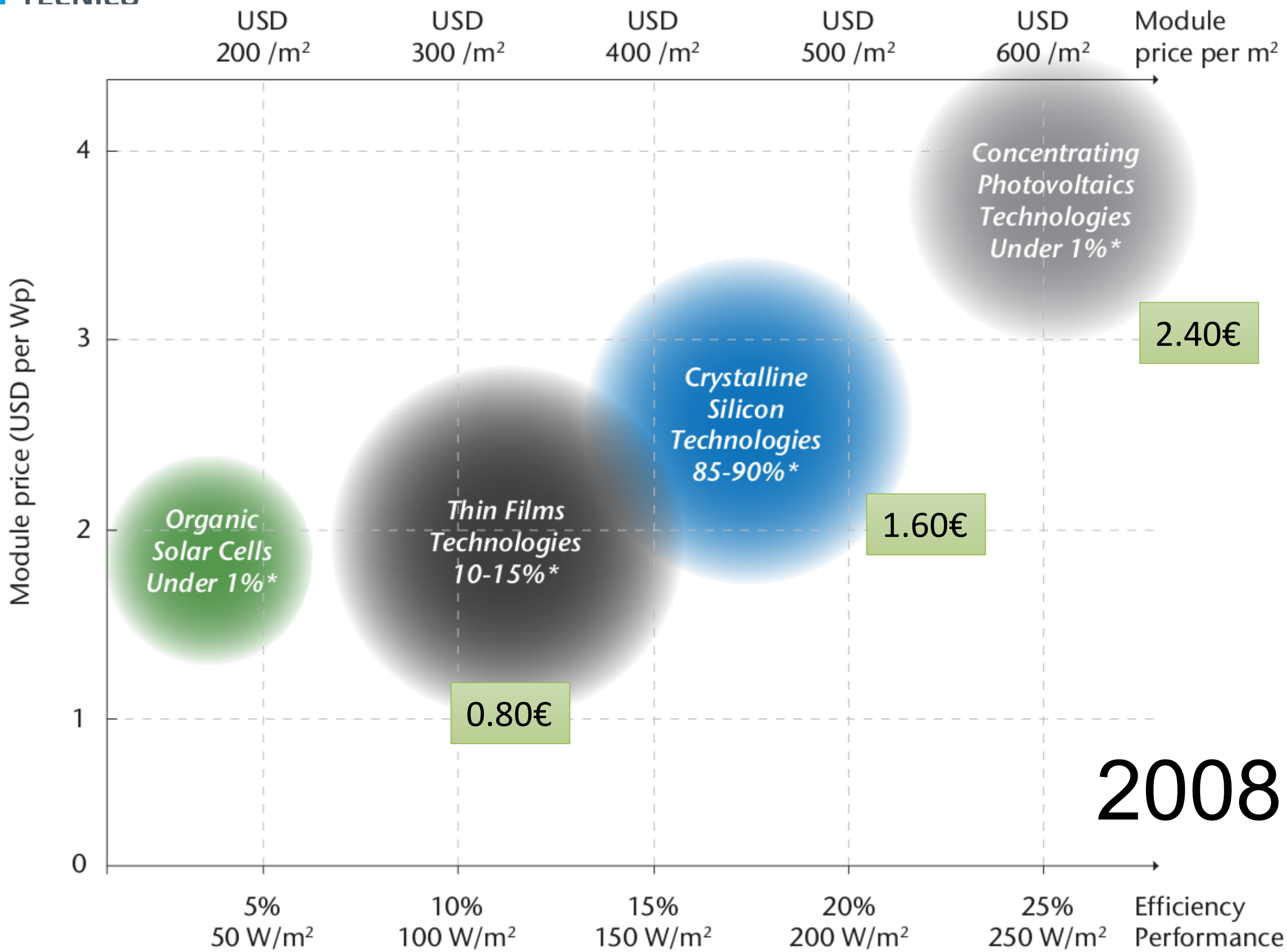
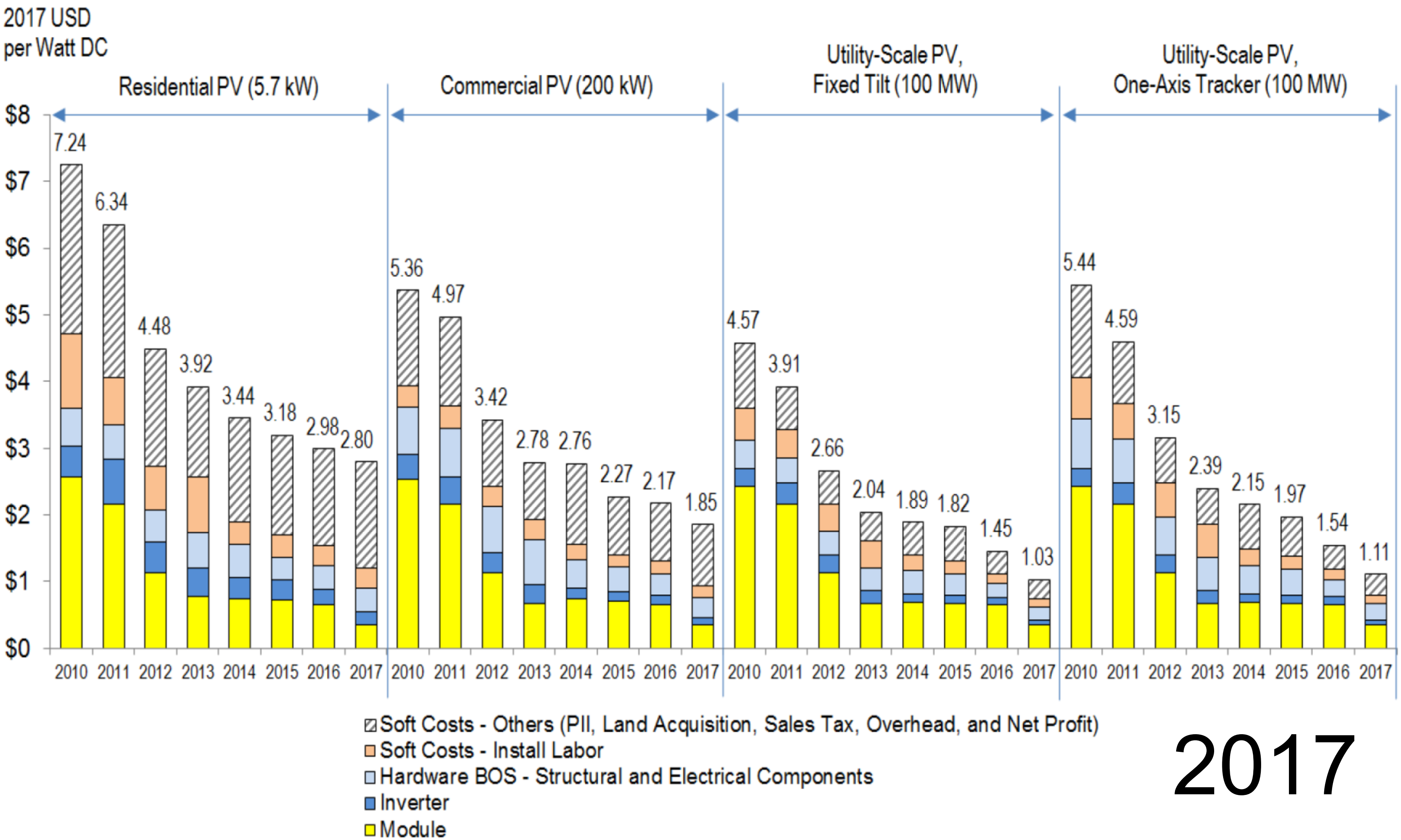
PHOTOVOLTAIC COSTS



Source: IEA, 2008



Source: NREL, USA, 2017

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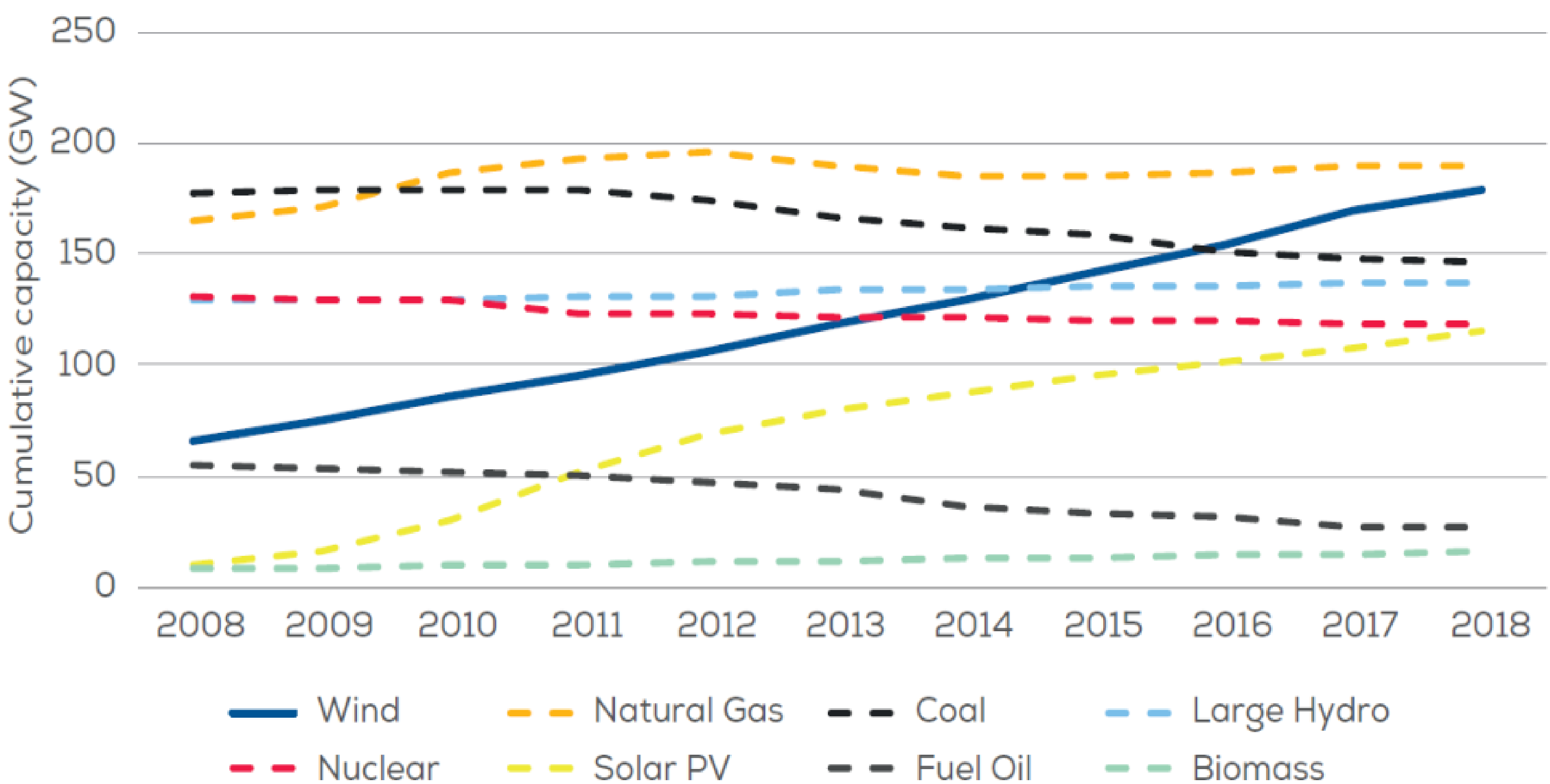
PV FACTS AND FIGURES

FIGURE 1

Total power generation capacity in the European Union 2008-2018



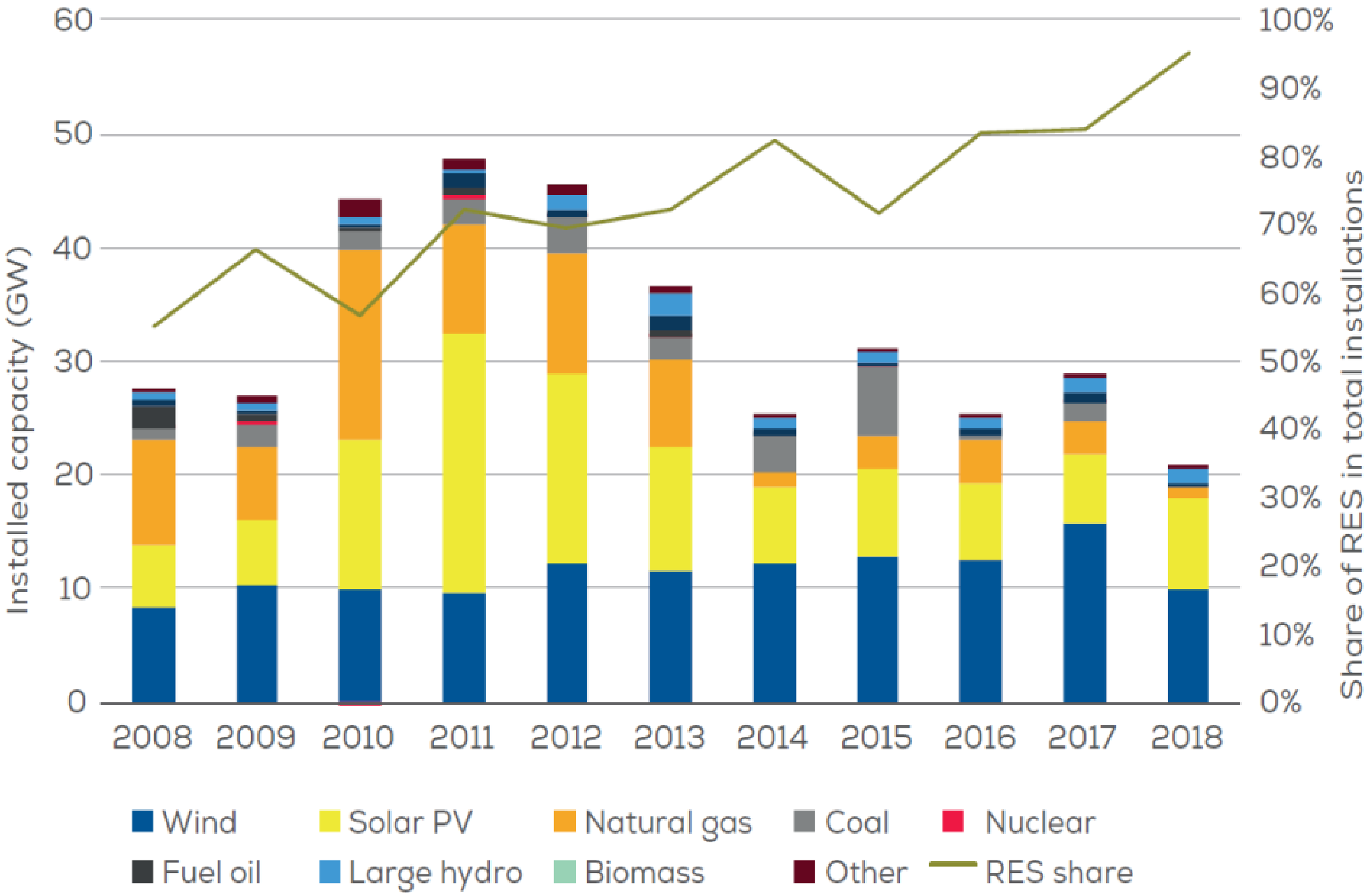
Source: WindEurope

FIGURE 15

Annual installed capacity and renewable share in EU-28

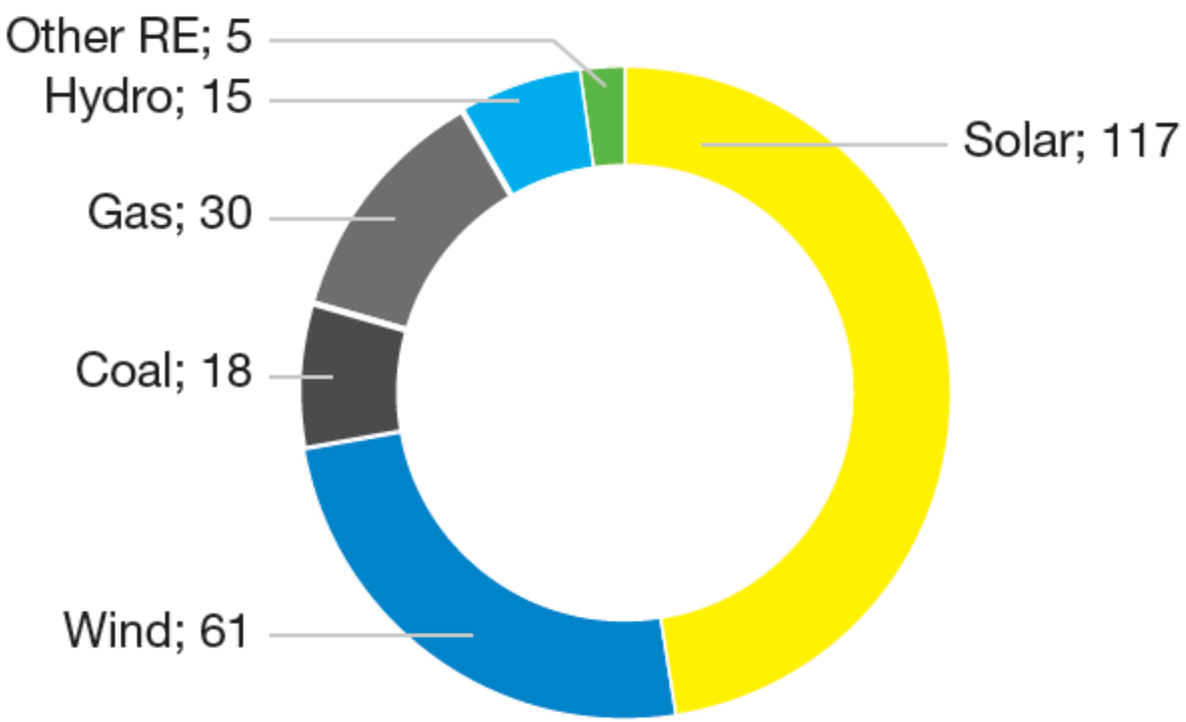
95%

OF NEW POWER CAPACITY IN THE EU-28 CAME FROM RENEWABLE ENERGY



Source: Platts, SolarPowerEurope, WindEurope

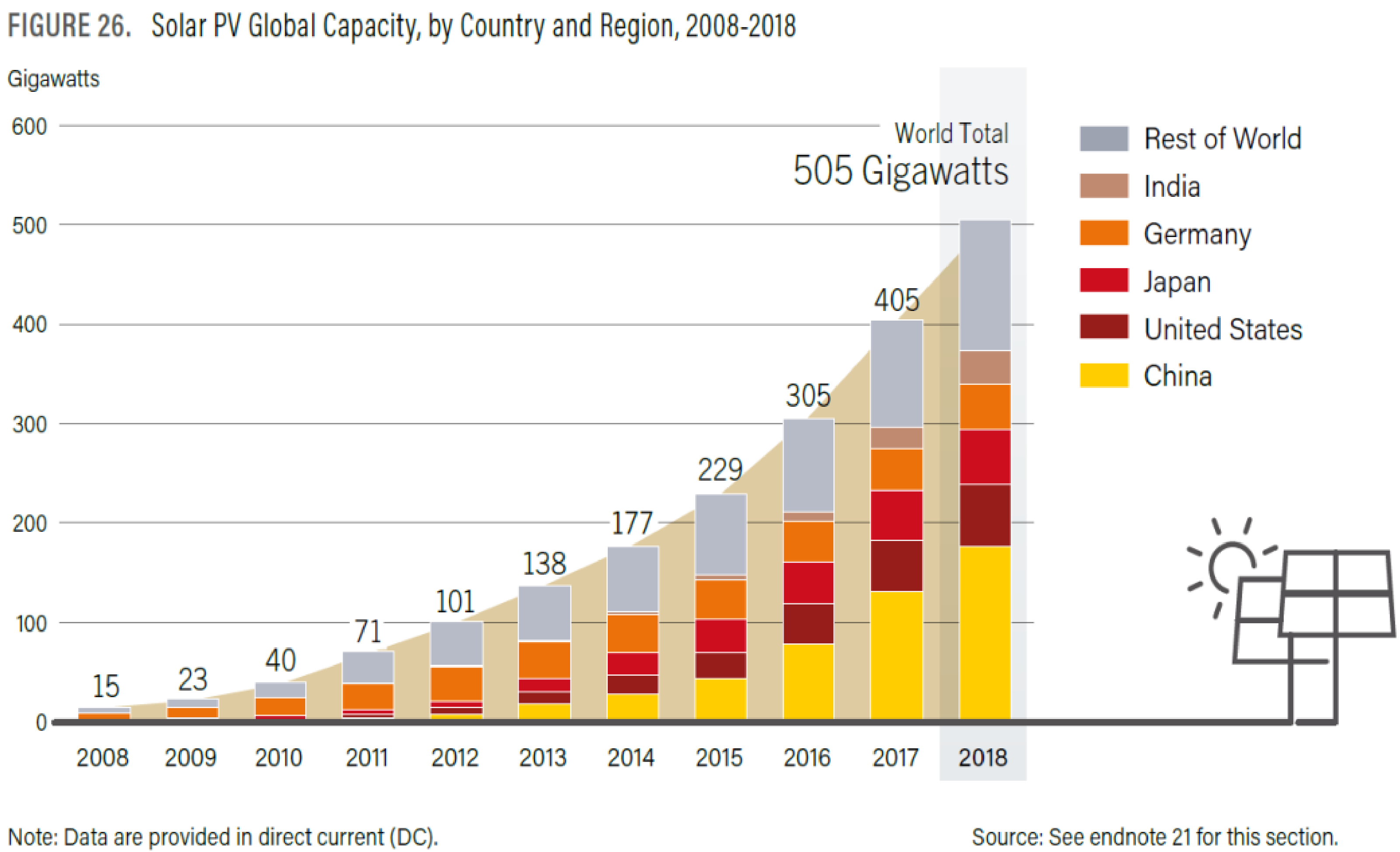
FIGURE 1 NET POWER GENERATING CAPACITY ADDED IN 2019 BY MAIN TECHNOLOGY



Source: Frankfurt School-UNEP Centre/BNEF (2020).

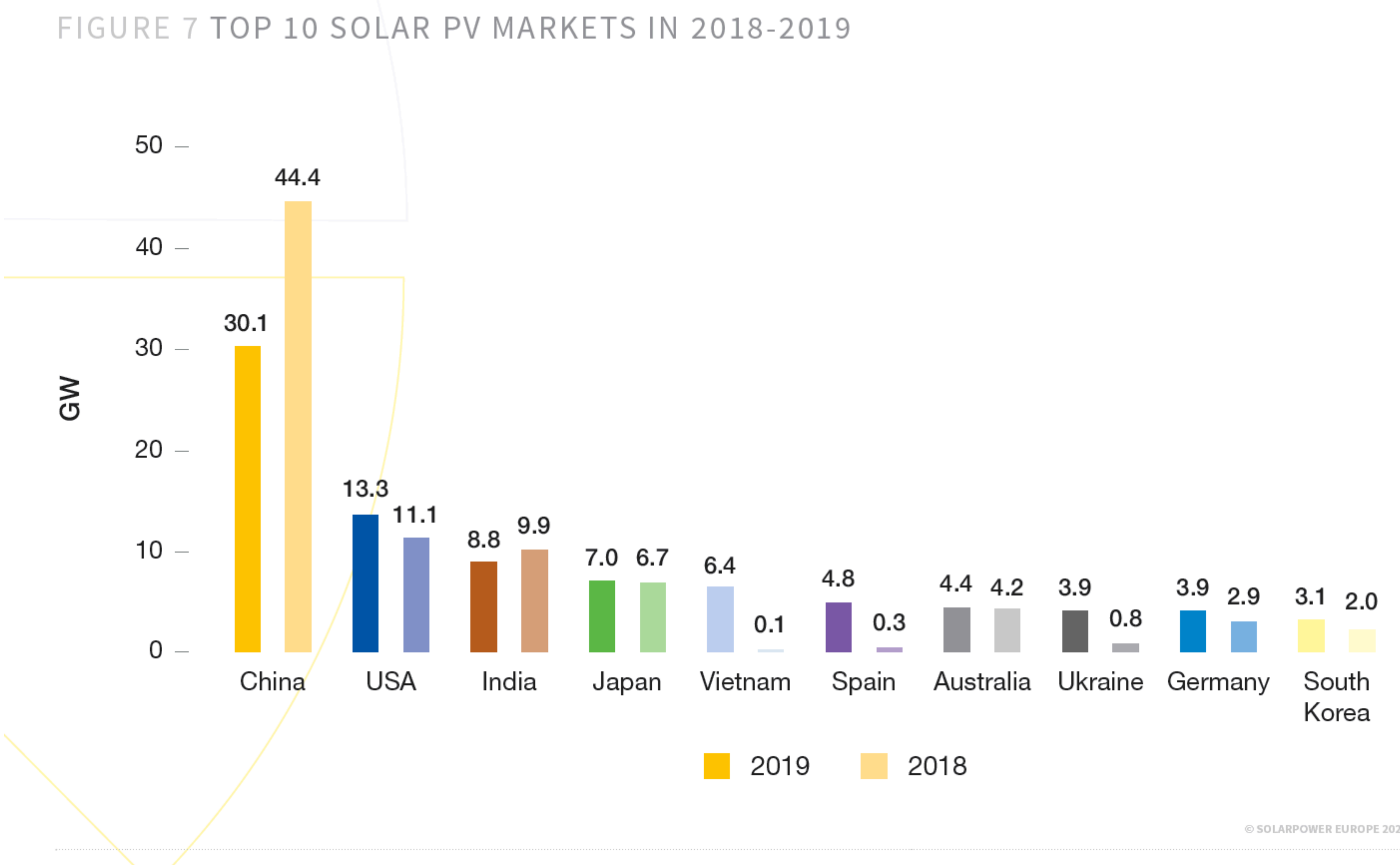
Source: Solar Power Europe

Global installed capacity



Source: REN21

Top 10 countries



Source: Solar Power Europe

PV IN PORTUGAL

PV is growing fast

- 175 MW PV (2011)
- 957 MW PV (Aug. 2020)
  - 376 MW (Aug. 2020) Micro/Mini generation + Production for self-consumption

Solar Auctions

- The winner is the company that offers to sell at the lowest price
- Two solar auctions already carried out
  - 1st : 1400 MW (2019)
  - 2nd : 700 MW (2020)
- Most of the projects in the 2nd auction include storage
- Selling prices as low as 15 €/MWh (1st) and 11 €/MWh (2nd)

Moura

Serpa

CONCENTRATED SOLAR POWER (CSP)

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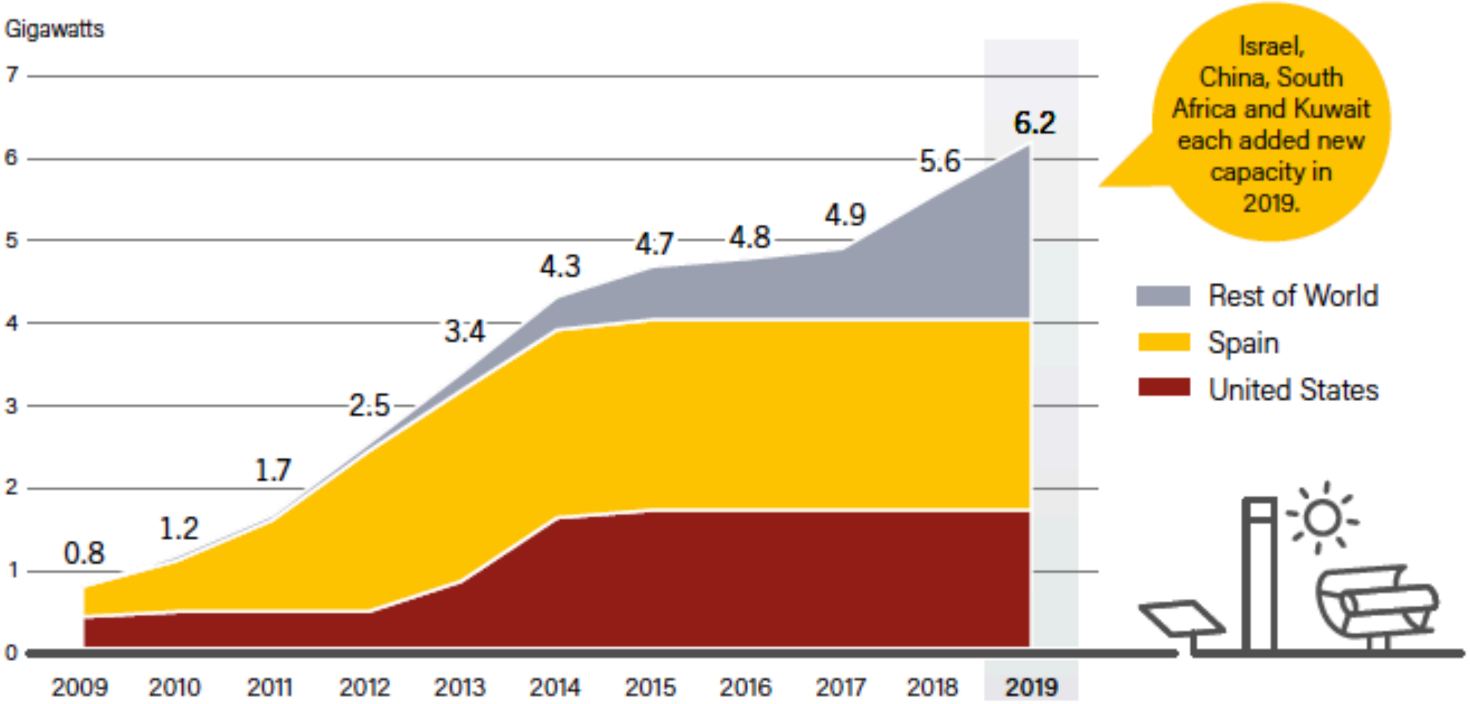
Operating principle

- Similar to the conventional thermal power plants
  - Water is overheated in a boiler; steam is produced and is expanded in a steam turbine; electricity is produced via a generator
- **The difference is in how steam is produced**
  - Thermal power plants: steam is produced from the combustion of a fossil fuel (coal, natural gas,…)
  - **CSP**: sunlight is focused on a receiver to obtain high temperature heat and produce steam; use of mirrors or lenses equipped with solar position tracking systems to focus the solar radiation

CSP capacity

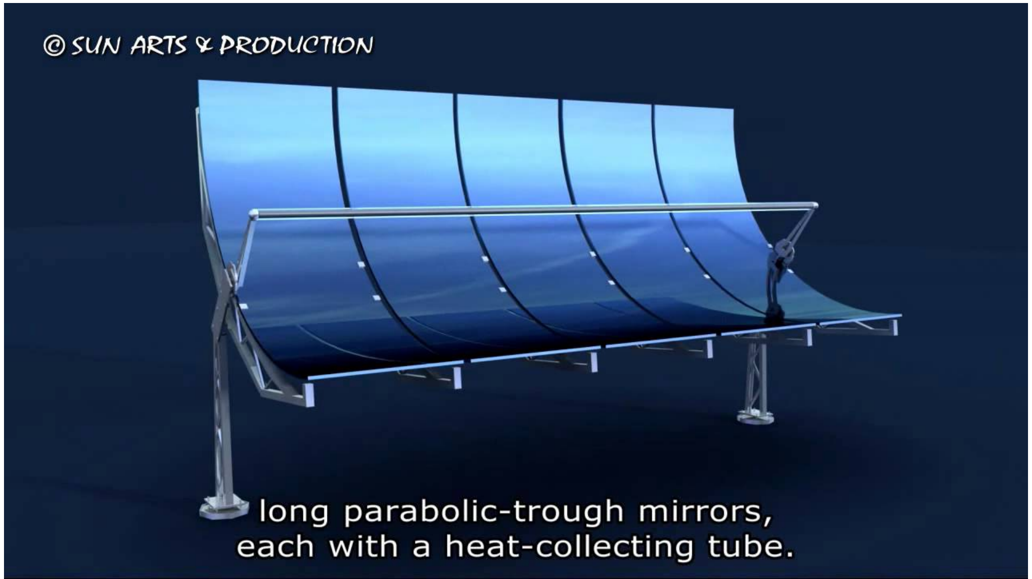
FIGURE 32. Concentrating Solar Thermal Power Global Capacity, by Country and Region, 2009-2019



Source: See endnote 2 for this section.

Parabolic trough

- Sunlight is concentrated using big rectangular mirrors curved in a parabolic shape in long heat collector pipes
  - 1 axis sun tracking system
  - Concentration ratio between 70 and 100



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Parabolic trough

- Inside the pipes there is a heat transfer fluid, capable of generating steam into a heat exchanger
  - Current plants use some synthetic oil as HTF
  - Alternative concepts include direct steam generation

Parabolic trough

- Troughs represent the most mature technology and the bulk of current projects; some have significant storage capacities
- The solar to electricity conversion can reach an efficiency between 10% and 15% (annual mean value)

Solar Tower

- Central receiver (or power tower) systems use a field of distributed mirrors – heliostats – that individually track the sun and focus the sunlight on the top of a tower
- By concentrating the sunlight 600–1000 times, they can achieve temperatures from 600–800°C

CSP – solar tower

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Solar Tower

- There are a cold tank and a hot tank containing the working fluid, normally molten salt
- In a heat exchanger the solar energy absorbed by the working fluid is used to generate steam to power a conventional turbine
- The average efficiency is in the range of 10%