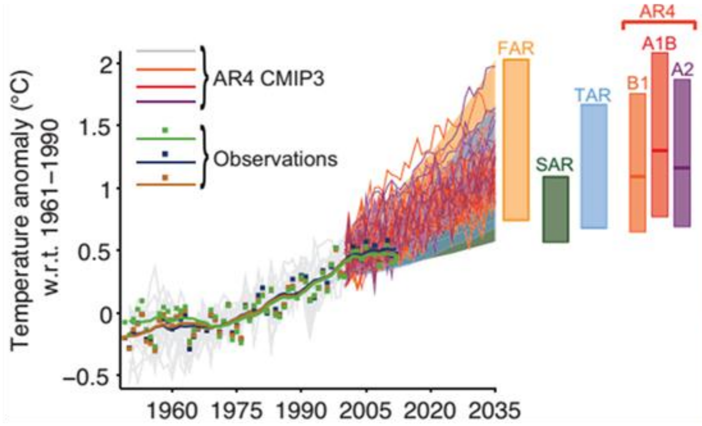
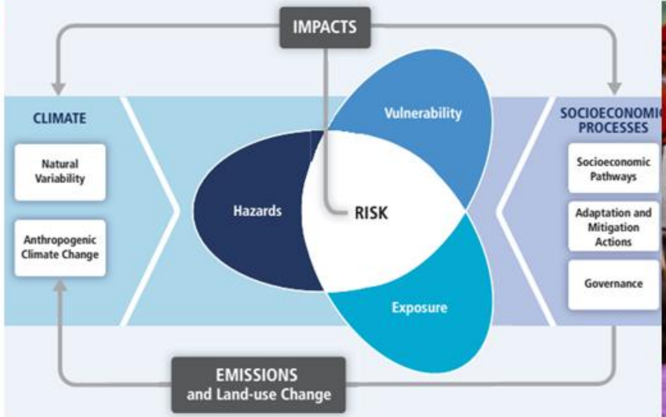
Energy Systems & Climate Change





4e: Solar energy



- The solar resource
- Photovoltaics (PV)
- Concentrated Solar Power
- The global and regional contexts

The solar resource

Generic pros and cons of solar power:

Pros:

- There's lots of it
- It's free
- It'll last "forever"

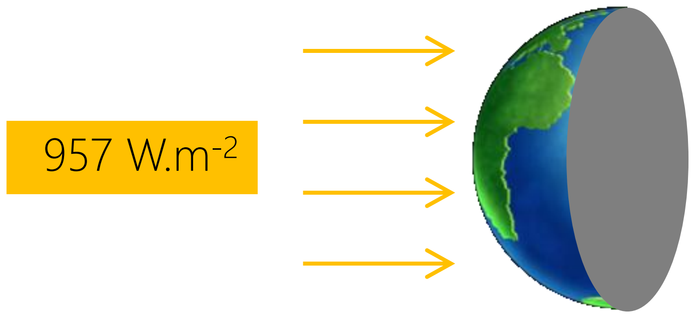
Cons:

- Available only during the day
- Large seasonal variability
- Large spatial variability
- Some degree of unpredictability

The solar resource

How much solar energy does earth receive?

- Total Solar Irradiance (outside the atmosphere): ~1,367 W.m^{-2}.
- ~30% reflected, so about 957 W.m^{-2} absorbed by earth-atmosphere system
- Cross-sectional area of earth = πr^2_{earth} = π (6,371 km)^2 = 127 x 10^6 km^2
- ∴ the rate at which solar energy is absorbed = (957 x 10^6) (127 x 10^6) ≈ 120 x 10^{15} W (120 PW)



For comparison:

- Global PER ≈ 14 Gtoe per year ≈ 18 x 10^{12} W (18 TW)
- Global electricity demand in 2020 ≈ 3.1 TW; in 2050 ≈ 10 TW (?)

Hence:

- Assuming an *overall* sunshine-to-electricity conversion effectiveness of 5%, "we" would need to capture 200 TW of solar power – *i.e.* <0.2% of the incident level – to satisfy 100% of global electricity demand in 2050[1].

[1] Note that there are lots of simplifying assumptions embedded here…

The solar resource

However:

- *Where* e.g. deserts
- and *when*… e.g. summer, daytime

…the resource is available may not coincide with demand.

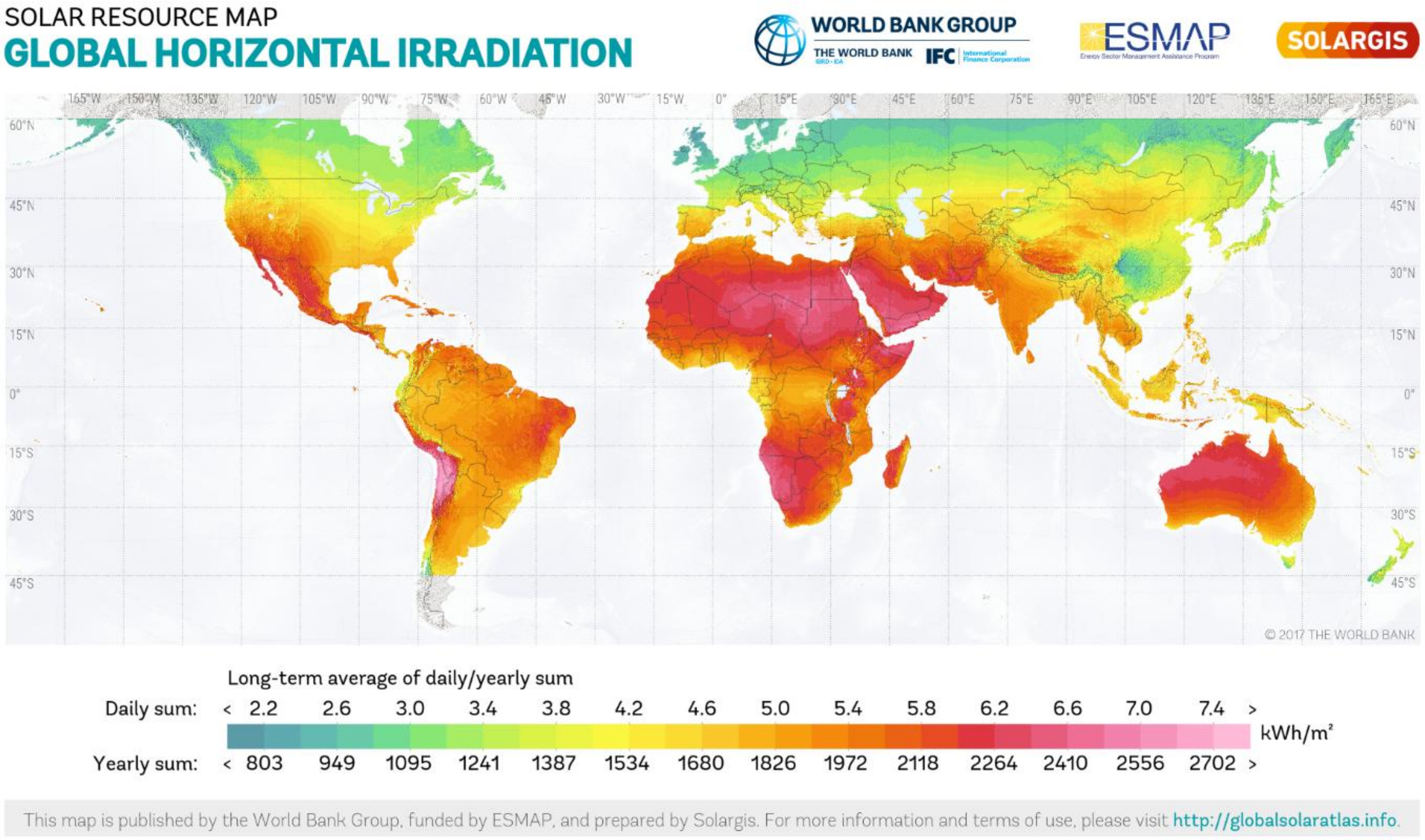
e.g. cities, winter, night

So we'll need

Technical problem

- Storage and/or time-shifting
- Transmission

Political, legal, and technical problems

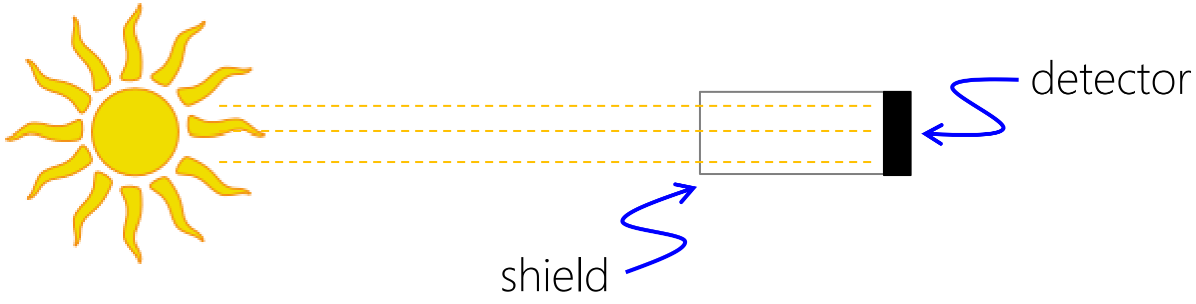

SOLAR RESOURCE MAP
GLOBAL HORIZONTAL IRRADIATION
WORLD BANK GROUP
THE WORLD BANK
IFC International Finance Corporation
ESMAP
SOLARGIS
165°W 150°W 135°W 120°W 105°W 90°W 75°W 60°W 45°W 30°W 15°W 0° 15°E 30°E 45°E 60°E 75°E 90°E 105°E 120°E 135°E 150°E 165°E
60°N 45°N 30°N 15°N 0° 15°S 30°S 45°S
© 2017 THE WORLD BANK
Long-term average of daily/yearly sum
Daily sum: < 2.2 2.6 3.0 3.4 3.8 4.2 4.6 5.0 5.4 5.8 6.2 6.6 7.0 7.4 >
kWh/m²
Yearly sum: < 803 949 1095 1241 1387 1534 1680 1826 1972 2118 2264 2410 2556 2702 >
This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info.

Solar radiation can be either direct or diffuse

- Direct irradiance travels in a straight line from the sun: all photons striking the measuring point come from a single direction.

  Also referred to as beam radiation

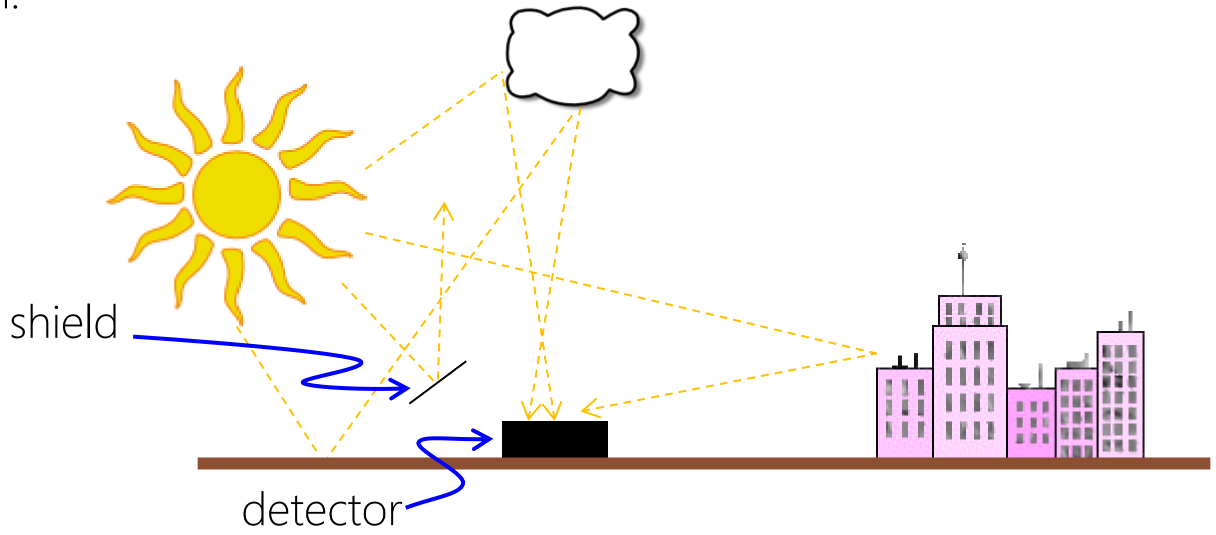
  We can focus direct radiation with a lens or a mirror.



- Diffuse irradiance has bounced off clouds, dust particles, buildings, cars, etc.: photons strike from random directions.

  Clouds reduce direct radiation, and increase diffuse radiation.

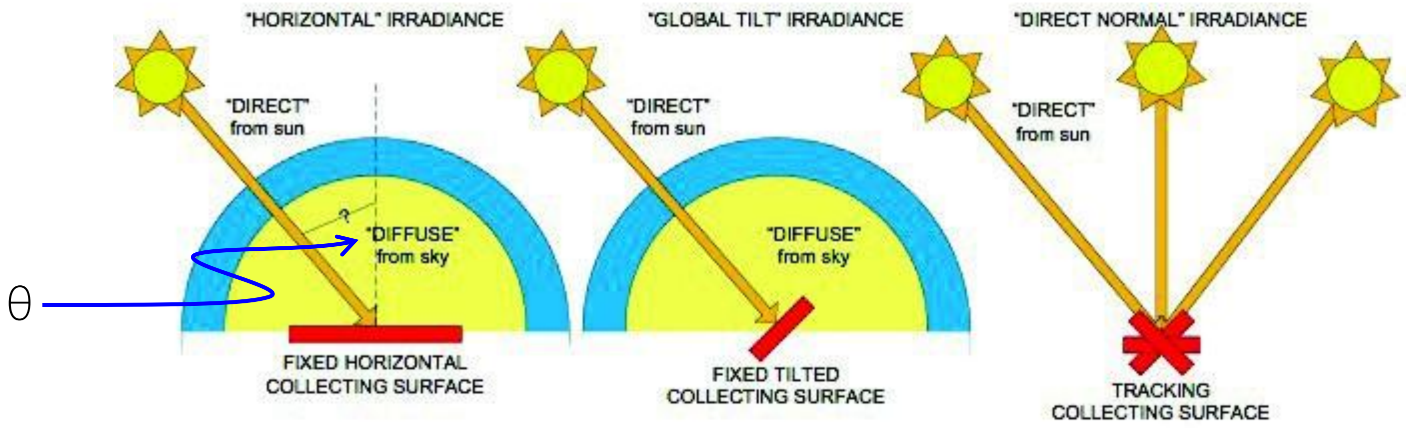
  Diffuse radiation cannot be focused.



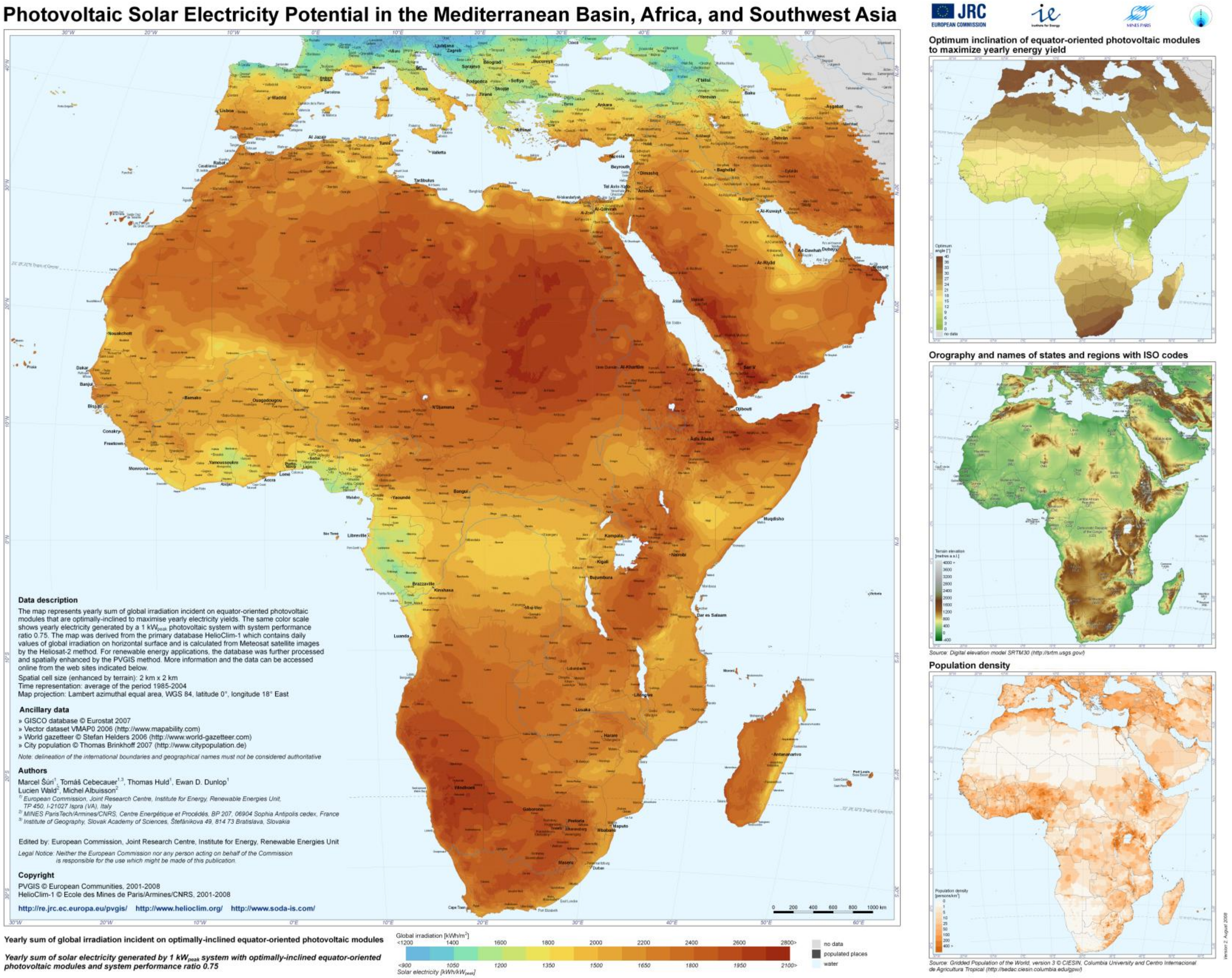
Three metrics are commonly used to quantify solar irradiance at a given location:

- DHI (diffuse horizontal insolation): the diffuse radiation incident on a horizontal surface
- DNI (direct normal insolation): the direct radiation incident on a surface that is always normal to the sun
- GHI (global horizontal insolation): the total (direct + diffuse) radiation incident on a horizontal surface

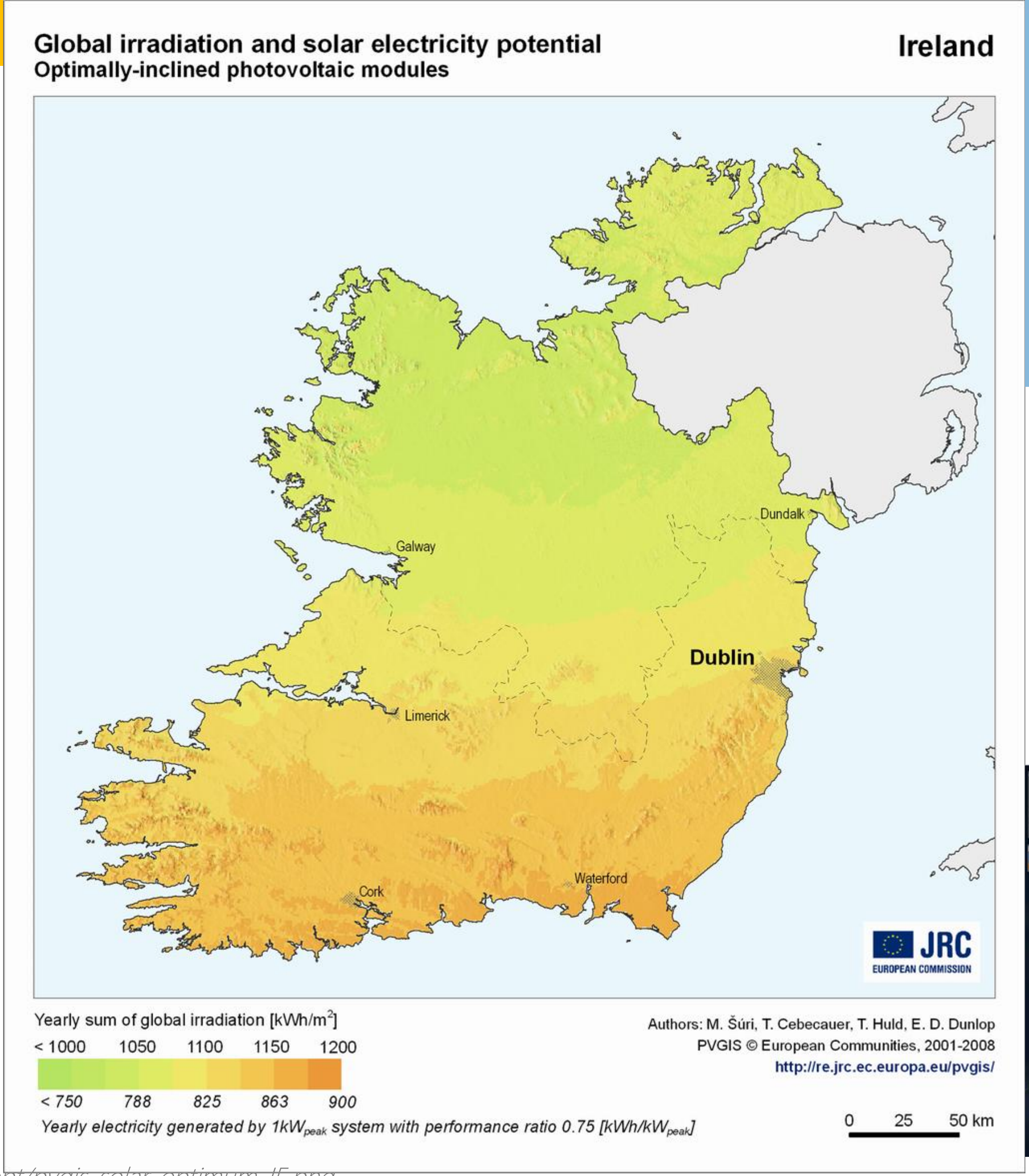
$$\boxed{GHI = (DNI \times \cos\theta) + DHI}$$

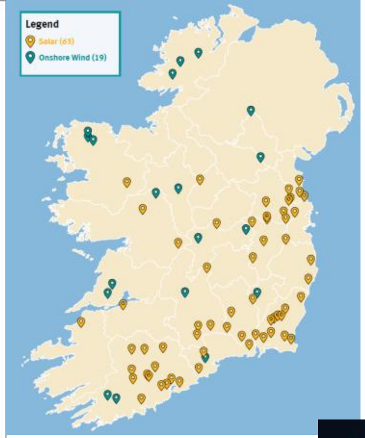


The solar resource

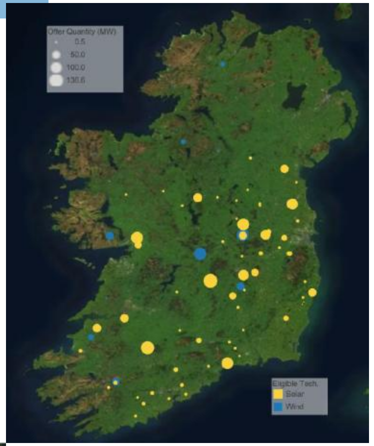


The solar resource





RESS 1



RESS 2

RESS 3

http://re.jrc.ec.europa.eu/pvgis/cmaps/eu_opt/pvgis_solar_optimum_IE.png

The solar resource

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Monthly average irradiance [W m⁻²]												
Limassol	105	136	189	250	285	325	325	299	255	185	126	96	215
Malaga	105	135	188	225	265	295	318	284	225	154	108	89	199
Athens	83	105	153	217	266	313	317	288	232	146	90	68	190
Lisbon	95	125	179	215	255	269	287	264	213	143	95	77	185
Madrid	80	115	170	201	244	272	296	263	205	128	82	66	177
Rome	74	105	155	203	249	285	295	264	201	128	83	65	176
Toulouse	58	89	133	168	201	215	244	211	170	103	66	52	143
Bern	46	74	114	150	196	211	237	206	153	91	53	38	131
Paris	37	68	109	165	204	201	223	192	139	83	47	30	125
Munich	44	75	118	165	202	194	214	186	133	83	43	33	124
Brussels	31	55	95	153	195	187	201	175	119	72	38	23	112
London	28	53	93	145	189	188	198	167	119	69	37	22	109
Hamburg	23	46	87	153	203	186	186	162	108	62	29	17	105
Dublin	23	45	82	138	183	179	179	142	112	60	32	18	99
Oslo	13	36	70	130	194	202	191	140	93	43	18	8	95
Edinburgh	18	39	78	133	180	181	172	142	101	50	25	13	94

http://lightbucket.wordpress.com/2008/02/24/insolation-and-a-solar-panels-true-power-output

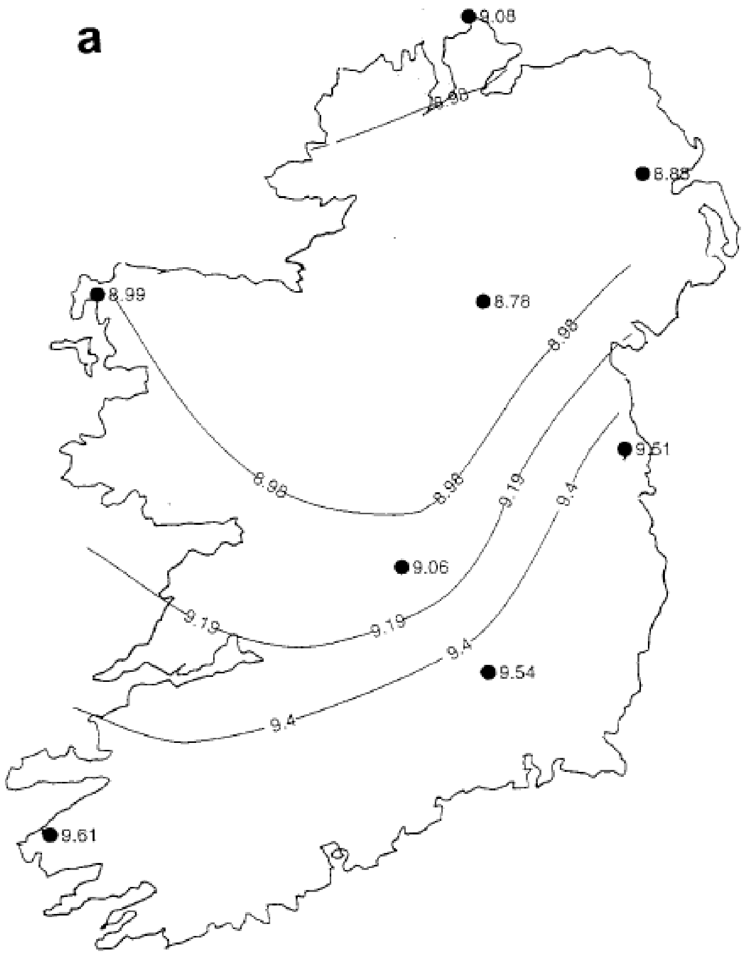
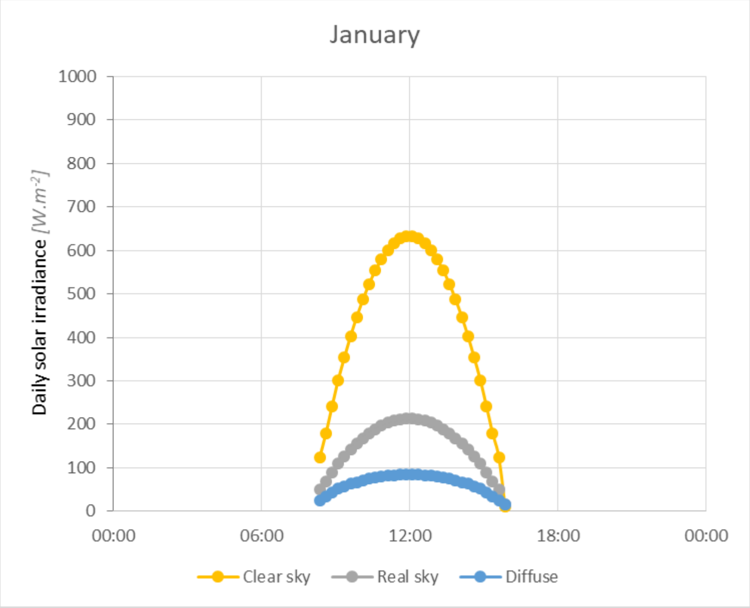


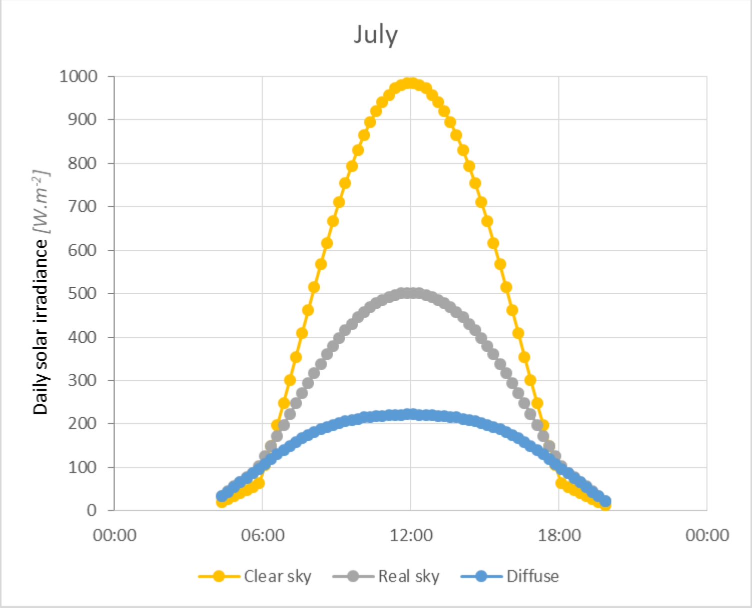
Figure 2. Spatial variation of global and diffuse irradiance 1982–1995 (MJ m^{-2} day^{-1}) (a) $K\downarrow$ mean annual (b) $K\downarrow$ midsummer (c) $K\downarrow$ midwinter (d) D mean annual (e) D midsummer (f) D midwinter

Int. J. Climatol. **18**: 1015–1030 (1998)

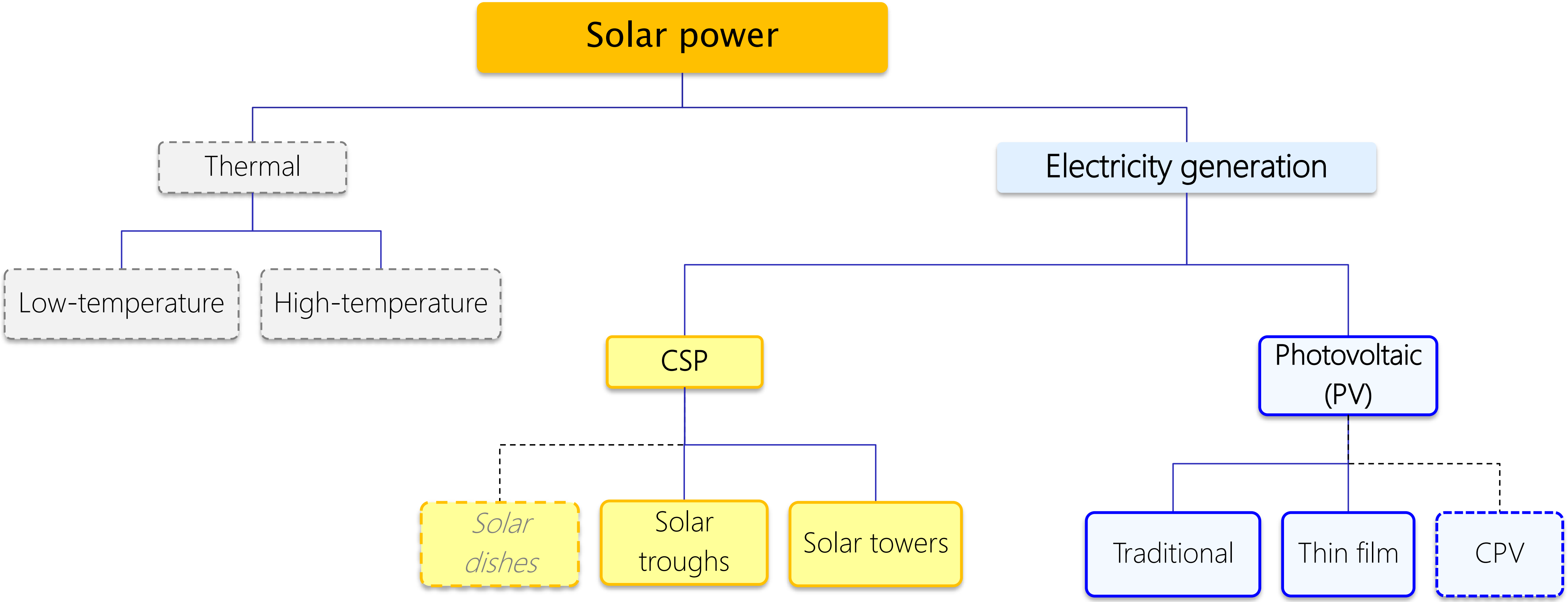
Note:

$9.5\ \mathrm{MJ.m^{-2}.day^{-1}} = 972\ \mathrm{kWh.m^{-2}.year^{-1}} = 2.66\ \mathrm{kWh.m^{-2}.day^{-1}} = 110\ \mathrm{W.m^{-2}}$





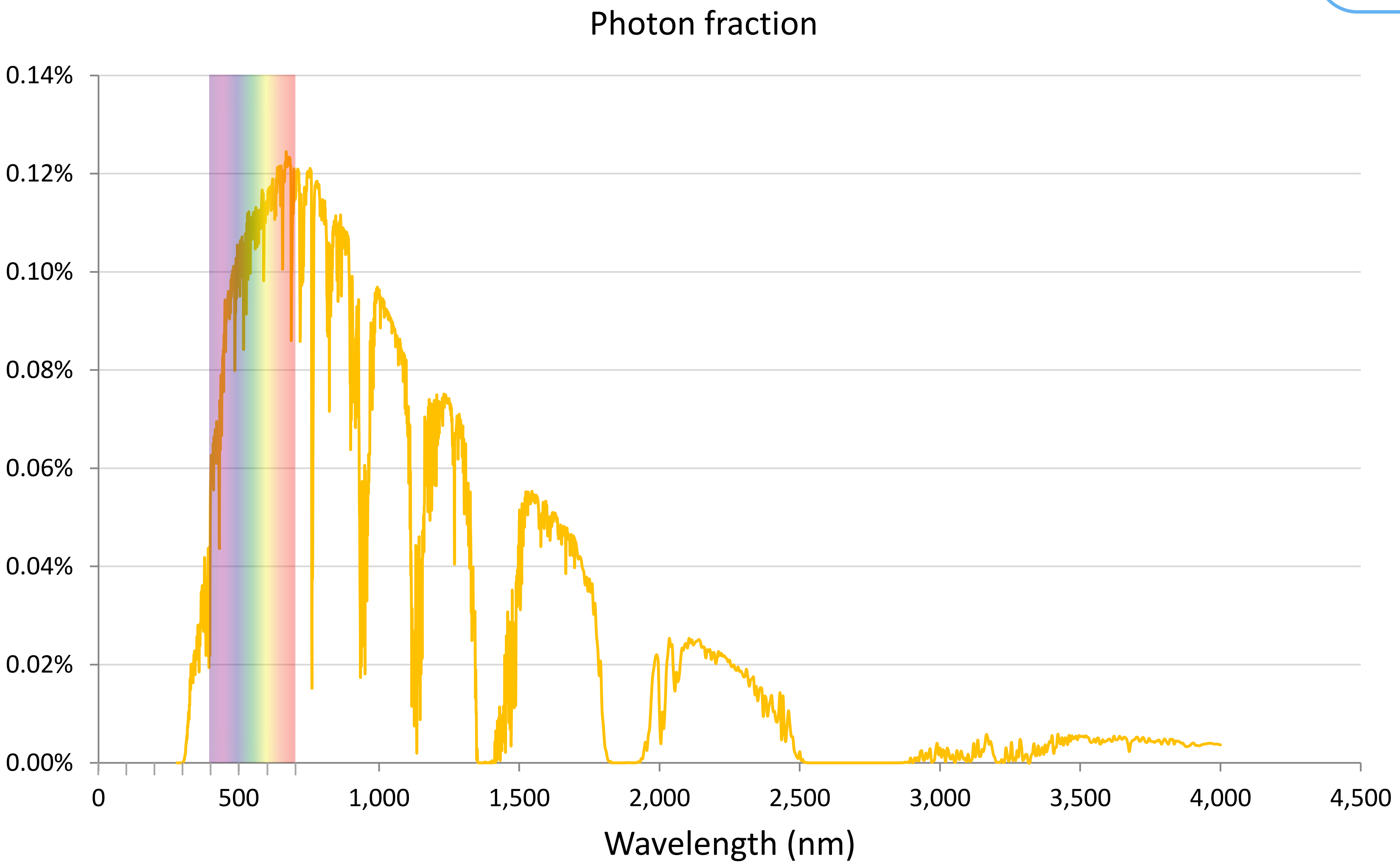
See also: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#


Solar power
Thermal
Electricity generation
Low-temperature
High-temperature
CSP
Photovoltaic (PV)
Solar dishes
Solar troughs
Solar towers
Traditional
Thin film
CPV

Photovoltaics (PV)

Solar radiation: characteristics

How does a solar cell work?



- Sunlight (photons) that reach earth's surface have a range of wavelengths.

Solar radiation: characteristics

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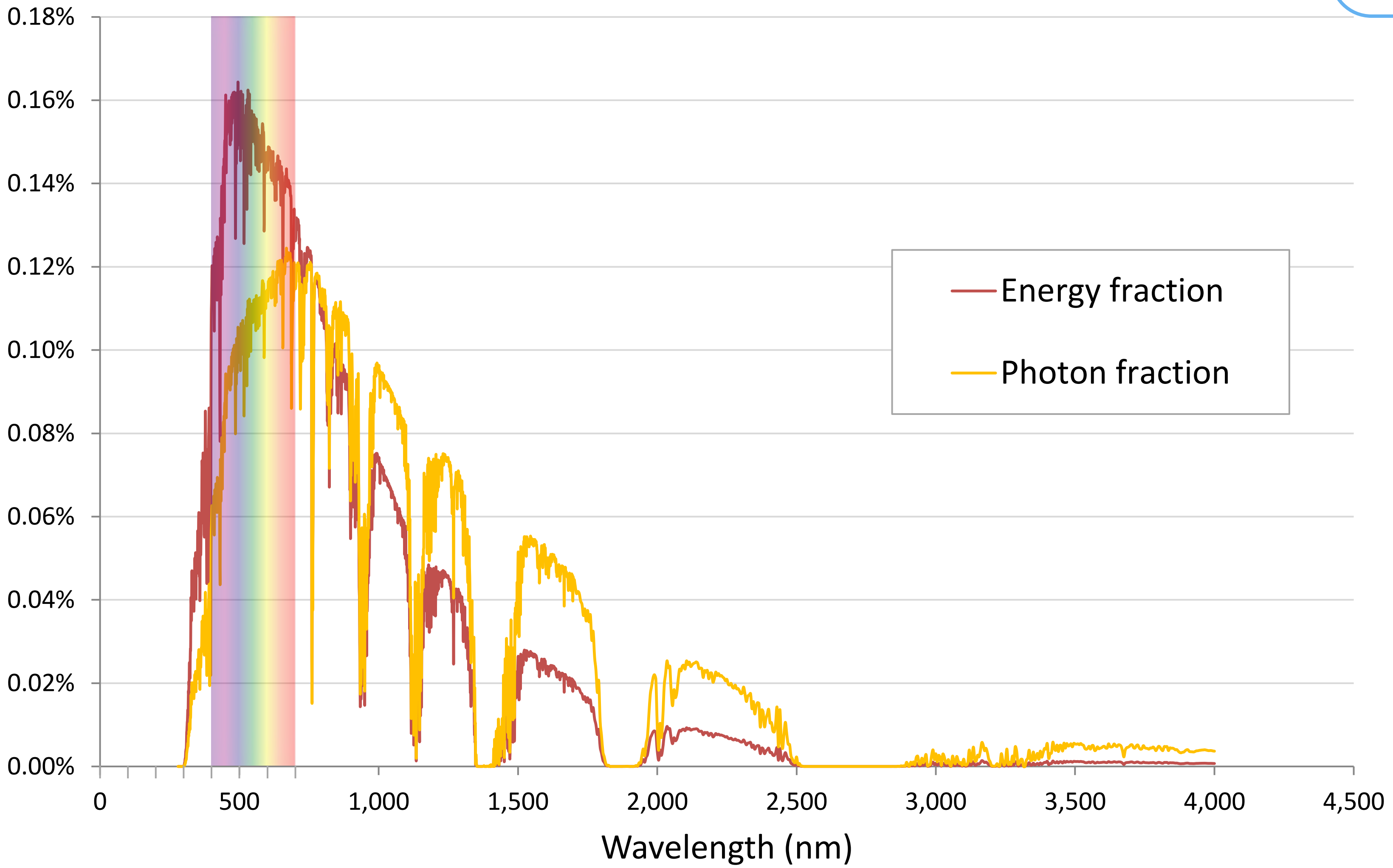
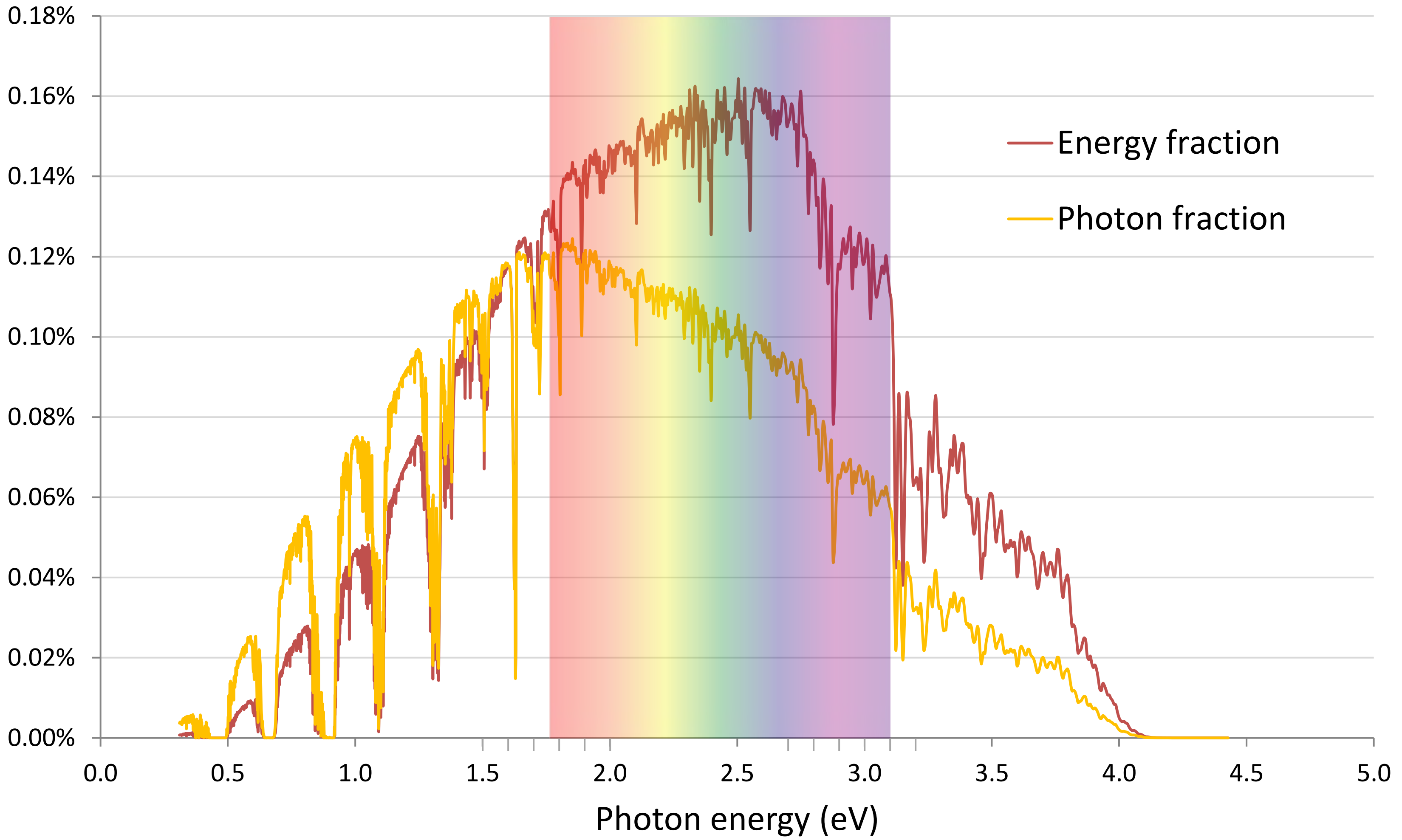


- Sunlight (photons) that reach earth's surface have a range of wavelengths.
- Short wavelength photons have high energy

Solar radiation: characteristics

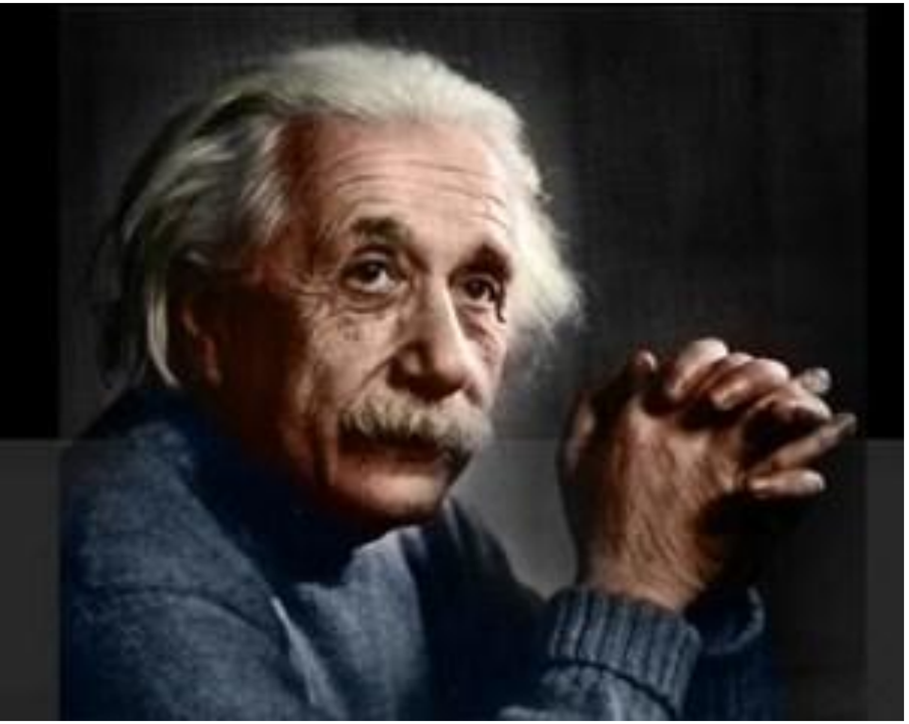
How does a solar cell work?



- We can plot the data as a function of photon energy, instead of photon wavelength.

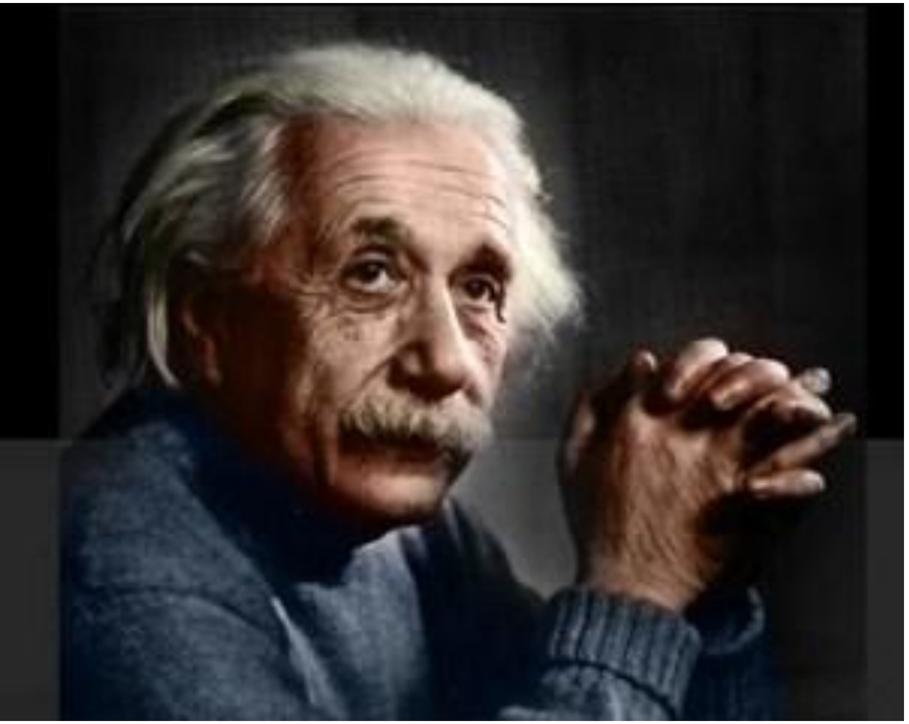
Photovoltaics (PV)

How does a solar cell work?



- The photoelectric effect is well established
- The photovoltaic effect is similar, but electrons are knocked out of their atomic orbitals, not out of the material itself
- When light falls on a Silicon p-n junction, some photons may be absorbed by electrons, promoting them from the valence band to the conduction band.
- The minimum energy that the photon must have, for this to occur, equals the band gap E_{gap}.
- For Silicon, E_{gap} =1.1 eV, which corresponds to a photon wavelength of ~ 1.1 µm.
- Only photons with at least this much energy will produce an effect.

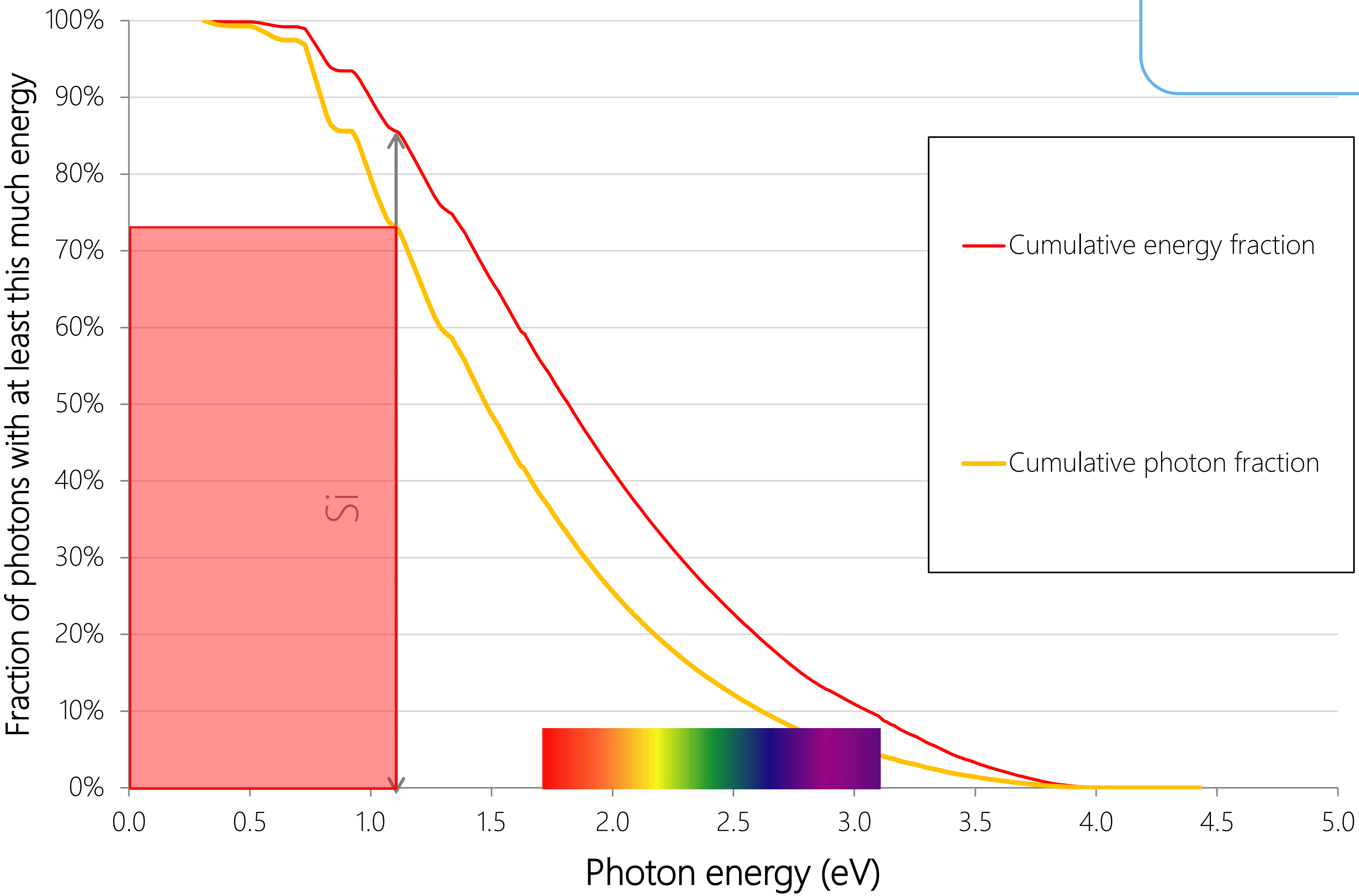
How does a solar cell work?



- Only photons with energy <u>at least</u> equal to the material's bandgap will produce an effect.
- The amount of energy absorbed from each of those photons will be equal to $E_{bandgap}$.
- The maximum (theoretical) fraction of incoming solar energy that we can harvest, therefore, is given by:

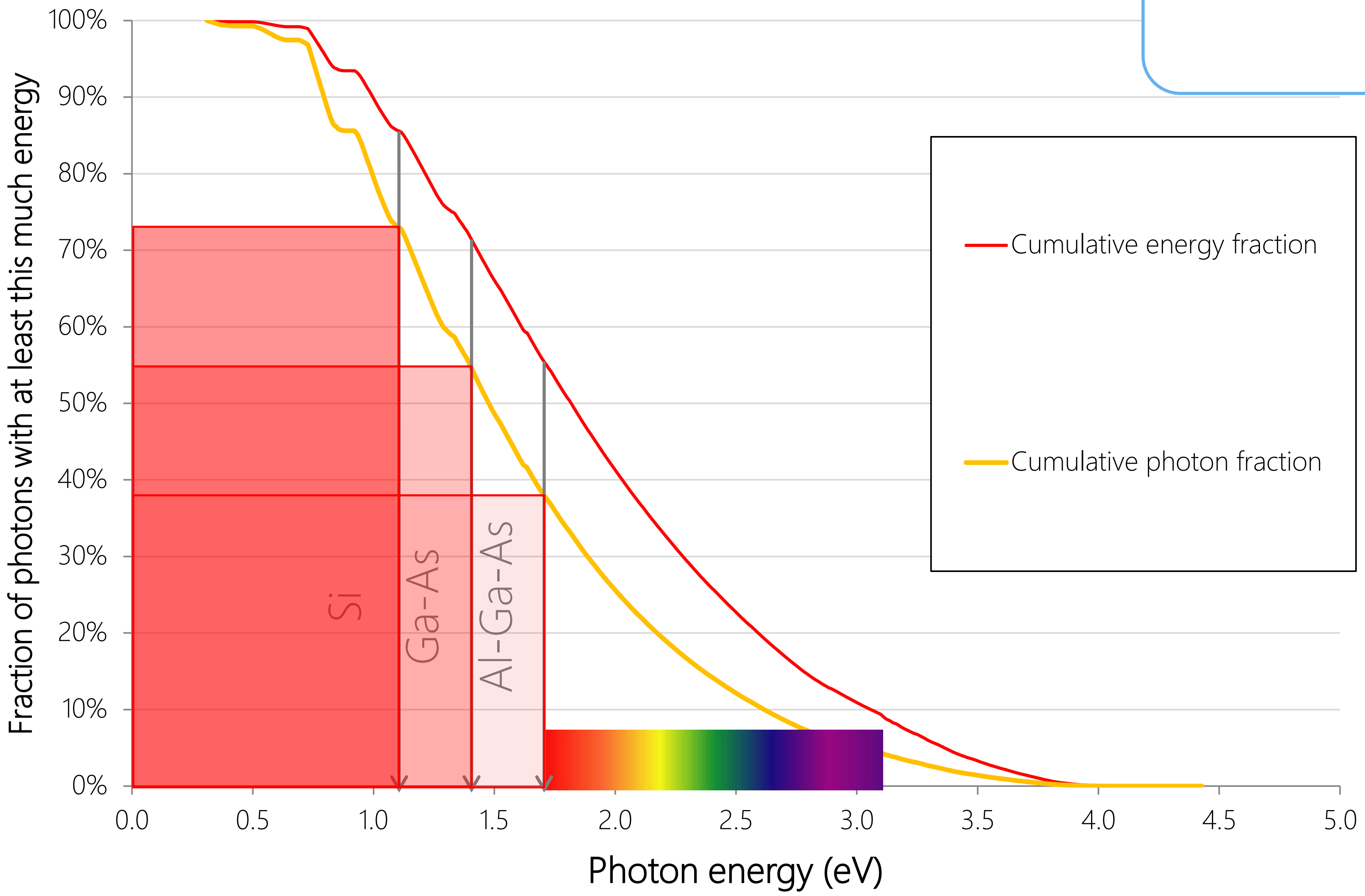
$$\text{fraction of photons with energy} >= E_{bandgap} \times E_{bandgap}$$

How does a solar cell work?



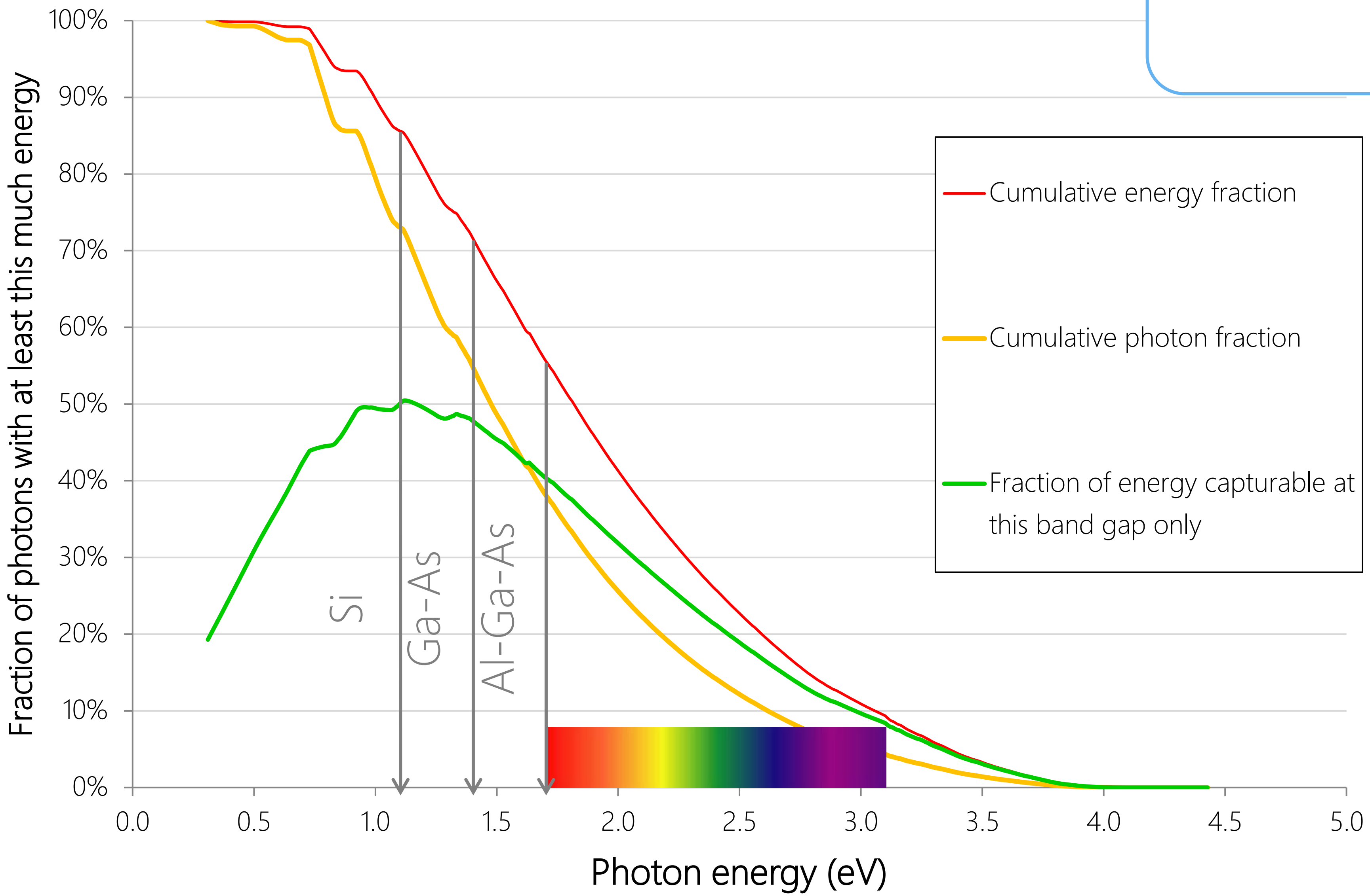
- For Silicon $E_{bandgap}$ = 1.1 eV.
- 73% of photons have energies >= 1.1 eV; they account for 86% of incident solar energy.
- However, only 1.1 eV of the energy carried by more energetic photons can be captured…
- …this corresponds to 50% of the incident solar energy.

How does a solar cell work?



- Other materials can also be used to make PV junctions.
- For a Ga-As junction, $E_{bandgap} = 1.4$ eV
- For an Al-Ga-As junction, $E_{bandgap} = 1.7$ eV

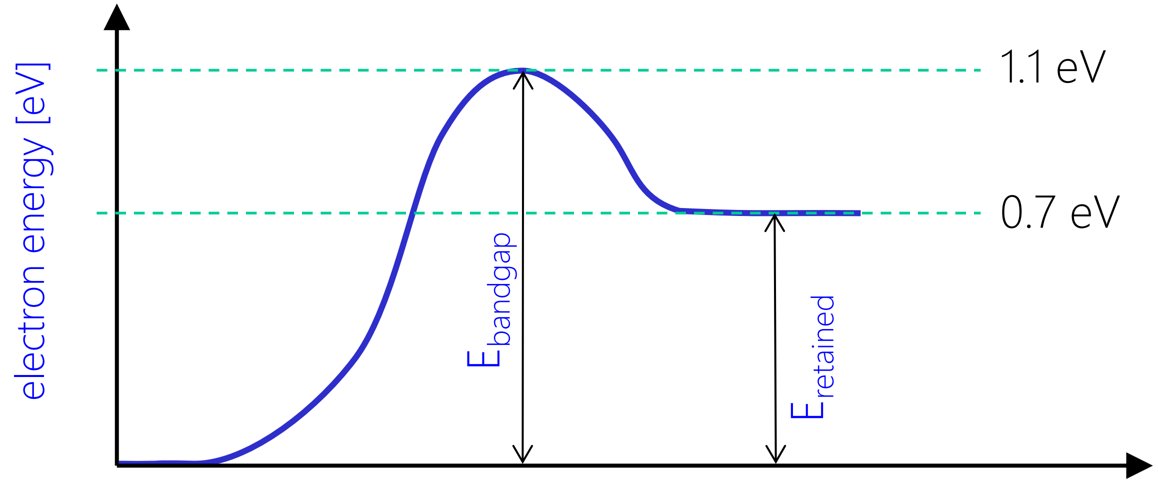
How does a solar cell work?



- The fraction of solar energy that can – theoretically – be recovered by a PV cell, depends on its $E_{bandgap}$.
- Si happens to work very well.
- It is also very abundant, and pretty cheap

Maximum theoretical efficiency of a Si-based PV cell

- 27% of photons have energies < 1.1 eV; they account for 14% of incident solar energy, but are not absorbed.
- 73% of photons have energies >= 1.1 eV; they account for 86% of incident solar energy.
- However, only 1.1 eV of the energy carried by more energetic photons can be captured…
- …this corresponds to 50% of the incident solar energy, with the remaining 36% being converted to heat.
- Although the energy required to promote an electron is ~ 1.1 eV, that electron carries energy of only ~ 0.7 eV, or 65% of that value.



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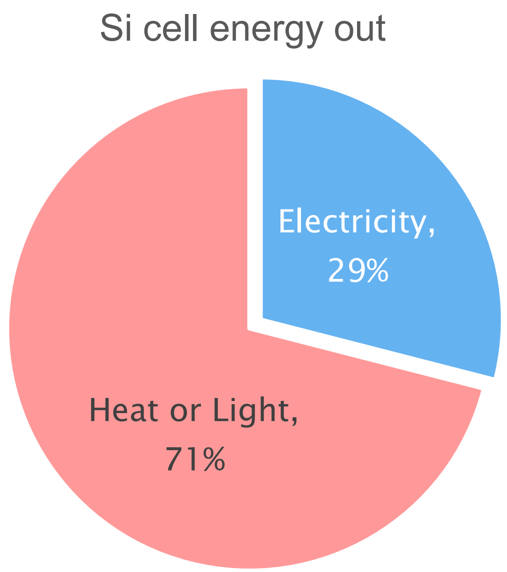
- About 10% of electron-hole pairs recombine prior to leaving the cell.
- So the maximum (theoretical) energy conversion efficiency is given by:

$$\eta_{max} = 0.5 \times 0.65 \times 0.9 = 0.29$$

- Actual conversion efficiency of Si-based cells is generally lower – see NREL chart later.



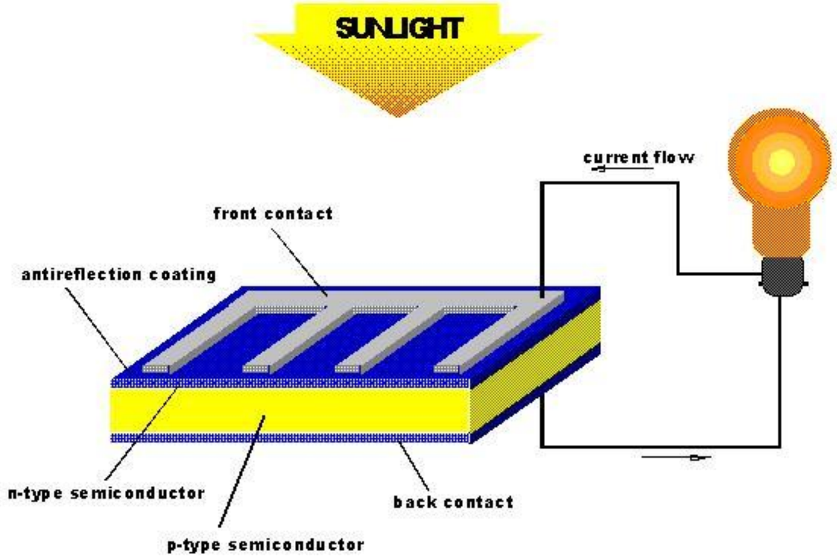
Photovoltaics (PV)

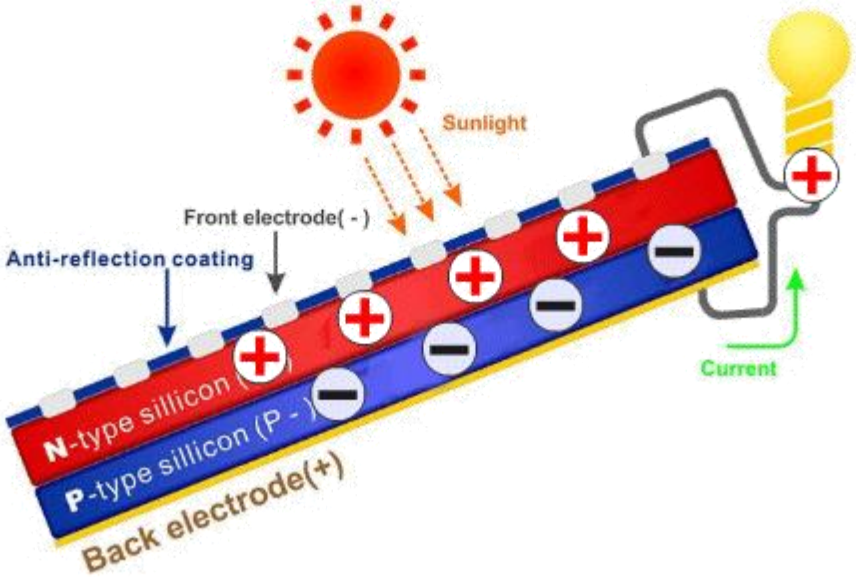
How does a solar cell work?

See YouTube for lots of good explanatory videos, e.g.:

https://www.youtube.com/watch?v=L_q6LRgKpTw

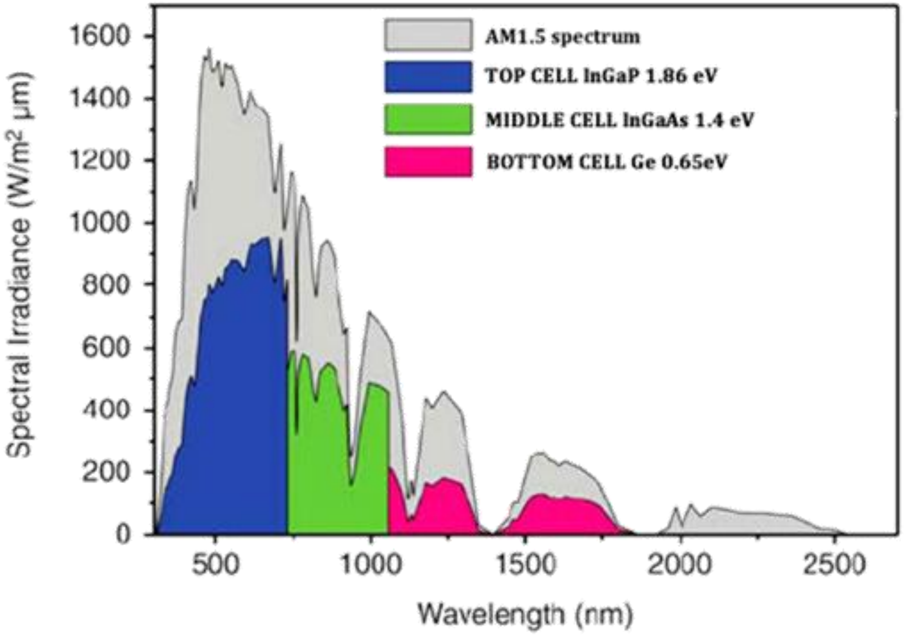
https://www.youtube.com/watch?v=nUDNYoQJx7k

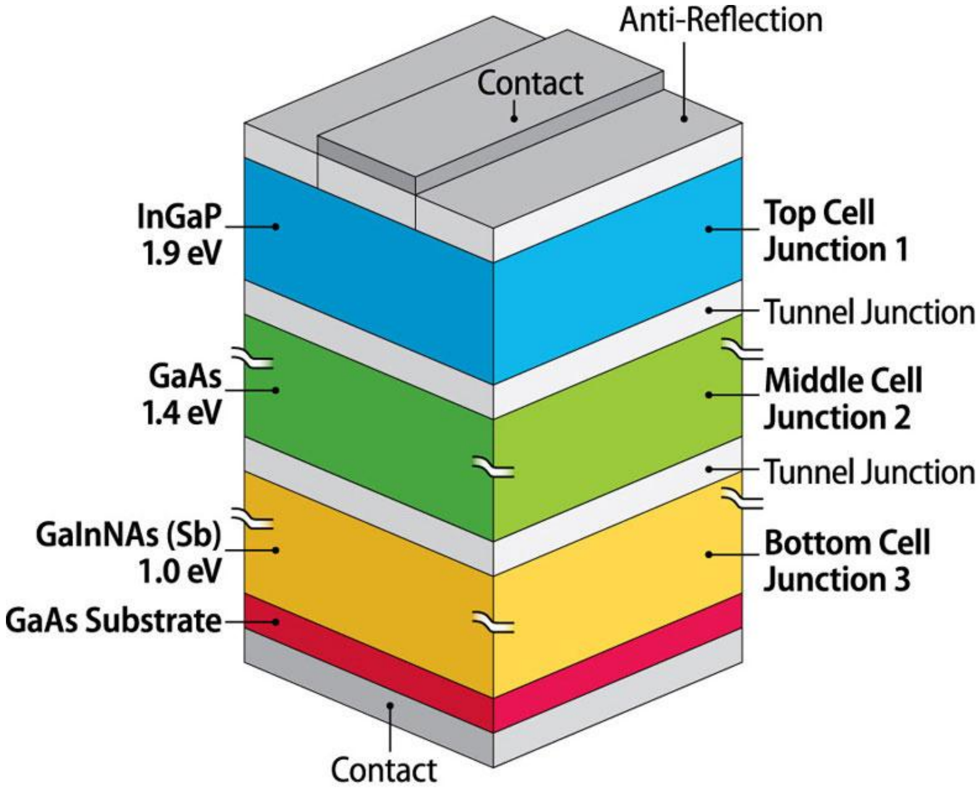




Multi-junction cell

- Combines 2 or more cell chemistries.
- Cells of decreasing band-gap layered one under another.
- Captures a larger fraction of available solar energy (higher efficiency).
- More expensive, thicker, heavier, more complex.

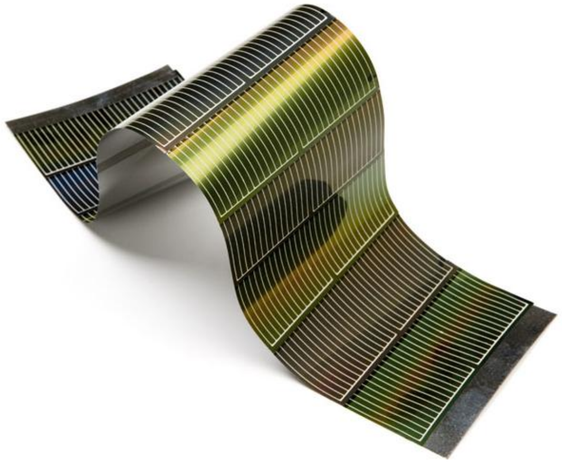


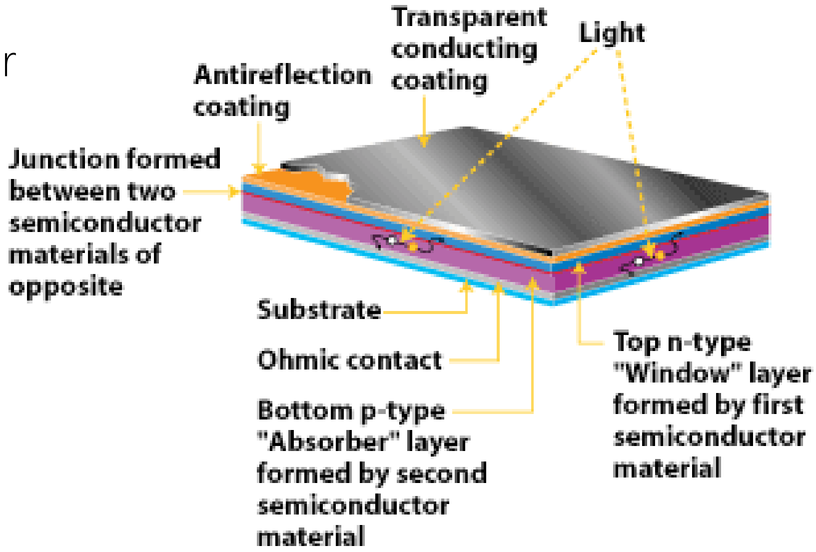


Example of a three-junction cell

Thin-film PV

- Thin layers (nanometres to microns) of semi-conductor material are deposited “sprayed” onto an appropriate (cheap) substrate, in thin films.
- Generally uses a junction between two dissimilar materials – a heterojunction – rather than the homojunction between between two differentially-doped layers of Silicon.
- Most widely-used layer pairs are:
  - Cadmium-Telluride* (*CdTe*)
  - Copper-Indium-Gallium-Selenide (*CIGS*)
  - Amorphous Silicon (α-Si)
  - *Gallium-Arsenide** (GaAs)*





- Perovskite cells are progressing strongly (see, for instance https://www.energy.gov/eere/solar/perovskite-solar-cells)

* Cadmium is a highly-toxic heavy metal, ten times more toxic the Hg or Pb.

** GaAs cells are much more expensive than other thin-film types, but also lighter and more efficient. Their main application is in aerospace.

Advantages of thin-film cells include:

- Layer is very thin: less semi-conductor material used

  can make cell flexible – potential to be integrated onto curved surfaces, etc.

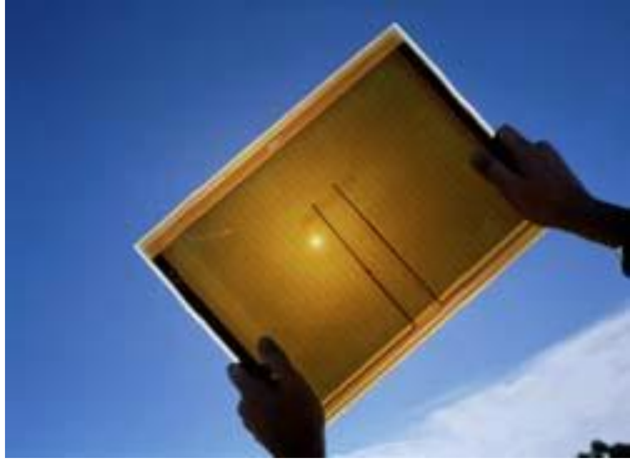
  can make cell translucent – potential for use on windows, etc.

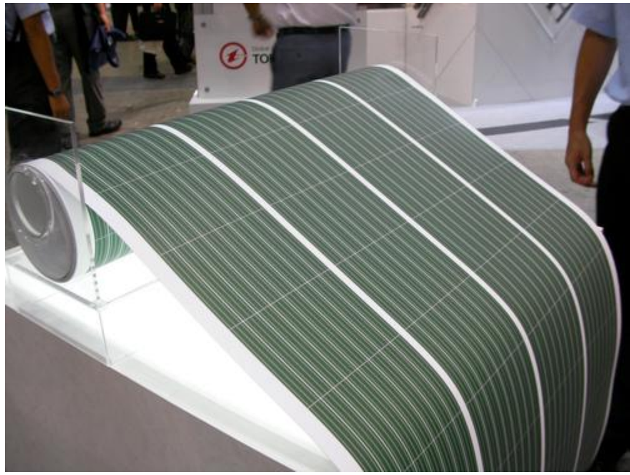
  can make cell lighter – potential for use on UAV, etc.

- Layer is “sprayed”: cells can be made to any size

  a range of backing materials can be used (stiff, flexible, etc.)

  cheap(er) to scale up to large-scale manufacture

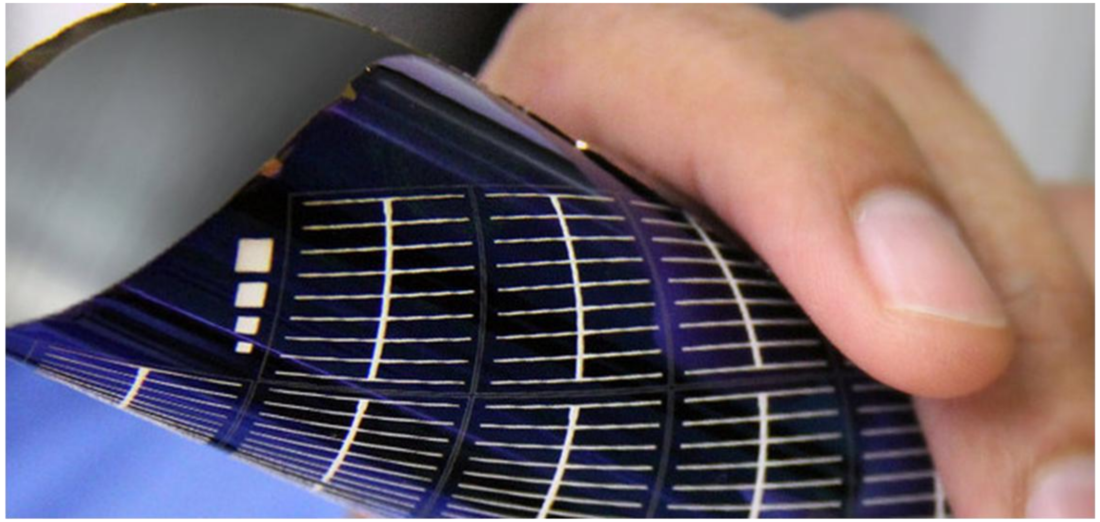




However, some **challenges** exist when using thin-film cells:

Drawbacks of thin-film cells include:

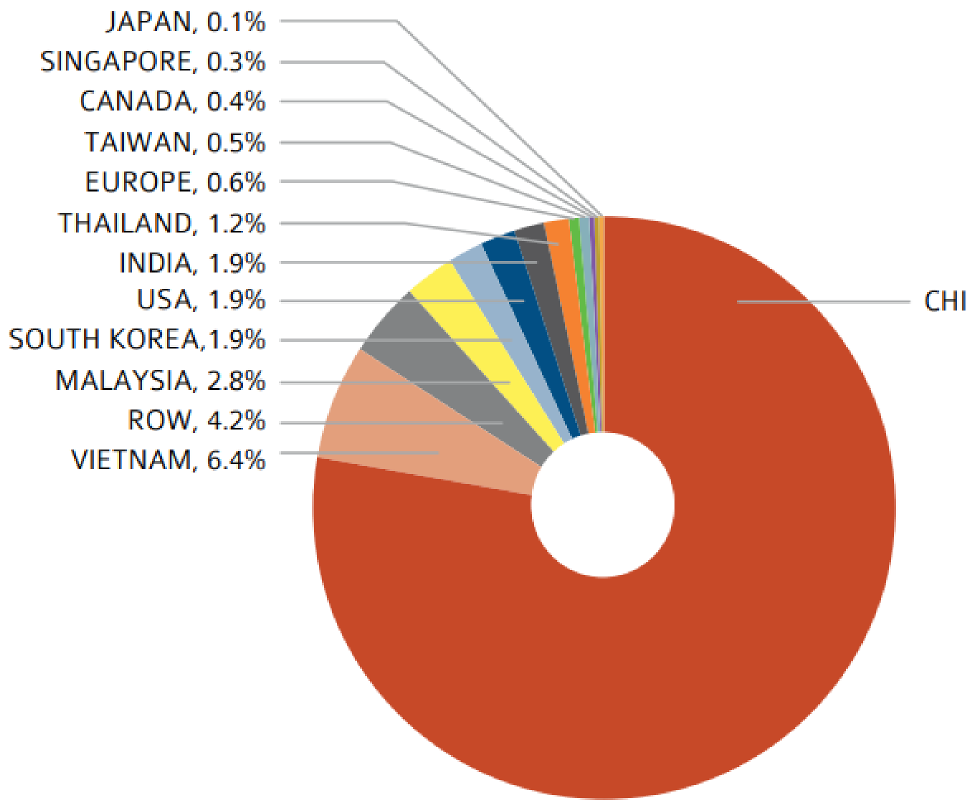
- Layer is very thin: needs extreme accuracy – especially for large cells

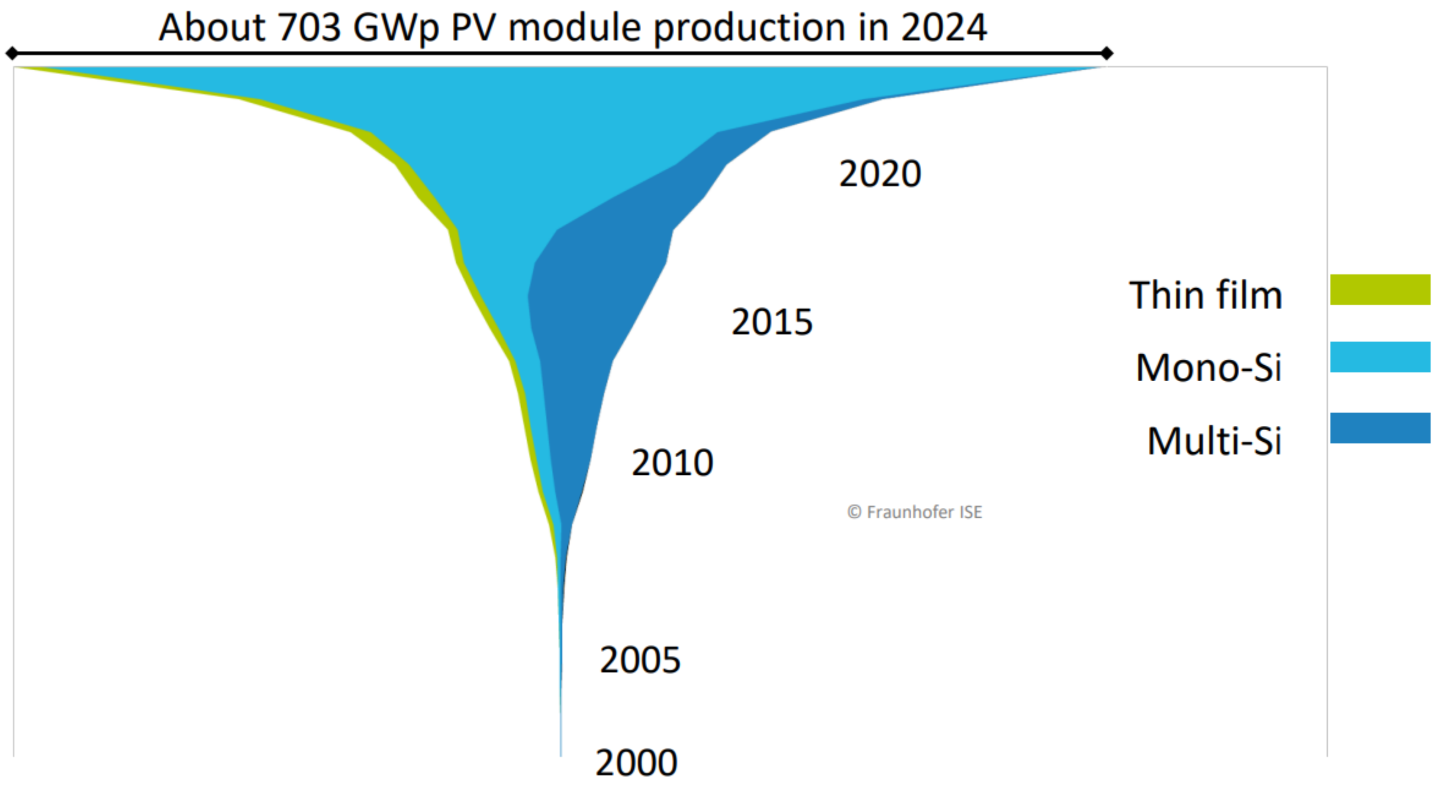


http://arstechnica.com/science/news/2012/03/ion-beam-manufacturing-halves-production-cost-of-pv-panels.ars

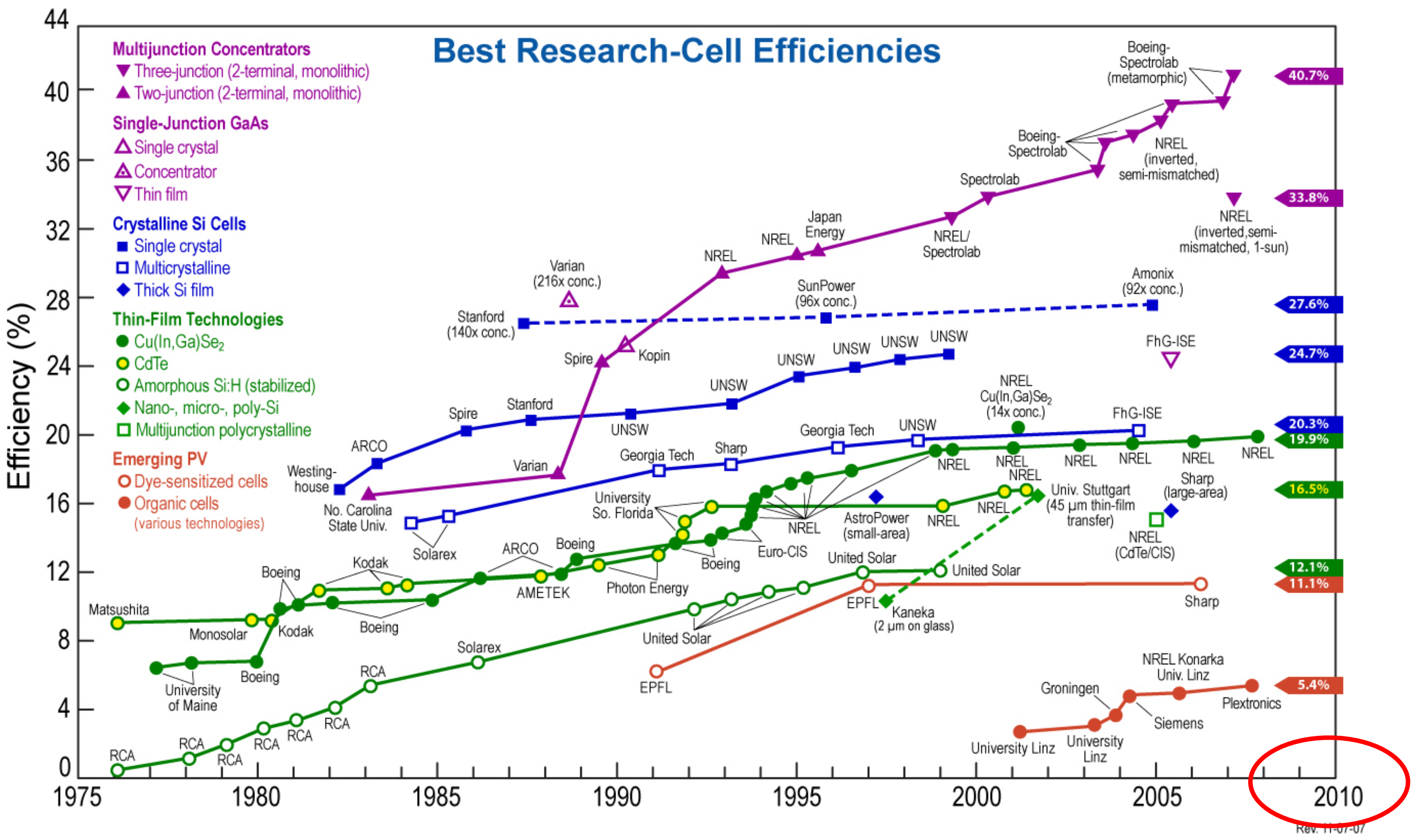
- Efficiency is lower than for c-Si cells
  - ➢ need more cell area for a given power output
  - ➢ balance of system costs are same as (higher than?) c-Si, so *overall* cost savings may be small

FIGURE 4.5: SHARE OF PV MODULE PRODUCTION IN 2022



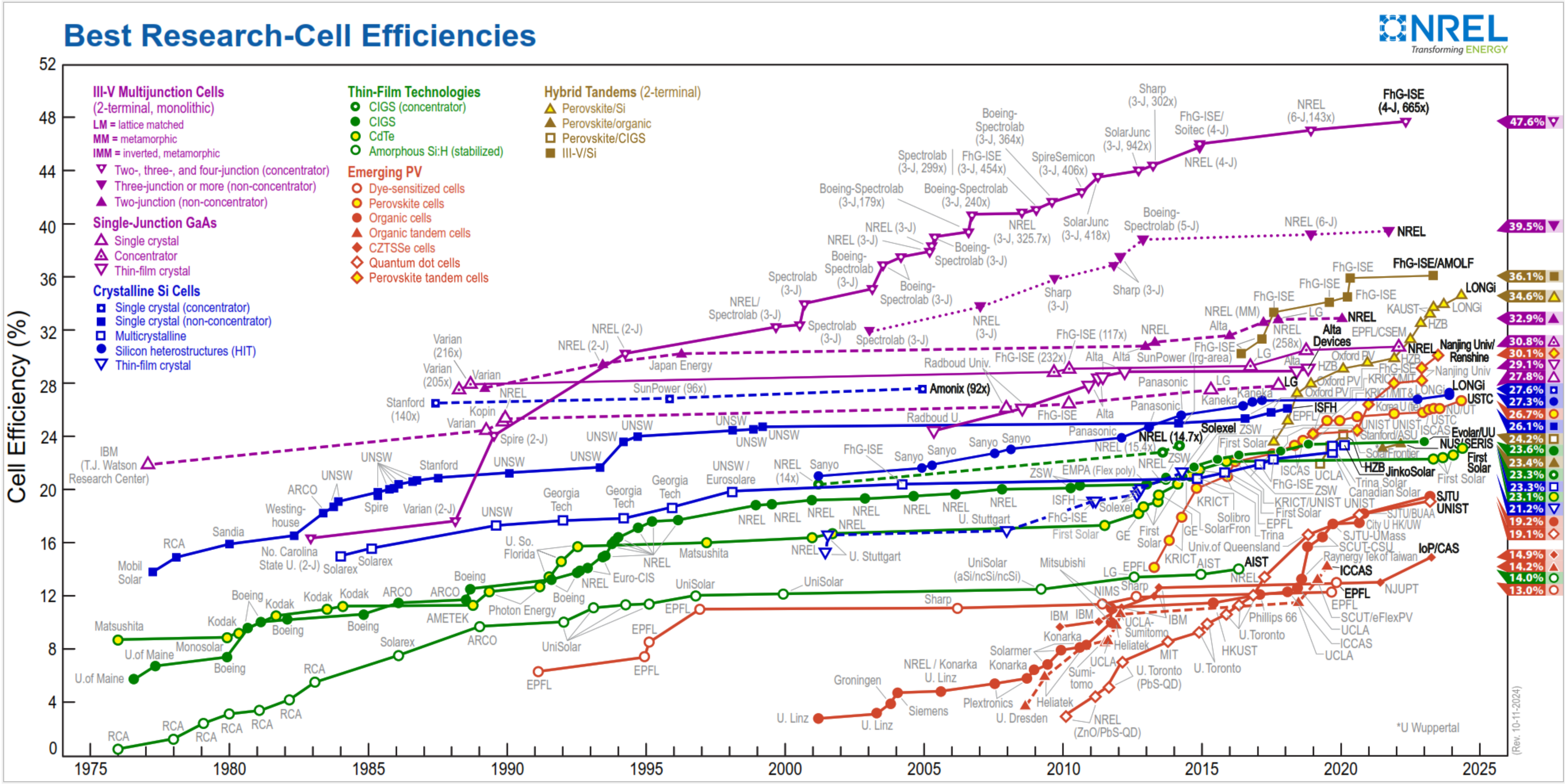


Source: International Energy Agency, "Trends in Photovoltaic Applications 2023", Report IEA-PVPS T1-43:2022 (left); Fraunhofer ISE (2025), "Photovoltaics Report". https://www.ise.fraunhofer.de (right)



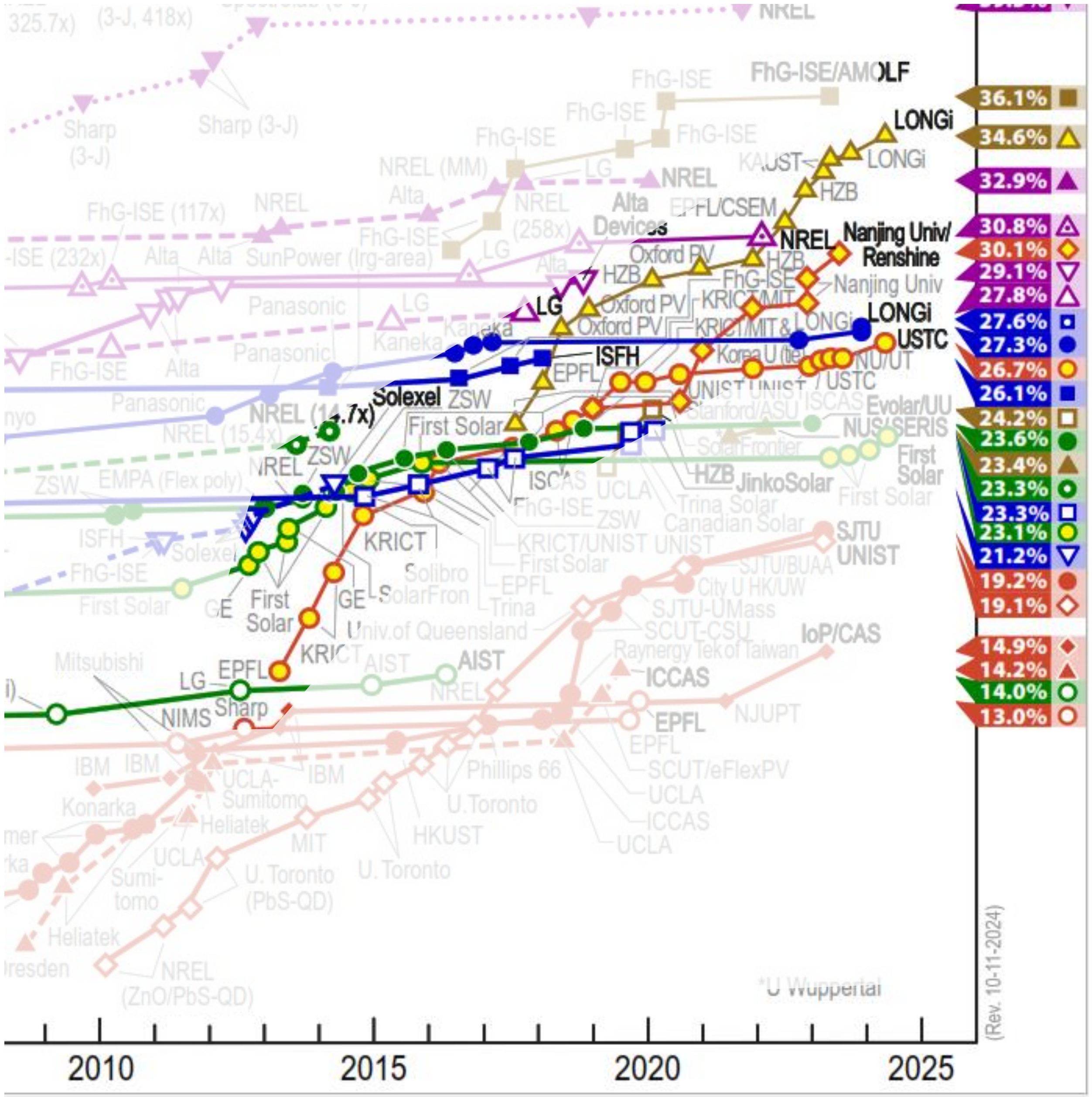
Source: NREL. http://www1.eere.energy.gov/solar

Photovoltaics (PV)



Source: NREL. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf

Photovoltaics (PV)



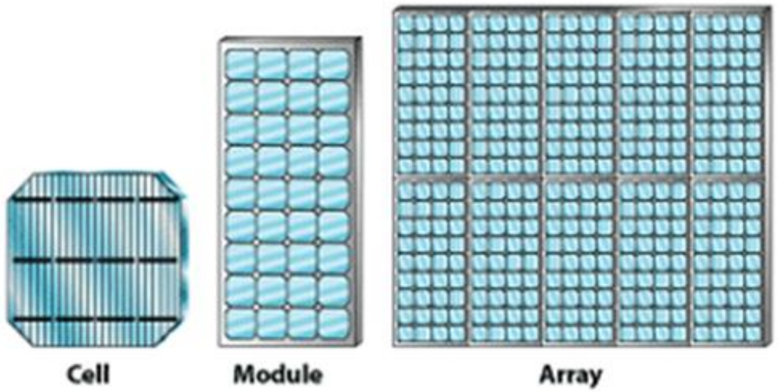
Source: NREL. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf

Photovoltaics (PV)

The voltage across an individual cell is low (~0.5 V), and its current-generating capacity is small. Typical *peak* power output is 3-5 W per 156 mm cell.

Multiple cells are therefore connected to form a single module – usually 50-100 cells per module yielding 150-500 Wp.

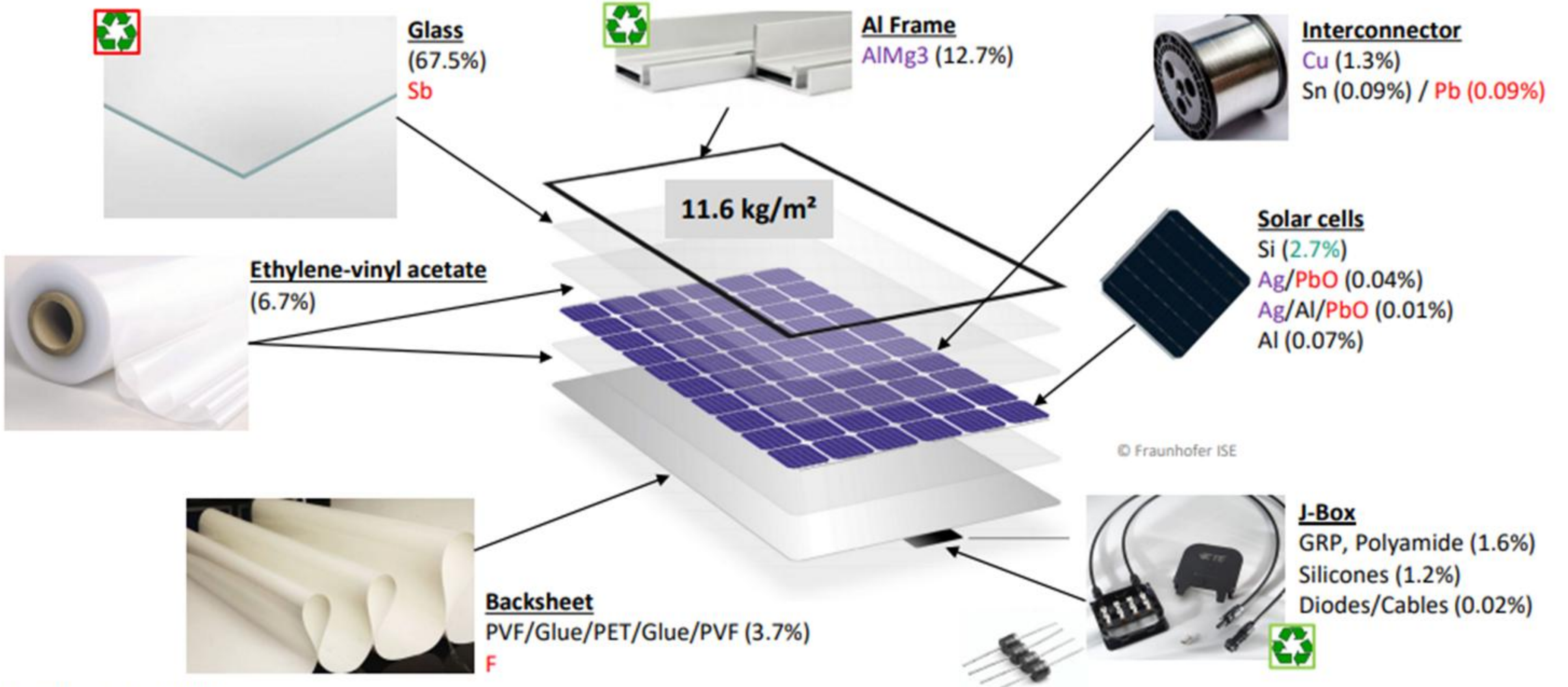
Modules, in turn, are connected to form arrays of 1-100 kW.



Each step in the scaling-up process reduces the fraction of exposed area that is active.

PV Module
Materials and Components

To survive outdoors in wind, rain, snow, etc, the fragile cells need to be encapsulated in a rigid housing.



Please note: Highly transparent glass can also be produced without antimony (Sb), and some European suppliers are doing so. It is technically feasible to recycle and reuse almost 100% of the materials used in PV modules. The European WEEE Directive stipulates that at least 80% of the module mass of old modules must be processed and recycled for reuse. For economic reasons, however, only the glass, frame and junction box (J-Box) are recycled today.

Color legend:
Available/harmless materials
Rare/valuable materials
Hazardous substances

Recycling takes place
Downcycling takes place

Source: Fraunhofer ISE © 2024

39

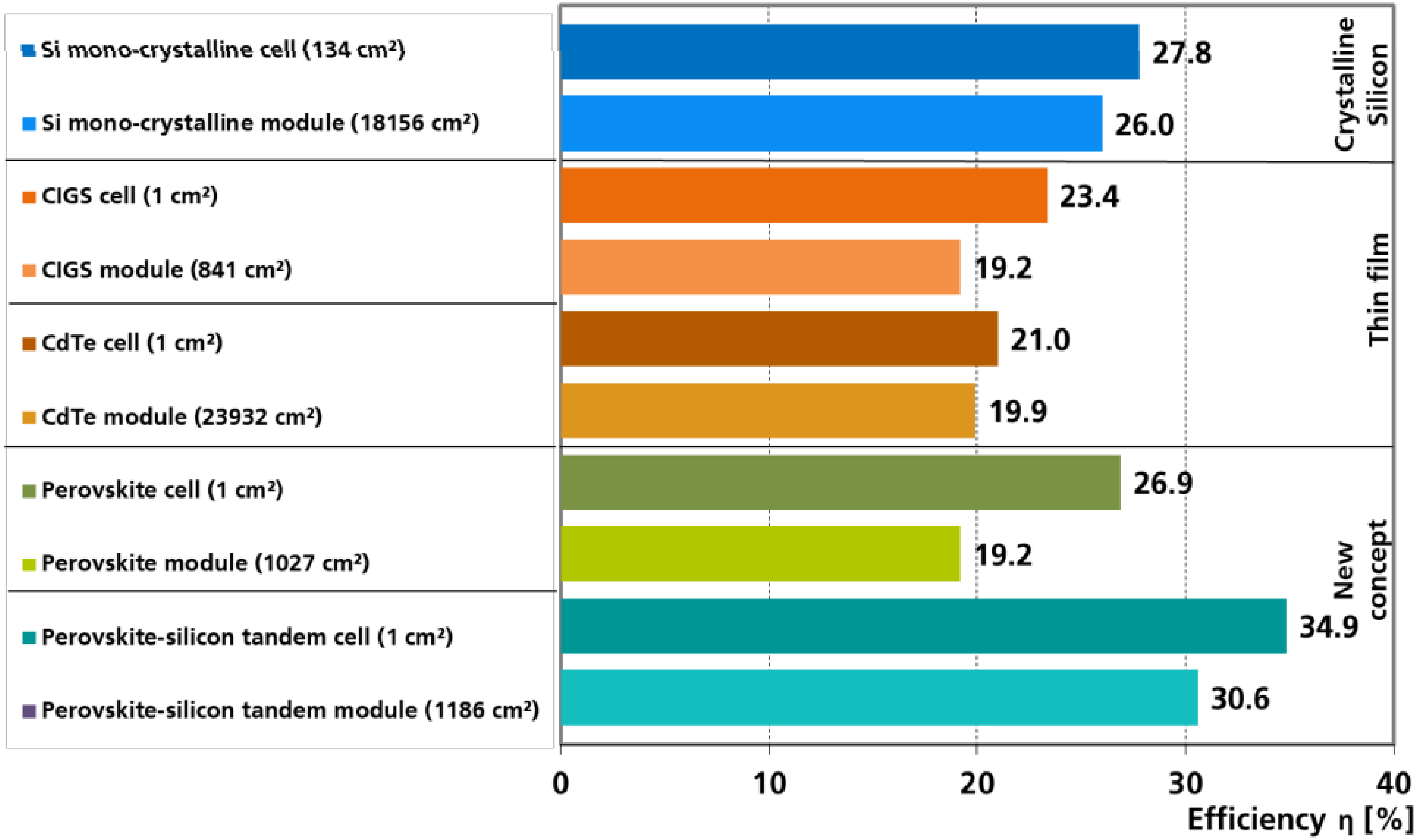
Mass fraction of substance in relation to total module mass of 11.6 kg/m² (100%) given in brackets; Date of data: 2021

Fraunhofer ISE

Source: *Photovoltaics Report. Fraunhofer ISE (2025). https://www.ise.fraunhofer.de*

Efficiency Comparison of Technologies

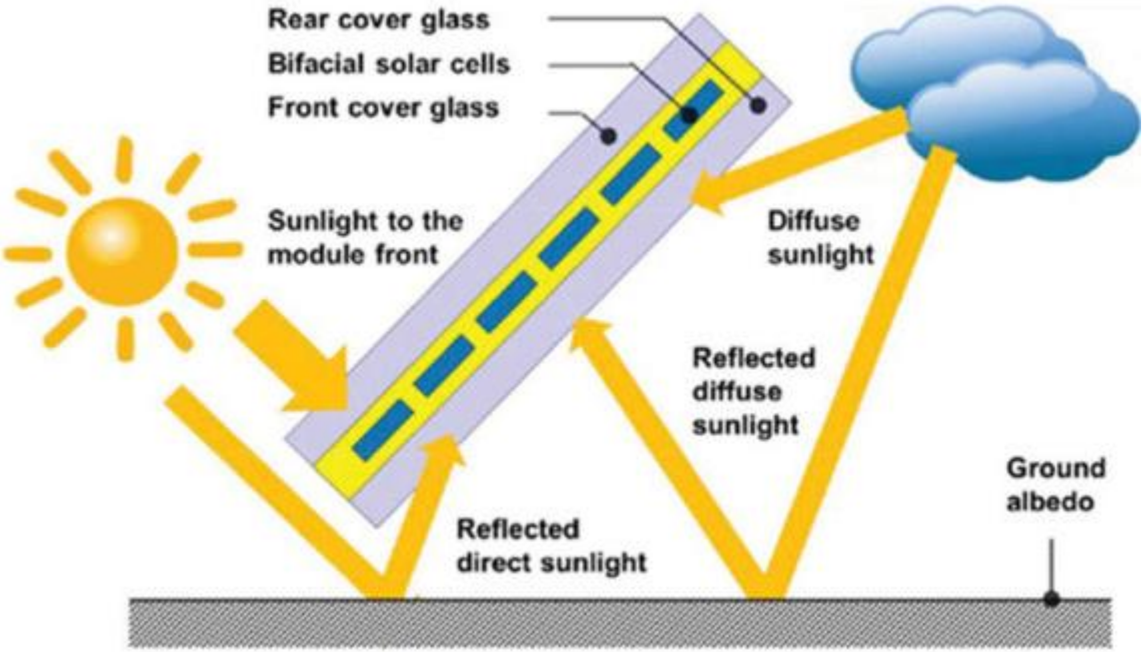
Best Lab Cells vs. Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables (Version 66), Progress in PV: Research and Applications 2025. Graph: PSE Projects GmbH 2025. Date of data: 04/2025

Source: Photovoltaics Report. Fraunhofer ISE (2025). https://www.ise.fraunhofer.de

Bifacial PV


Rear cover glass
Bifacial solar cells
Front cover glass
Sunlight to the module front
Diffuse sunlight
Reflected diffuse sunlight
Ground albedo
Reflected direct sunlight

PV mounting systems

- The most common array design uses flat-plate PV modules or panels.
- These panels can either be fixed in place or allowed to track the movement of the sun.

Fixed

Tracking

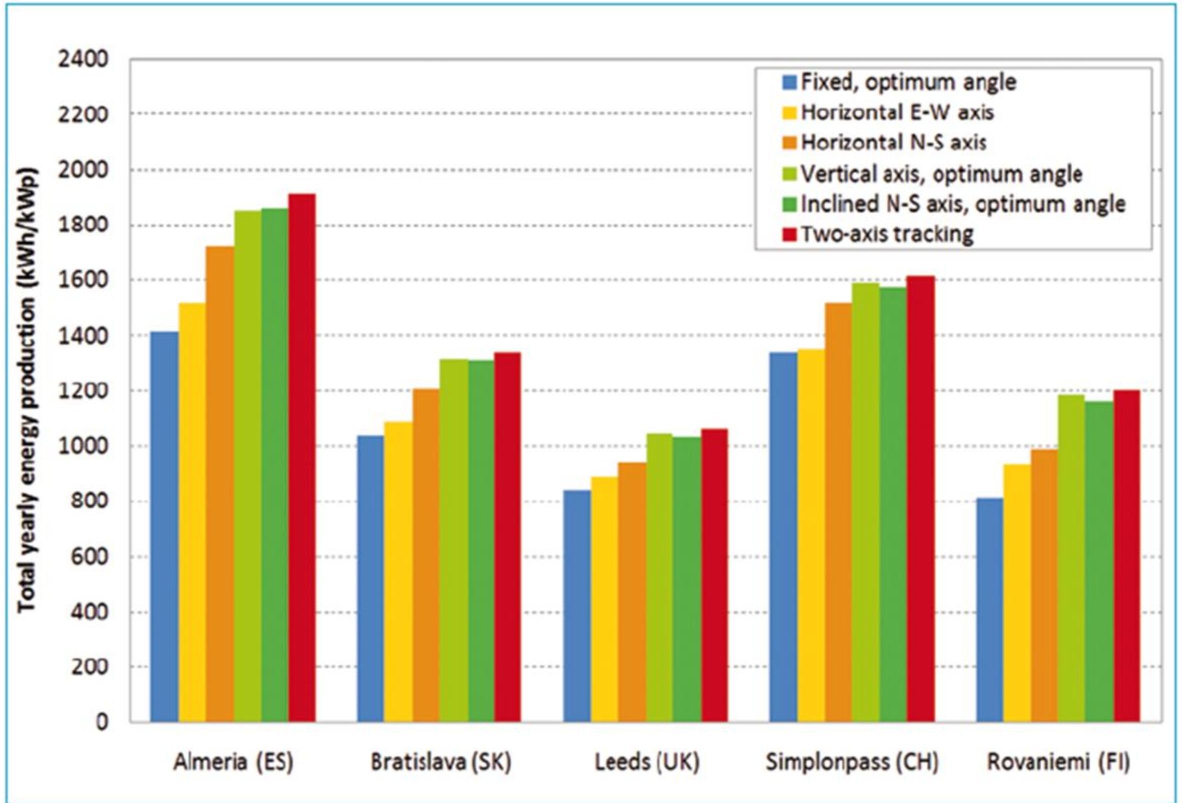


Figure 6. Comparison of the energy output from different system mountings for five locations in Europe. The comparison is made for a fixed system at optimum angle; for horizontal single-axis systems with axis pointing east/west or north/south; for vertical and inclined axis systems with optimum angle; and for a two-axis tracking system.

Source: Performance of single-axis tracking photovoltaic systems in Europe, European Commission.

Photovoltaics (PV)

Non-concentrating PV cells respond to all sunlight – either direct or diffuse.

- Even in clear skies, the diffuse component of sunlight constitutes 10% – 20% of total solar radiation on a horizontal surface.
- On partly sunny days, up to 50% of radiation is diffuse; on overcast days, 100% of the radiation is diffuse.
- PV cells (arrays) can continue to generate output even on a cloudy or overcast day.
- However, the output is a linear function of solar intensity, which decreases – sometimes drastically – when clouds are present.

A note on the power rating of photovoltaic systems:

- PV panels are rated using a set of Standard Test Conditions agreed by the solar power industry.
- 1,000 Wm^{-2} is defined as the standard illumination level for measuring and quoting a solar panel's power output.

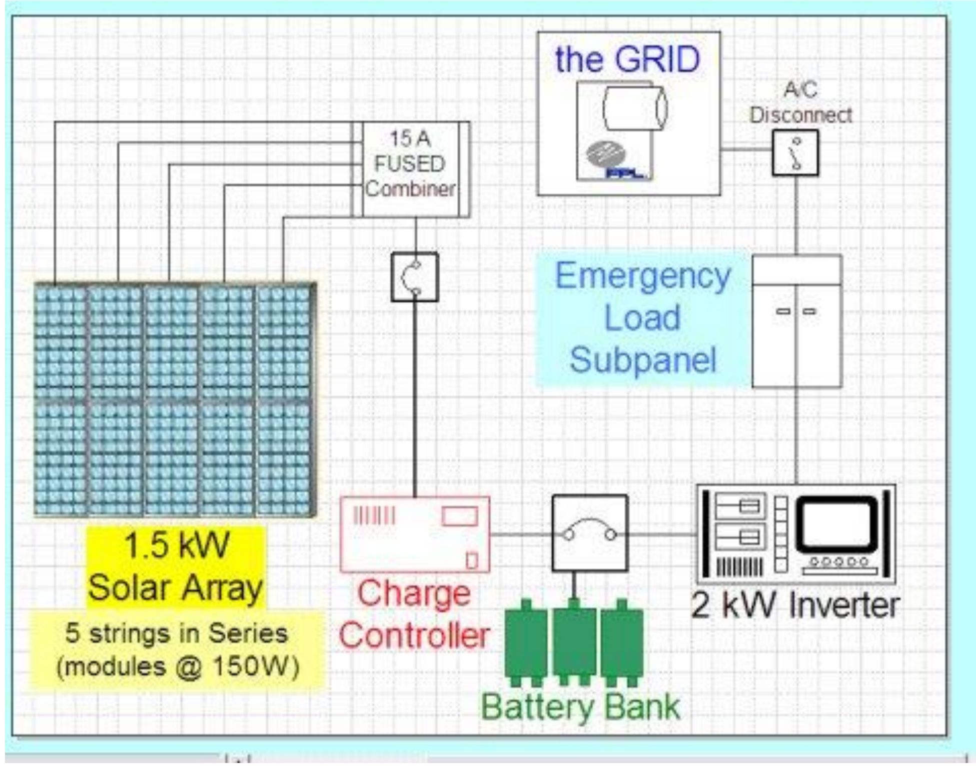
  (this is roughly equal to the intensity of sunlight falling on a horizontal surface, on a clear summer day, when the sun is directly overhead)

- The electrical power produced by a panel, illuminated by solar radiation of this intensity, is called the "peak output power" of the panel – expressed as W_p or kW_p.
- This is the figure that's normally listed in product brochures and data sheets.

Photovoltaics (PV)

A note on the installation of photovoltaic systems:

- PV panels generate DC power, at relatively low voltage.
- At a minimum, they will also require an inverter – to convert the DC to AC.
- Unless connected to the grid, substantial battery storage will be required, along with a charge controller for regulating the rate of current flow into the batteries.
- Other "balance of system" (BOS) includes mounting structures.
- As PV module prices continue to fall, BOS costs now account for up to 60% of total installation costs for grid-scale solar farms.



Performance ratio

depends on:
- a) system performance
- b) amount of sunshine (irradiance)

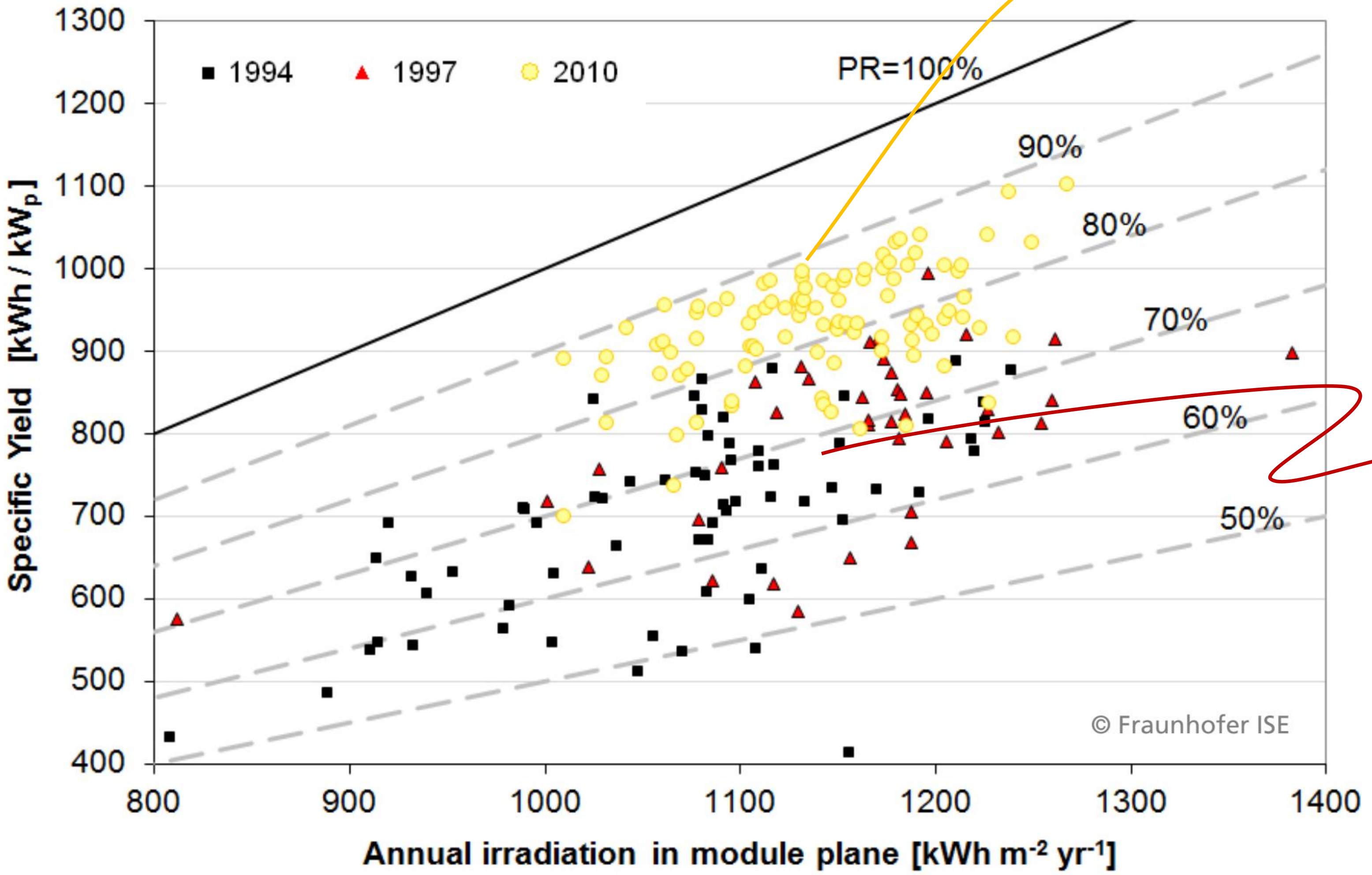
Energy yield = $\left(\dfrac{measured\ electricity\ output\ [kWh]}{reference\ power\ [kW_p]}\right)$ ...equivalent to "full-load hours" (FLH)

Relative irradiance = $\left(\dfrac{measured\ irradiance\ [Wh.m^{-2}]}{reference\ irradiance\ [W.m^{-2}]}\right)$

Performance ratio = $\dfrac{energy\ yield\ [h]}{relative\ irradiance\ [h]}$ - performance relative to laboratory conditions

Source: Photovoltaics Report. Fraunhofer ISE (2018). https://www.ise.fraunhofer.de

Performance Ratio Development for PV Systems
Germany



Today

- Typical PR ~80-90 %
- Less variance in PR as compared to 1990's

In the 1990's

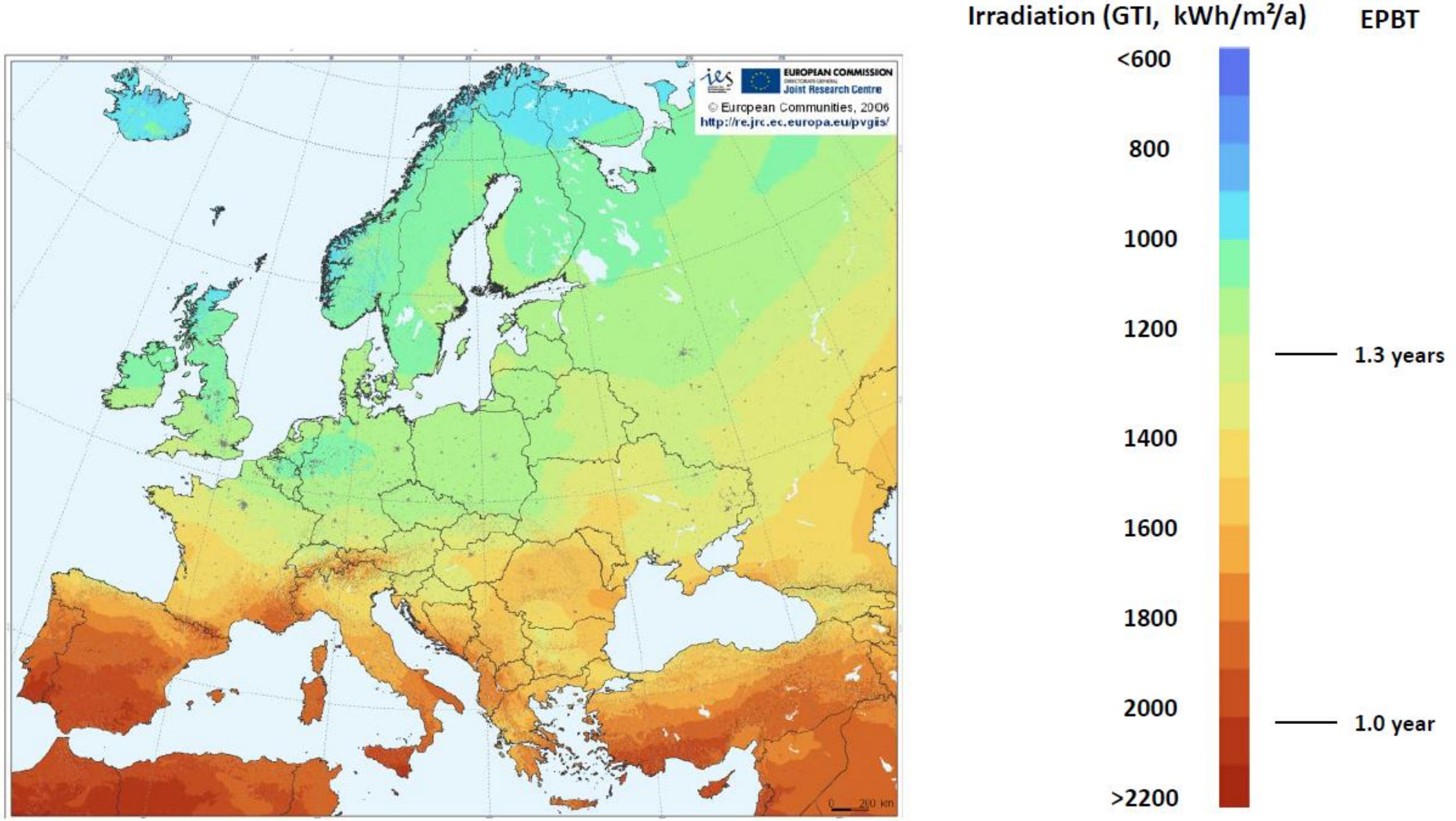
- Typical PR ~70 %
- Widely ranging PR values

Source: Photovoltaics Report. Fraunhofer ISE (2018). https://www.ise.fraunhofer.de

Energy pay-back time of multi-crystalline Silicon PV rooftop systems: a geographical comparison

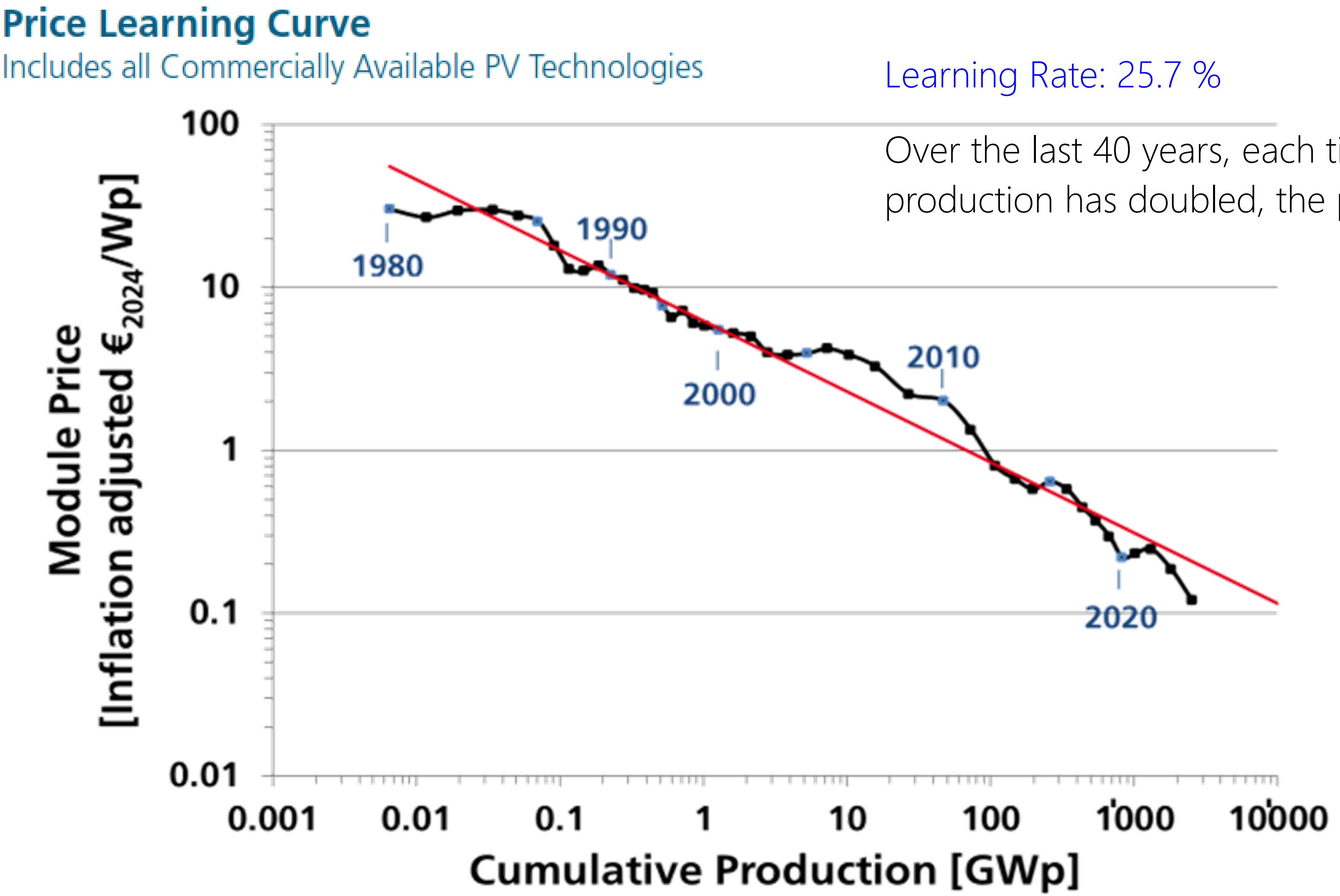
Depending on the technology and location of the PV system, the EPBT today ranges from 0.7 to 1.5 years.

Rooftop PV systems produce net clean electricity for approx. 95 % of their lifetime, assuming a life span of 30 years or more.



Source: Photovoltaics Report. Fraunhofer ISE (2018). https://www.ise.fraunhofer.de

Photovoltaics (PV)



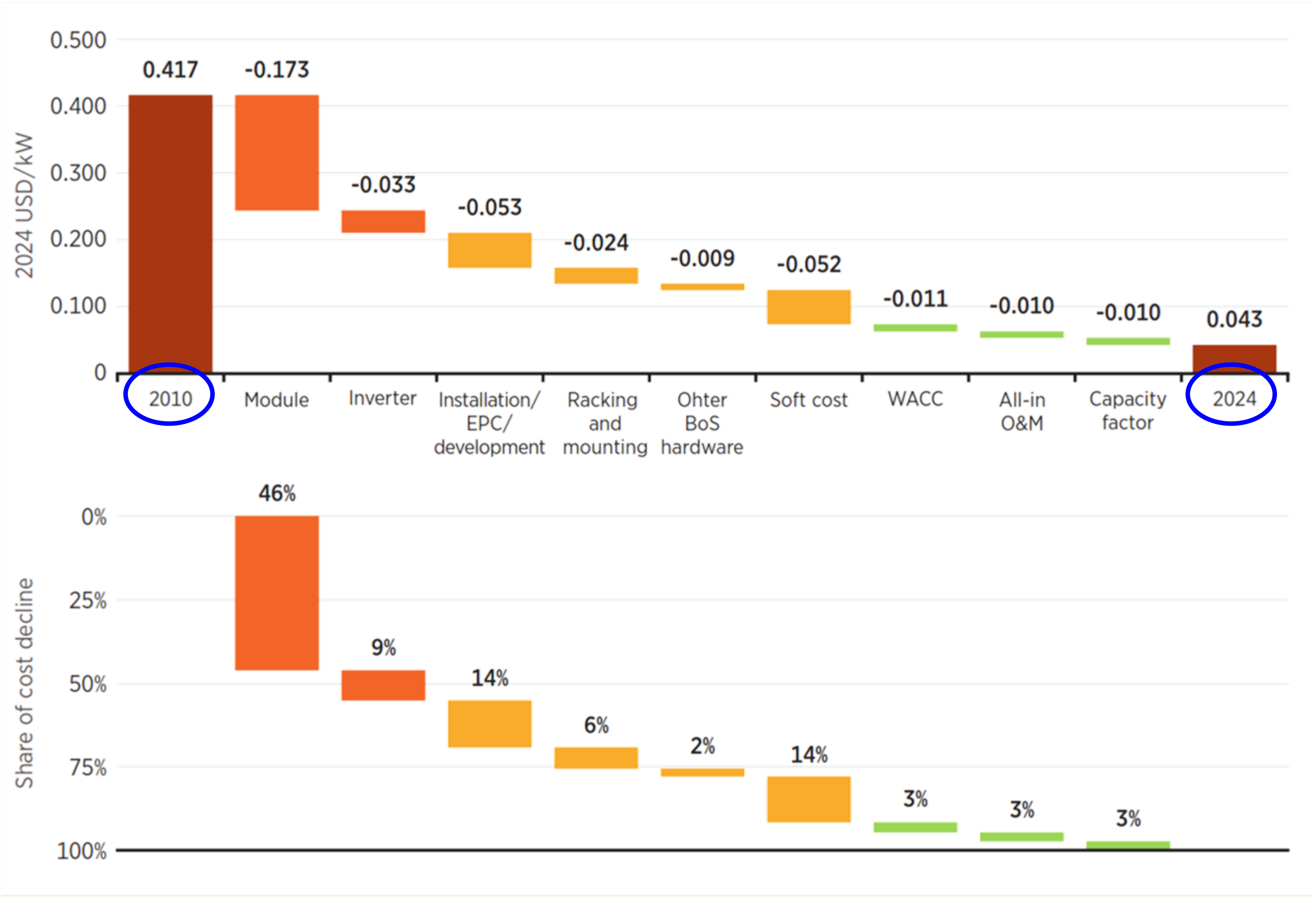
Learning Rate: 25.7 %

Over the last 40 years, each time that cumulative PV module production has doubled, the price has decreased by 25.7 %.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit from 2022; VDMA for 2024: ISE;

Source: Photovoltaics Report. Fraunhofer ISE (2025). https://www.ise.fraunhofer.de

Photovoltaics (PV)



Source: Renewable Power Generation Costs in 2024. *International Renewable Energy Agency (2025) https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024*

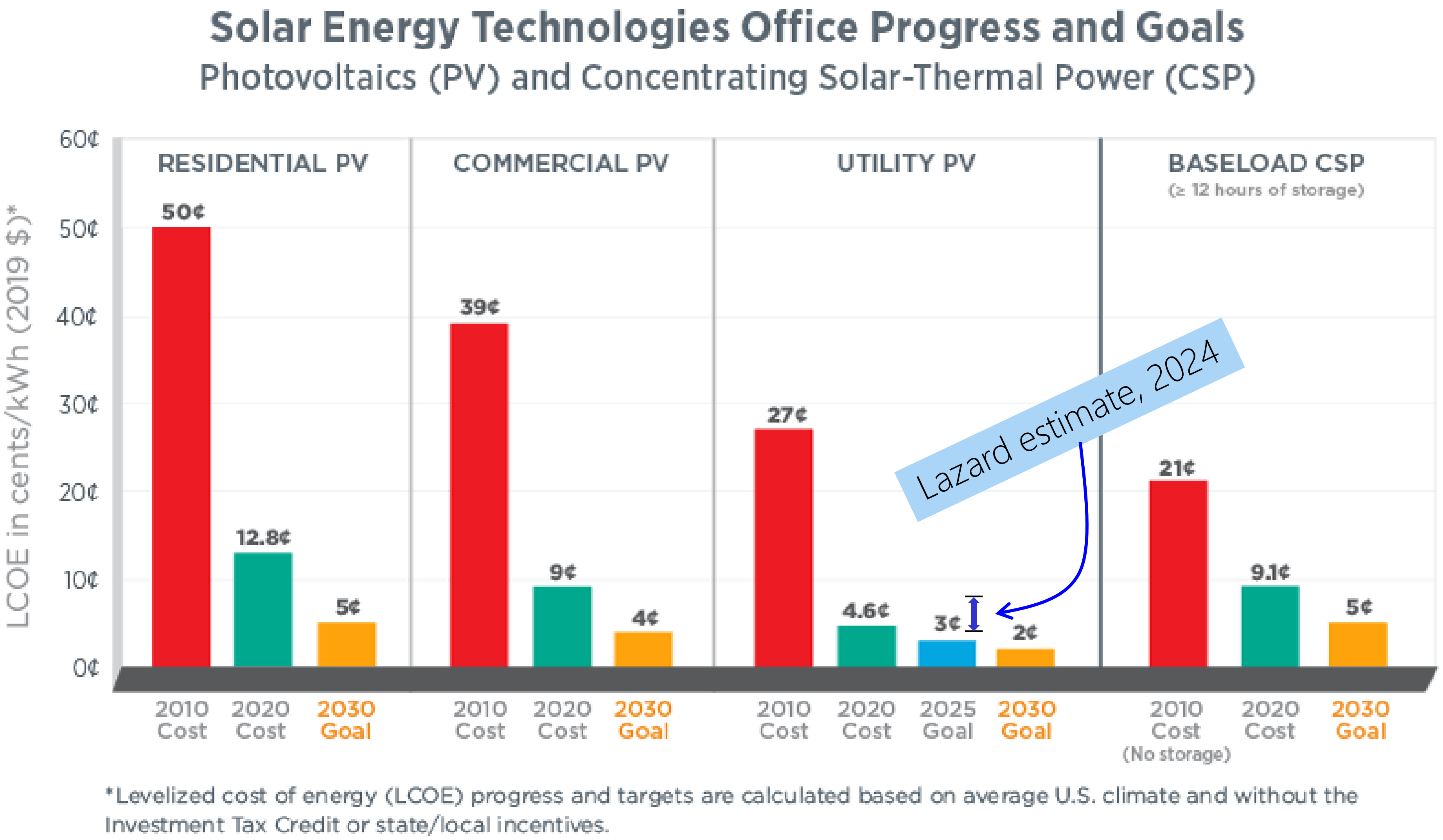


Image Source: https://www.energy.gov/eere/solar/goals-solar-energy-technologies-office

Solar panel prices increase nearly 5% as China tightens oversight

In a new weekly update for **pv magazine**, OPIS, a Dow Jones company, provides a quick look at the main price trends in the global PV industry.

AUGUST 29, 2025 OPIS

Renewable Energy Is Booming Despite Trump's Efforts to Slow It

With federal subsidies ending or becoming hard to claim, companies are racing ahead with solar, wind and battery projects.

US utility PV up 56% in 2024, accounting for 54% of all new capacity – LNBL

By Will Norman

October 16, 2025

Power Plants, Projects

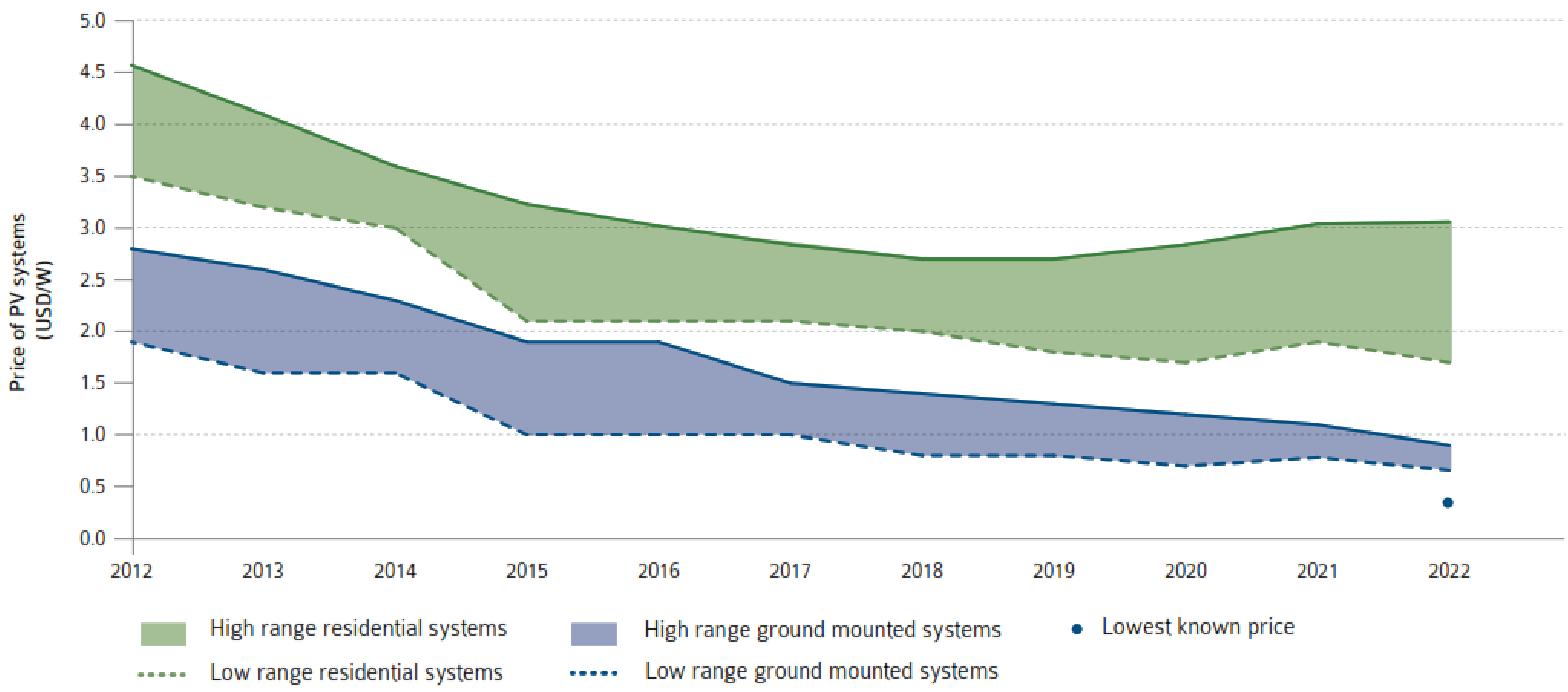
Trump tariffs deal damage to US solar

"It's a changed world in the renewables space," said Stefan Reisinger, partner at Norton Rose Fulbright.

APRIL 8, 2025 RYAN KENNEDY

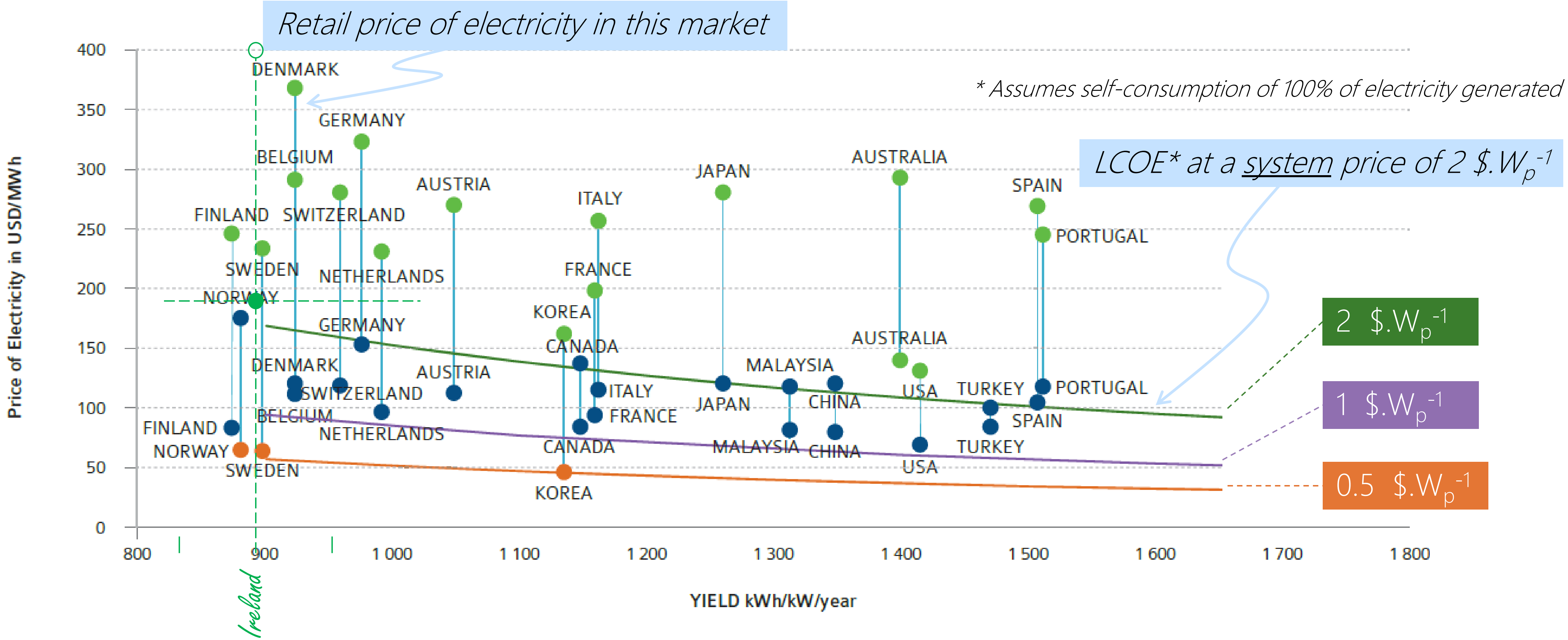
HIGHLIGHTS MARKETS MODULES & UPSTREAM MANUFACTURING POLICY UNITED STATES

FIGURE 6.5: EVOLUTION OF RESIDENTIAL AND GROUND-MOUNTED SYSTEMS PRICE RANGE 2012 - 2022 (USD/W)



Source: International Energy Agency, "Trends in Photovoltaic Applications 2023 Report IEA-PVPS T1-43:2023

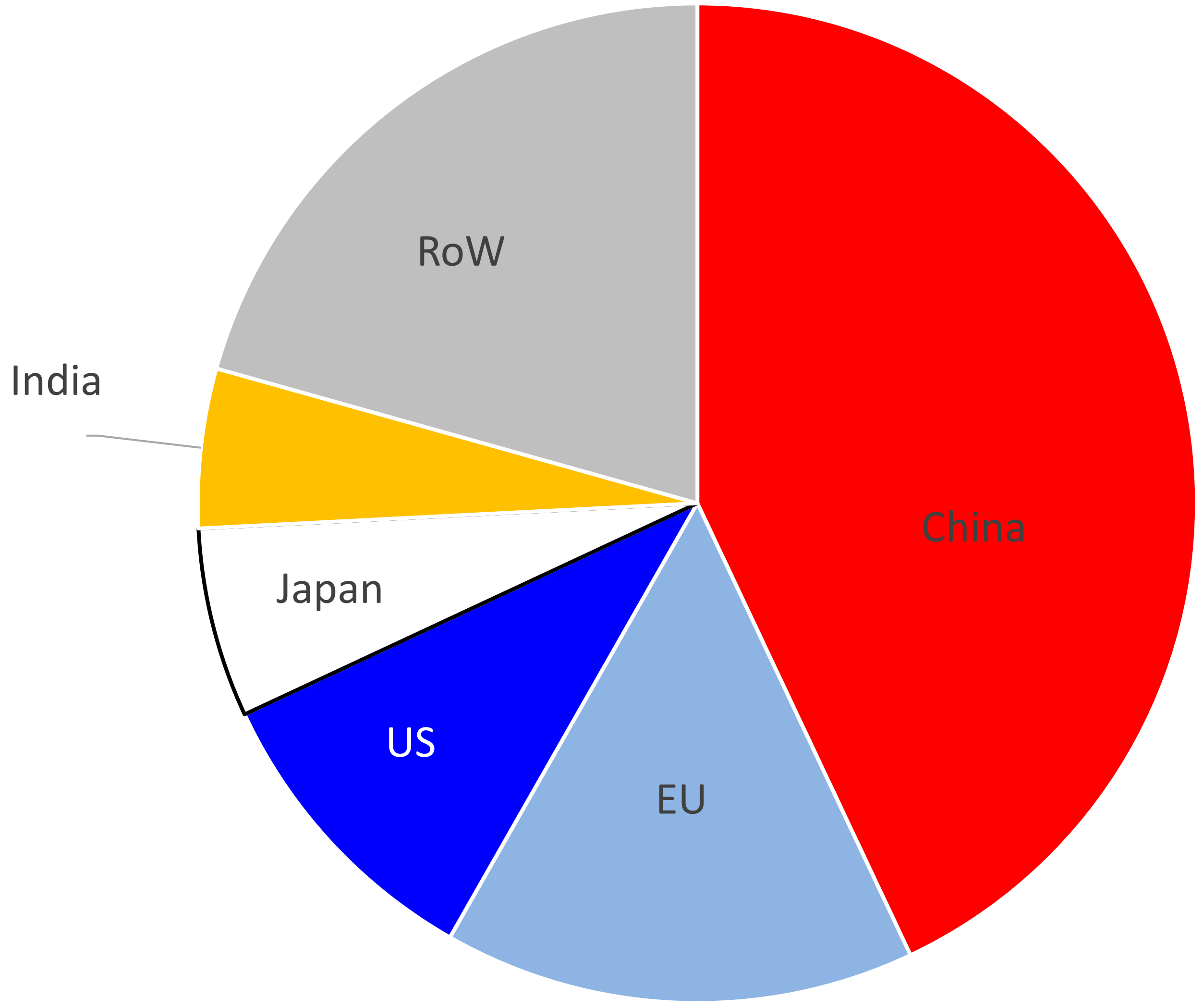
FIGURE 6.9: LCOE OF PV ELECTRICITY AS A FUNCTION OF SOLAR IRRADIANCE & RETAIL PRICES IN KEY MARKETS*



Source: International Energy Agency, "Trends in Photovoltaic Applications 2020", Report IEA-PVPS T1-38:2020

Trends…

Cumulative installed photovoltaic (PV) power* 2023



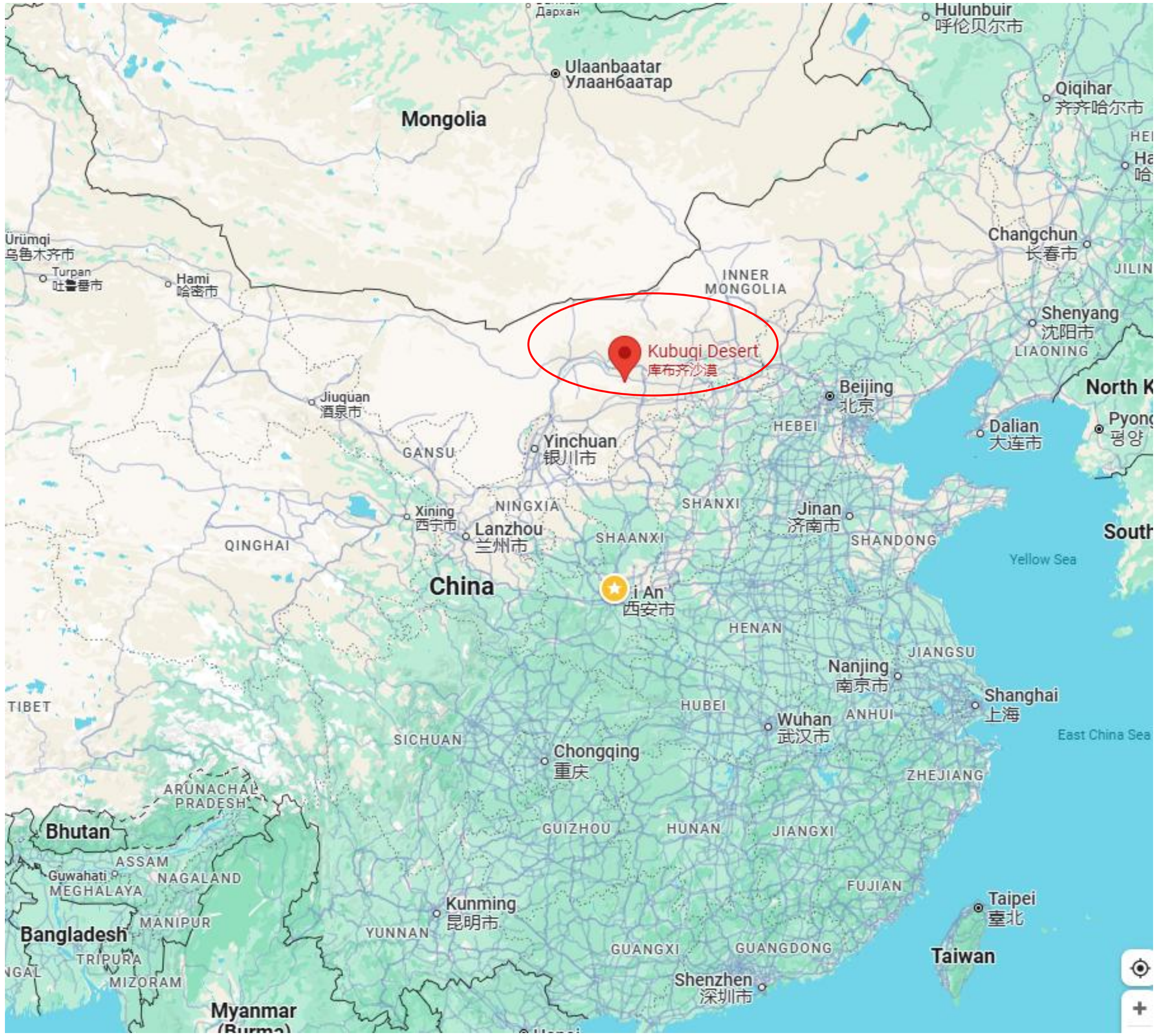
Raw data: Statistical Review of World Energy 2024

China's "Solar Great Wall"

Sandy, and mostly devoid of life, the Kubuqi Desert in Inner Mongolia once had a reputation for being a "sea of death."

More recently, its dune fields have been transformed by a swathe of newly installed solar panels.

The construction is part of China's multiyear plan to build a "solar Great Wall" – which will generate enough electricity to power Beijing.



Source: https://earthobservatory.nasa.gov/images/153759/building-a-great-solar-wall-in-china

China's "Solar Great Wall"?

The project, expected to be finished in 2030, will be 400 km long, 5 km wide, and achieve a maximum generating capacity of 100 GW.

https://earthobservatory.nasa.gov/images/153759/building-a-great-solar-wall-in-china

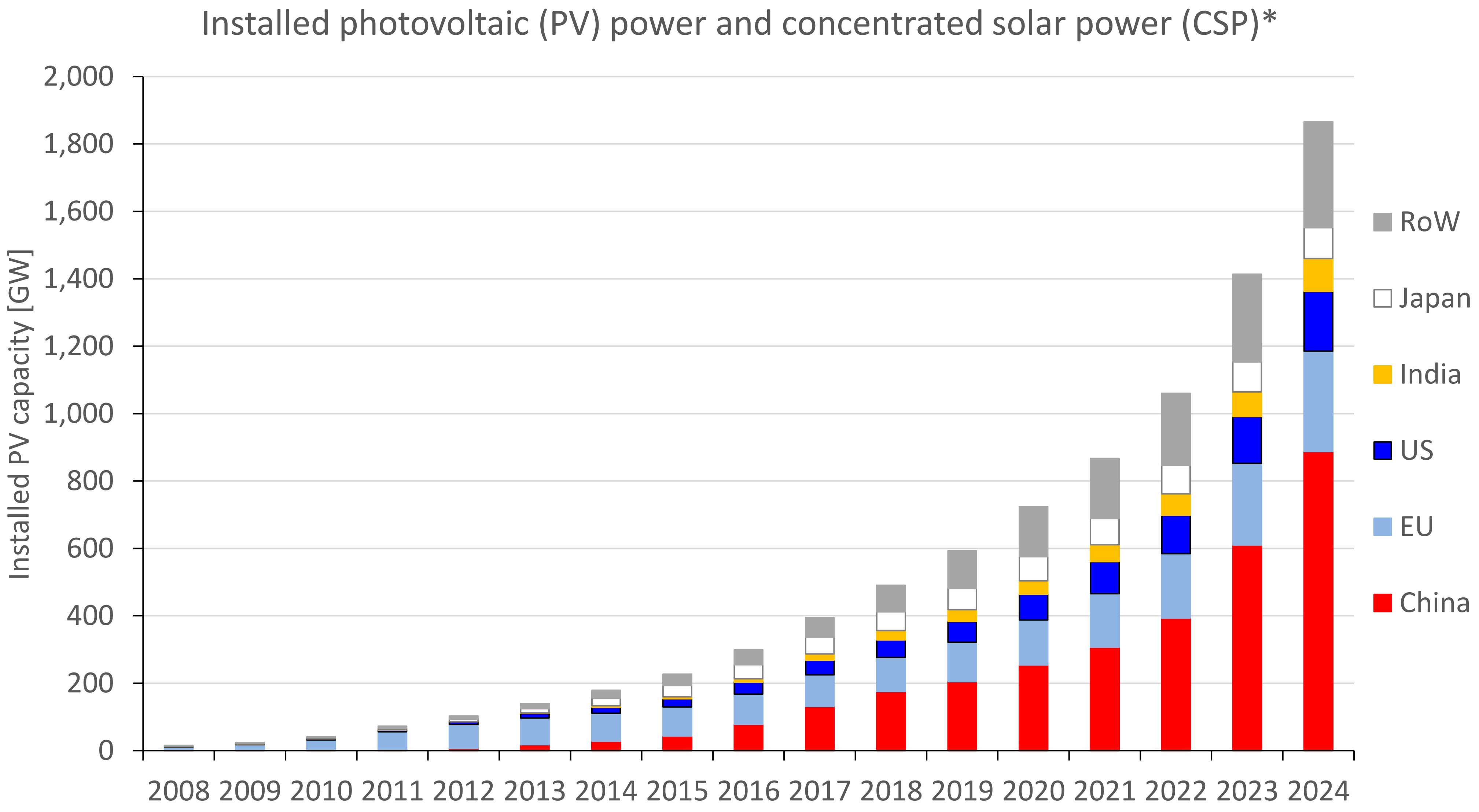
Source:

The Junma solar farm – Junma means “fine horse” in Mandarin – was completed in 2019, setting a Guinness world record for the largest image made of solar panels.

Co-benefits of locating the farm in a desert include:

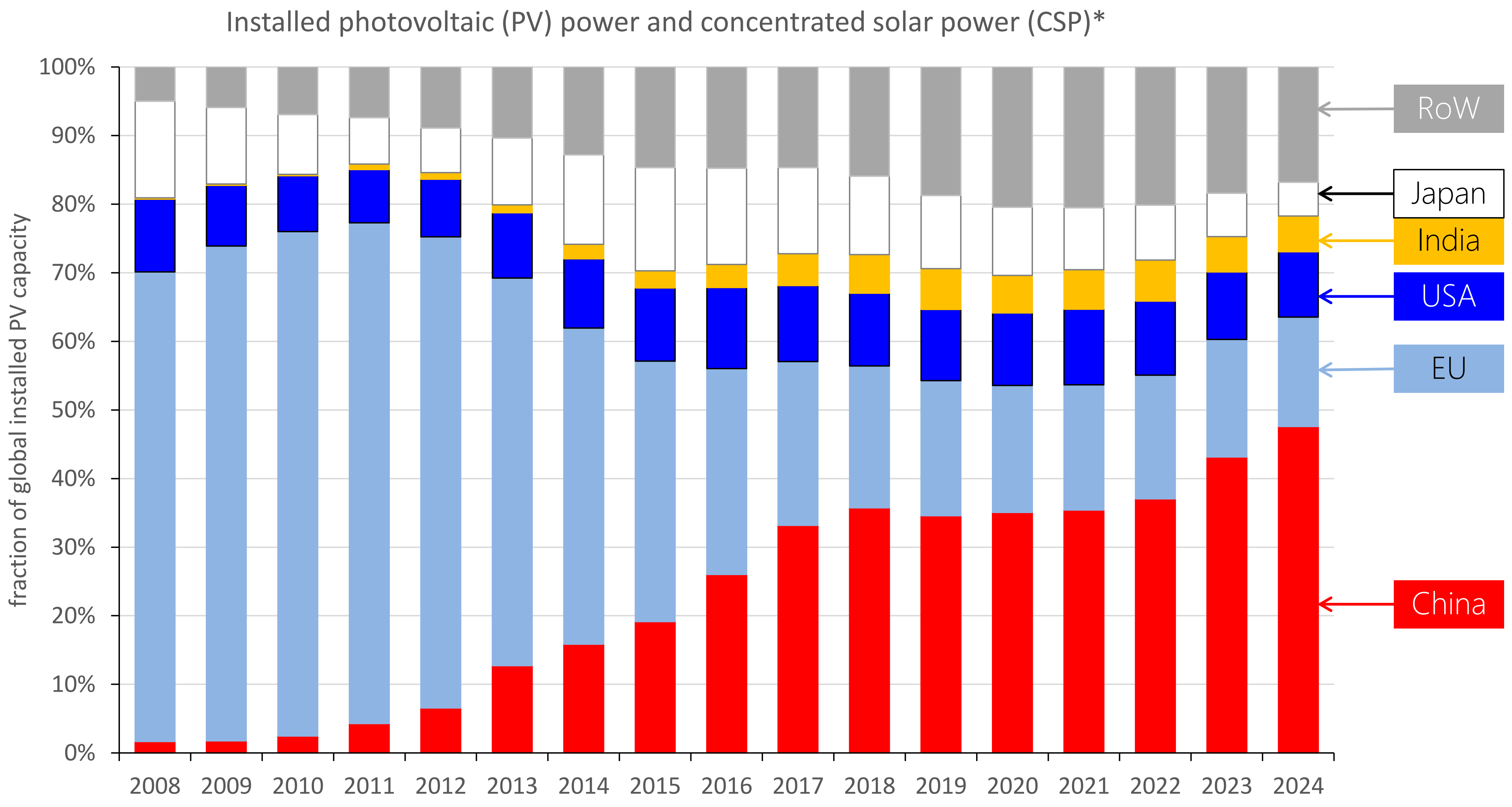
- Reversing desertification (“greening”)
- Reducing dune movement
- Slowing winds
- Reducing the intensity, frequency, and range of sandstorms.
- Bringing employment and opportunity to an impoverished area.

Source:

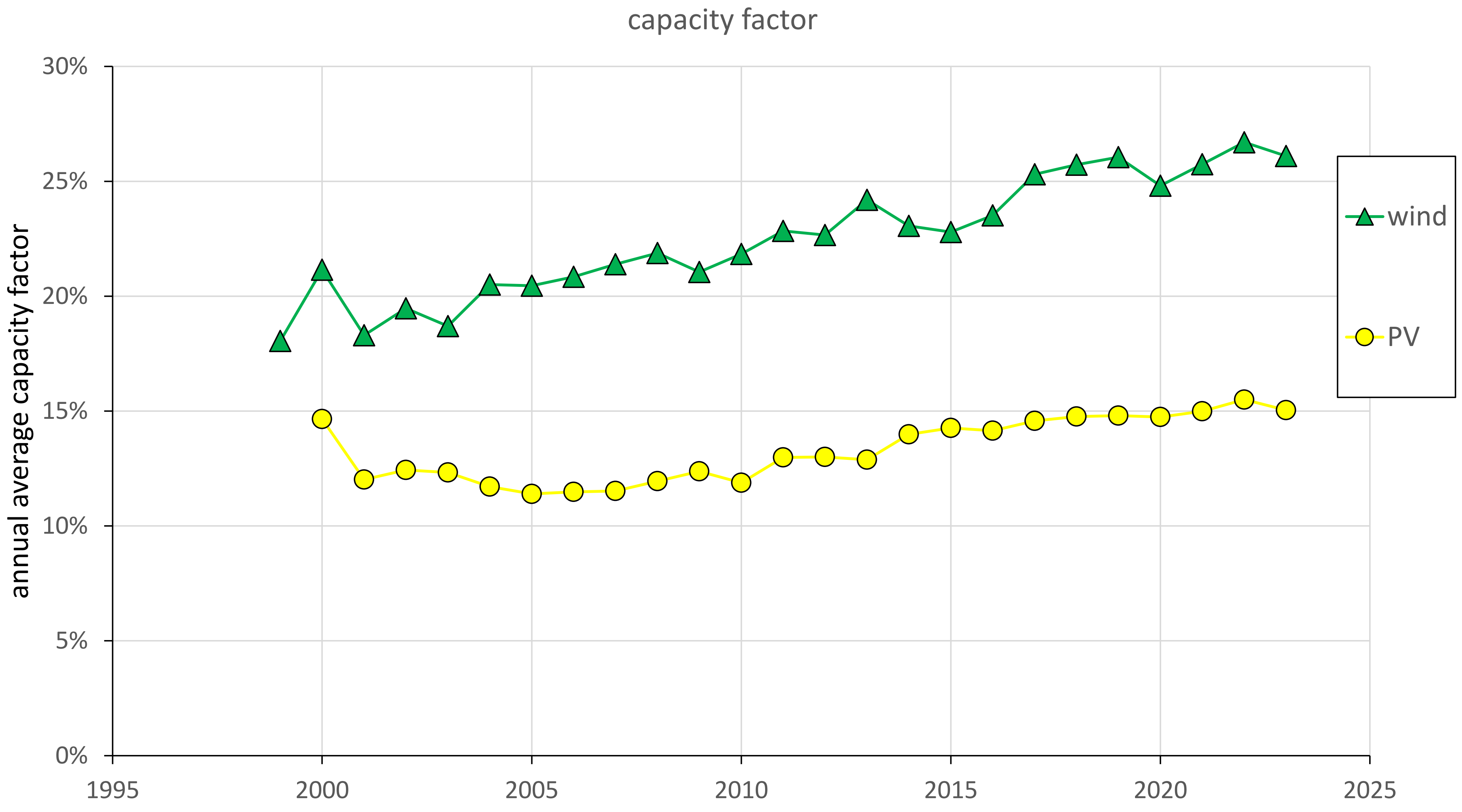


Raw data: Statistical Review of World Energy 2025

Photovoltaics (PV)

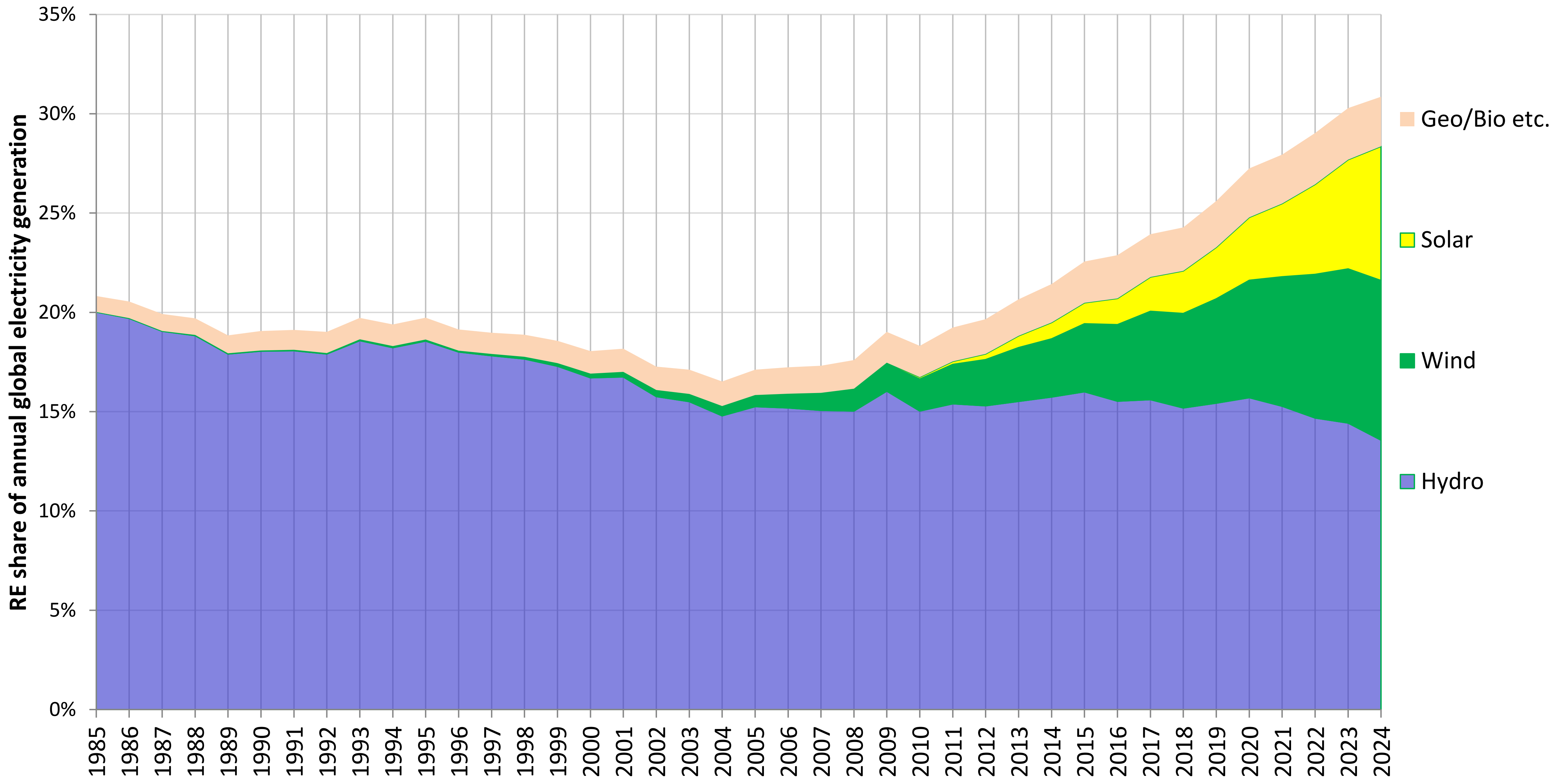


Raw data: Statistical Review of World Energy 2025



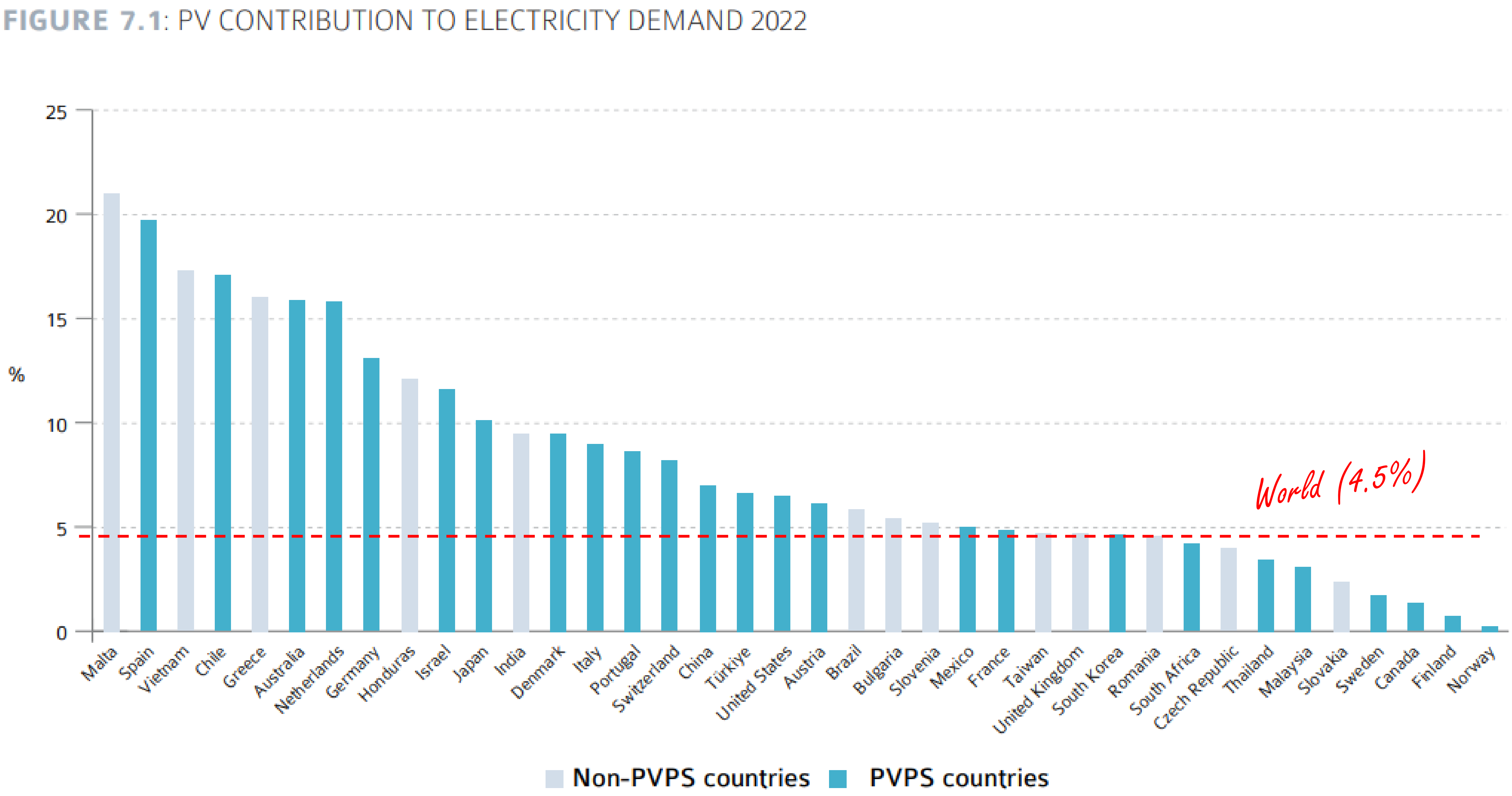
Raw data: BP Statistical Review of World Energy

Photovoltaics (PV)



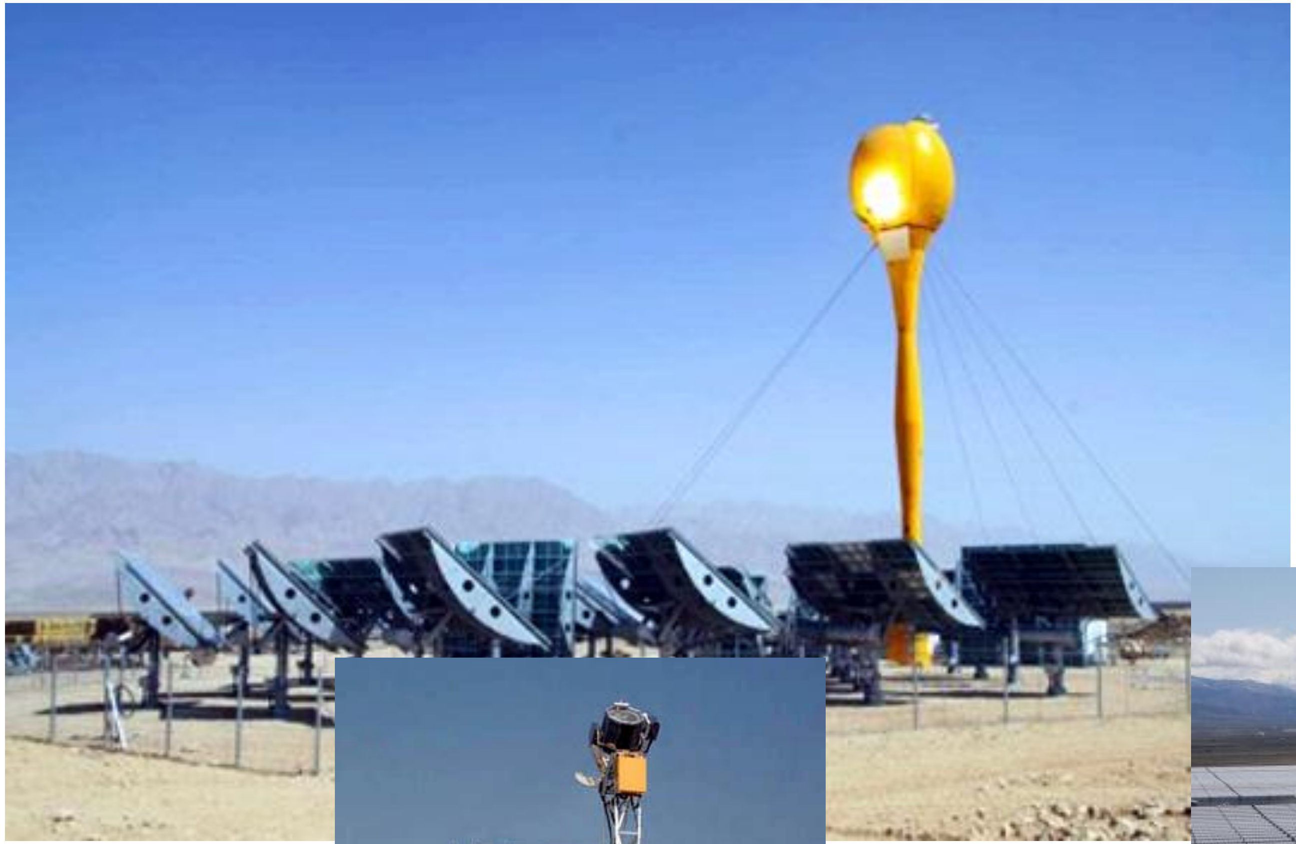
Raw data: Statistical Review of World Energy

Photovoltaics (PV)



Source: International Energy Agency, "Trends in Photovoltaic Applications 2023, Report IEA-PVPS T1-43:2023

Concentrating Solar Power (CSP)



Basic operating principle of CSP systems:

- Mirrors are used to concentrate solar radiation (need direct beam radiation), so that it can be collected as heat.
- That heat is used (in place of fossil fuel combustion) to generate steam for a conventional Rankine-cycle power plant.

Note: The efficiency and power output of Rankine-cycle plant increases with increasing $T_{max,\ steam}$.

Concentrating Solar Power (CSP)

Basic operating principle of CSP systems:

Two main options for the topology of a CSP plant:

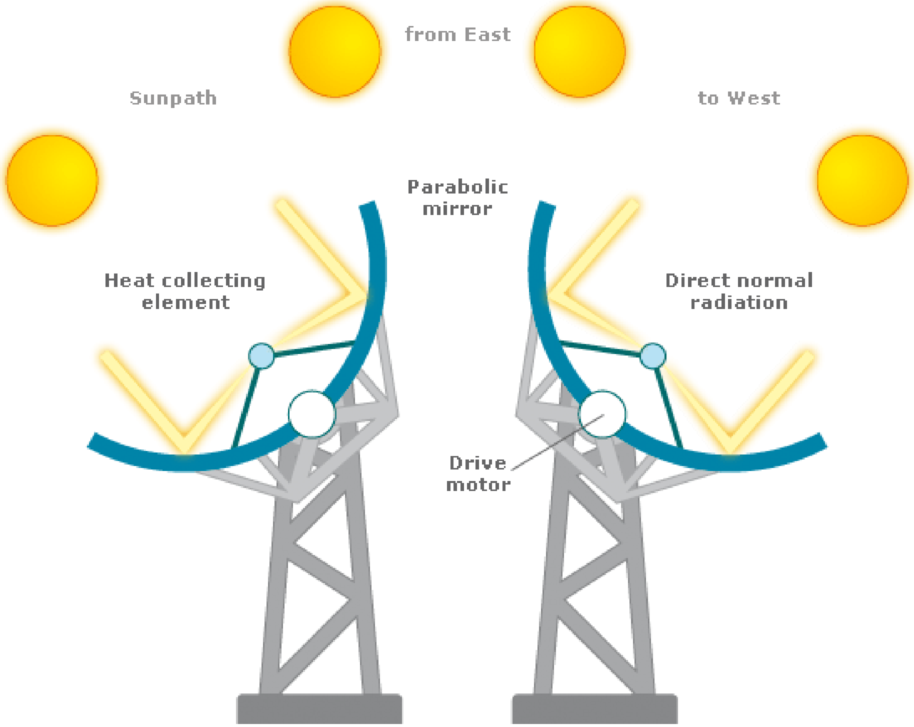
- Solar trough
- Solar tower

Solar tower has the potential to achieve higher operating temperatures (greater concentration of sunlight).

Either can – and almost always will – incorporate thermal storage to allow after-dark operation.

Parabolic trough CSP

- The sun's energy is concentrated by parabolic, trough-shaped reflectors onto a receiver pipe running along the inside of the curved surface.
- This energy heats a heat transfer fluid (HTF) – usually oil – flowing through the pipe.



Parabolic trough CSP

- The HTF transfers its heat to water, producing steam.
- The steam is used to generate electricity in a conventional Rankine-cycle steam plant.
- The HTF returns to the collector field, to be heated again.

Parabolic trough CSP

- A collector field comprises many troughs in parallel rows aligned on a north-south axis. This configuration enables the single-axis troughs to track the sun from east to west during the day.
- Trough designs can incorporate thermal storage, allowing for electricity generation several hours into the evening.

Concentrating Solar Power (CSP)

Solar trough, 2018

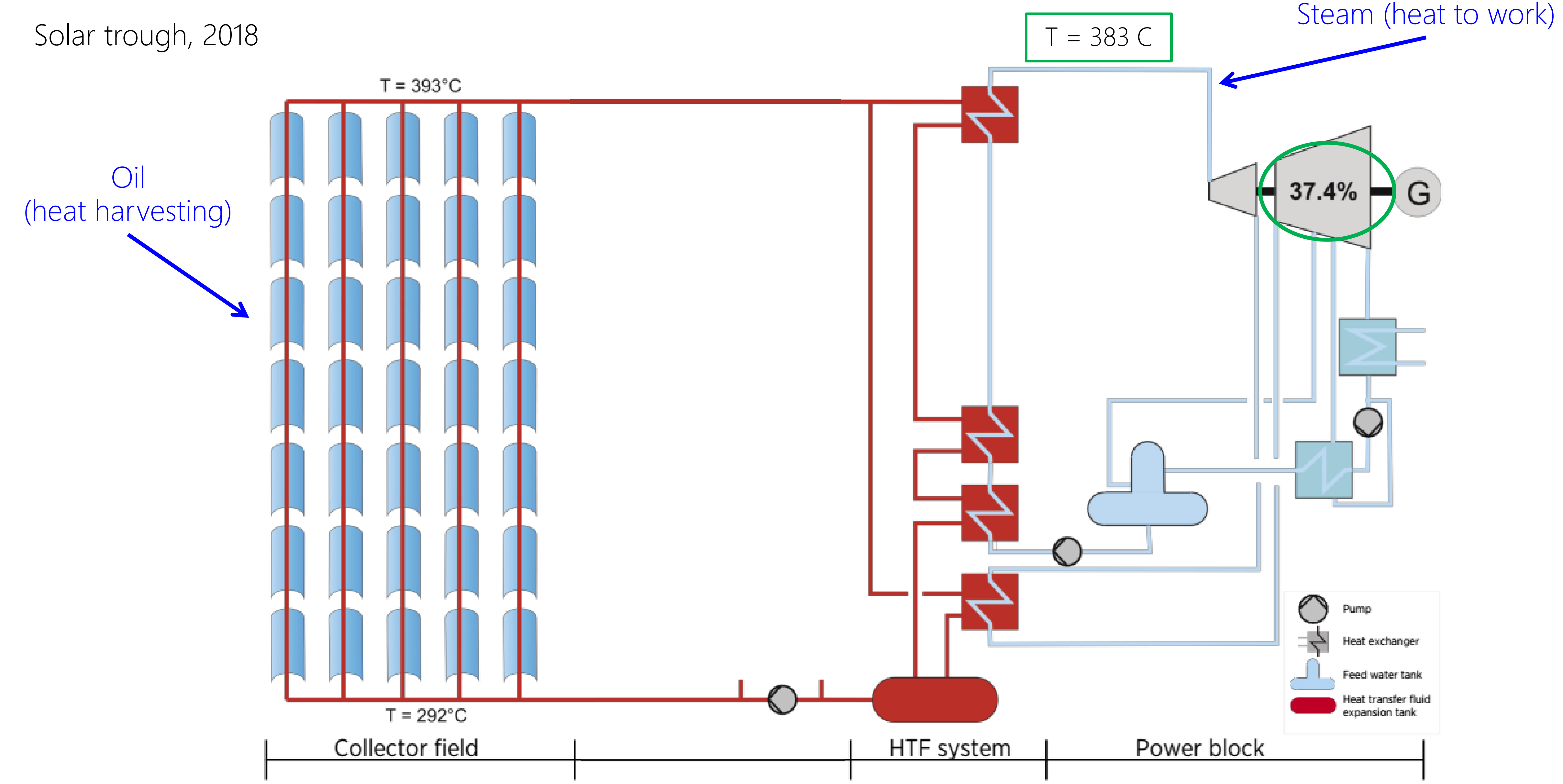


Image source: IRENA (2016), "The Power to Change: Solar and Wind cost reduction potential to 2025".

Concentrating Solar Power (CSP)

Solar trough, 2020

Molten salt
(heat harvesting
+
heat storage)

T = 510 C

Steam (heat to work)

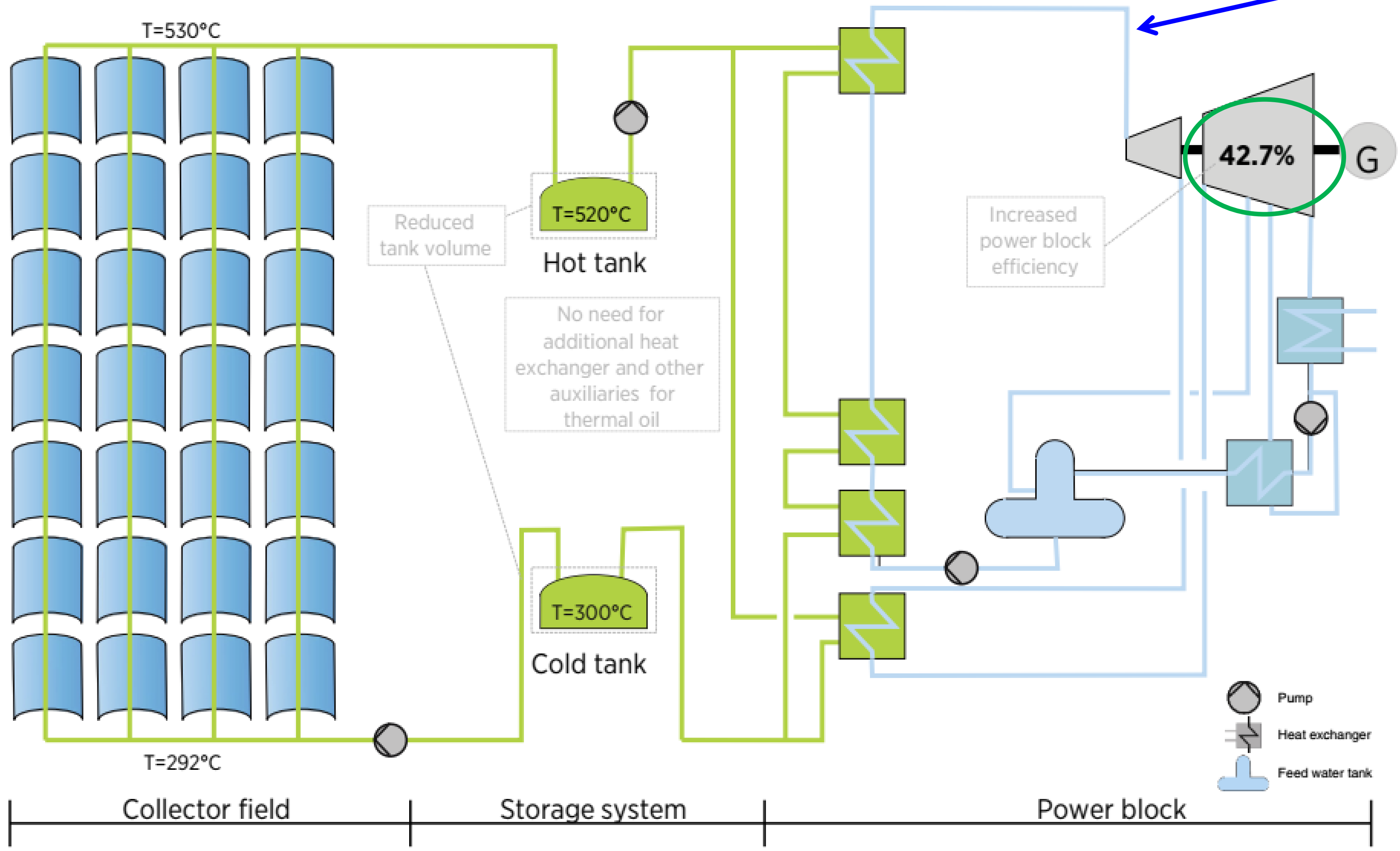


Image source: IRENA (2016), "The Power to Change: Solar and Wind cost reduction potential to 2025".

Concentrating Solar Power (CSP)

Power Tower CSP

- A power tower utilizes many large, sun-tracking mirrors (heliostats) to focus sunlight on a receiver at the top of a tower.

Power Tower CSP

- A heat transfer fluid (HTF) in the receiver – usually a molten nitrate salt – absorbs the solar energy.

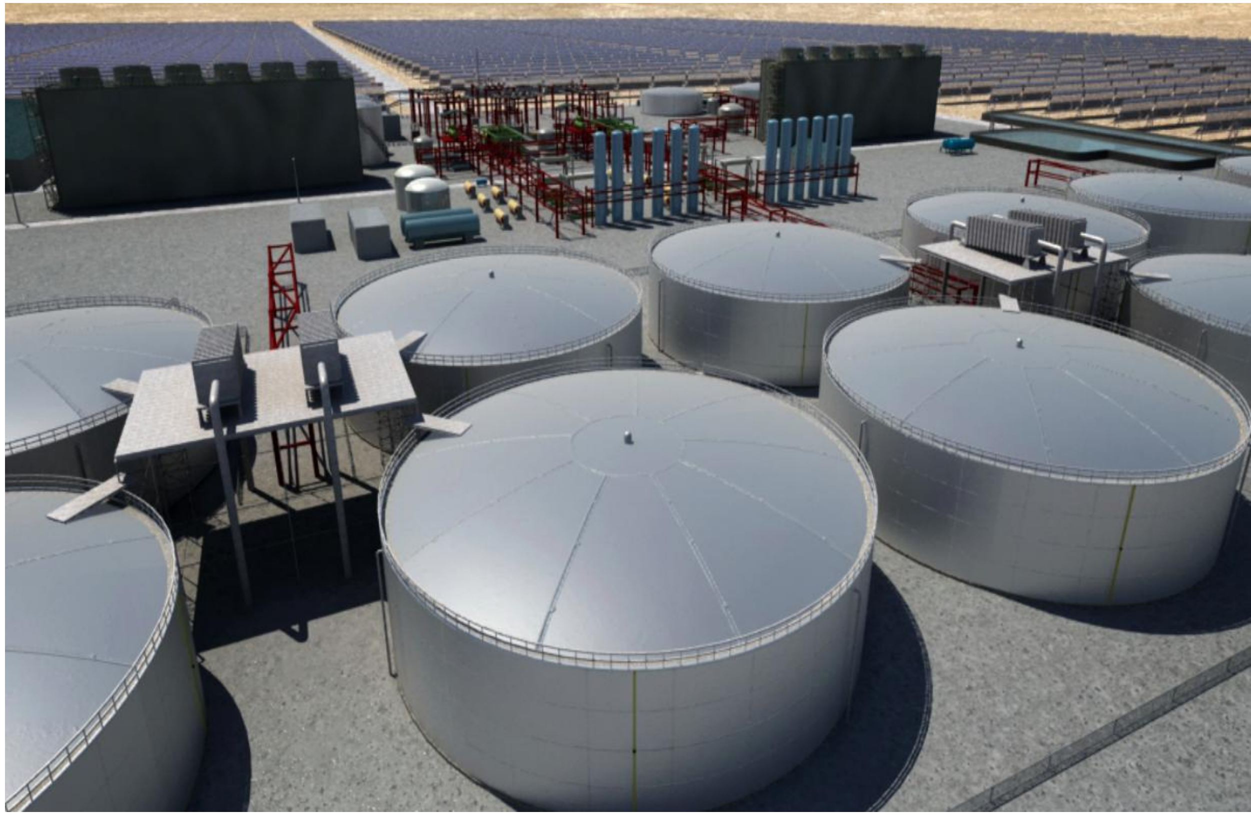
- The HTF transfers its heat to water, producing steam.

- The steam is used to generate electricity in a conventional Rankine-cycle steam plant.

- The HTF returns to the receiver, to be heated again.

Power Tower CSP

- Power tower designs always incorporate thermal storage.



NB: 1. Storing electrical energy costs ~100 times more than storing thermal energy.

2. Storing thermal energy at high temperature can be cheaper than at low temperature.

Concentrating Solar Power (CSP)

Power Tower CSP

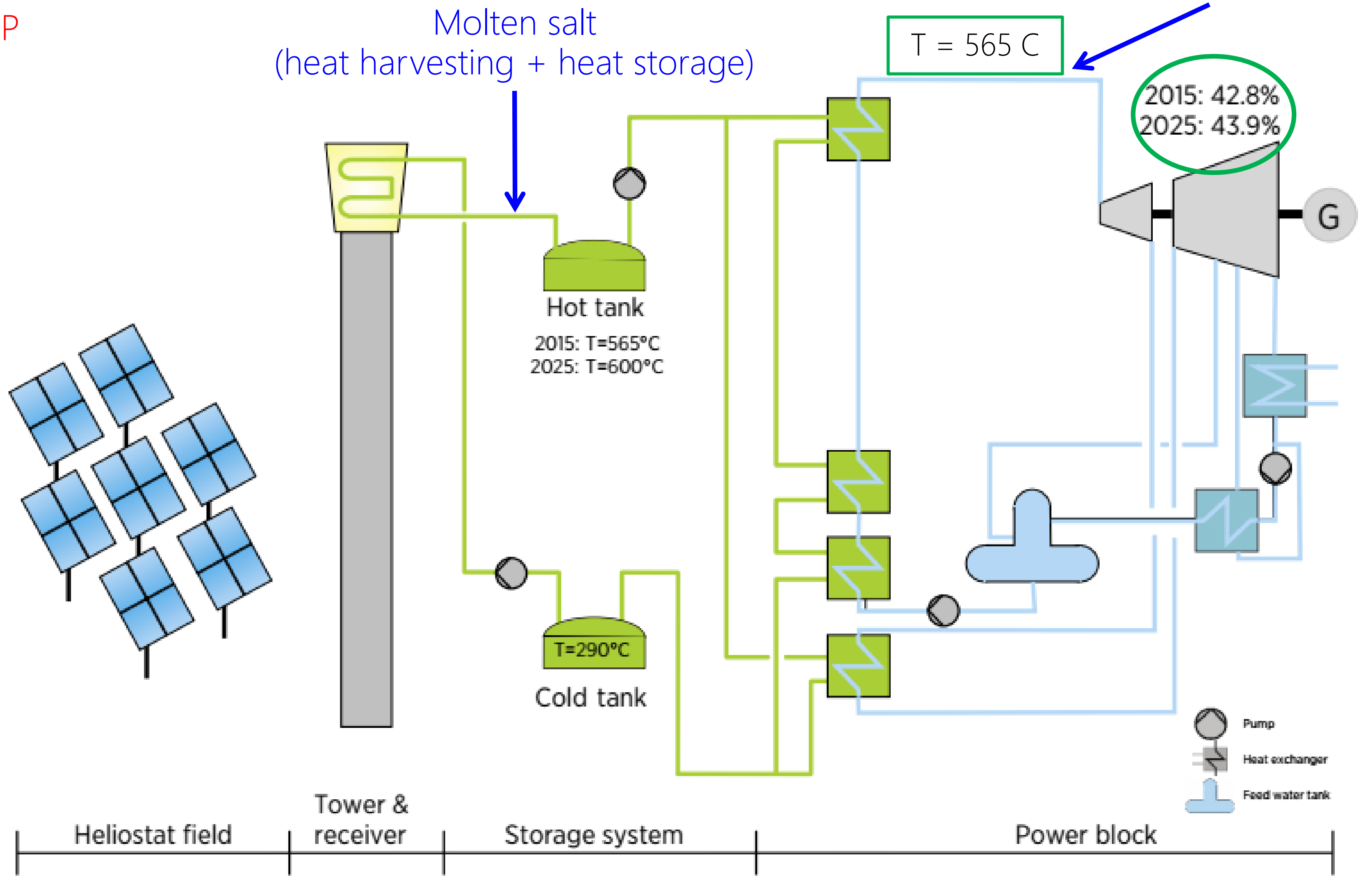
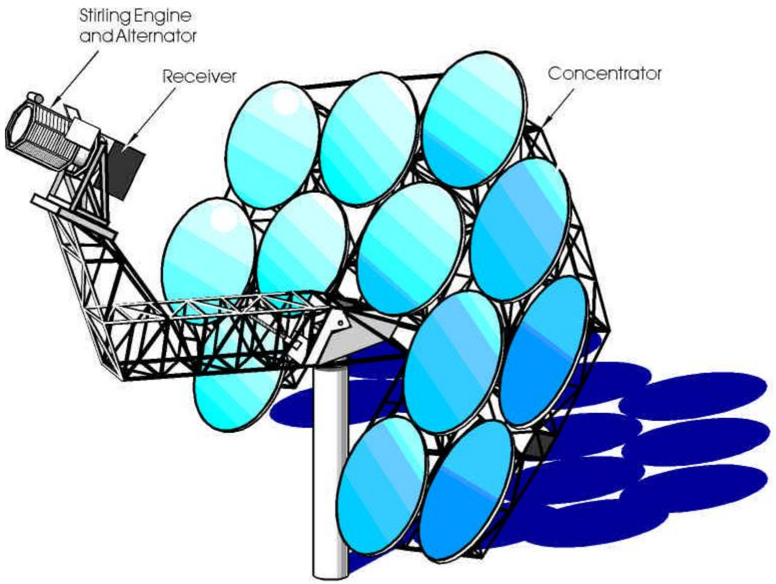


Image source: IRENA (2016), "The Power to Change: Solar and Wind cost reduction potential to 2025.

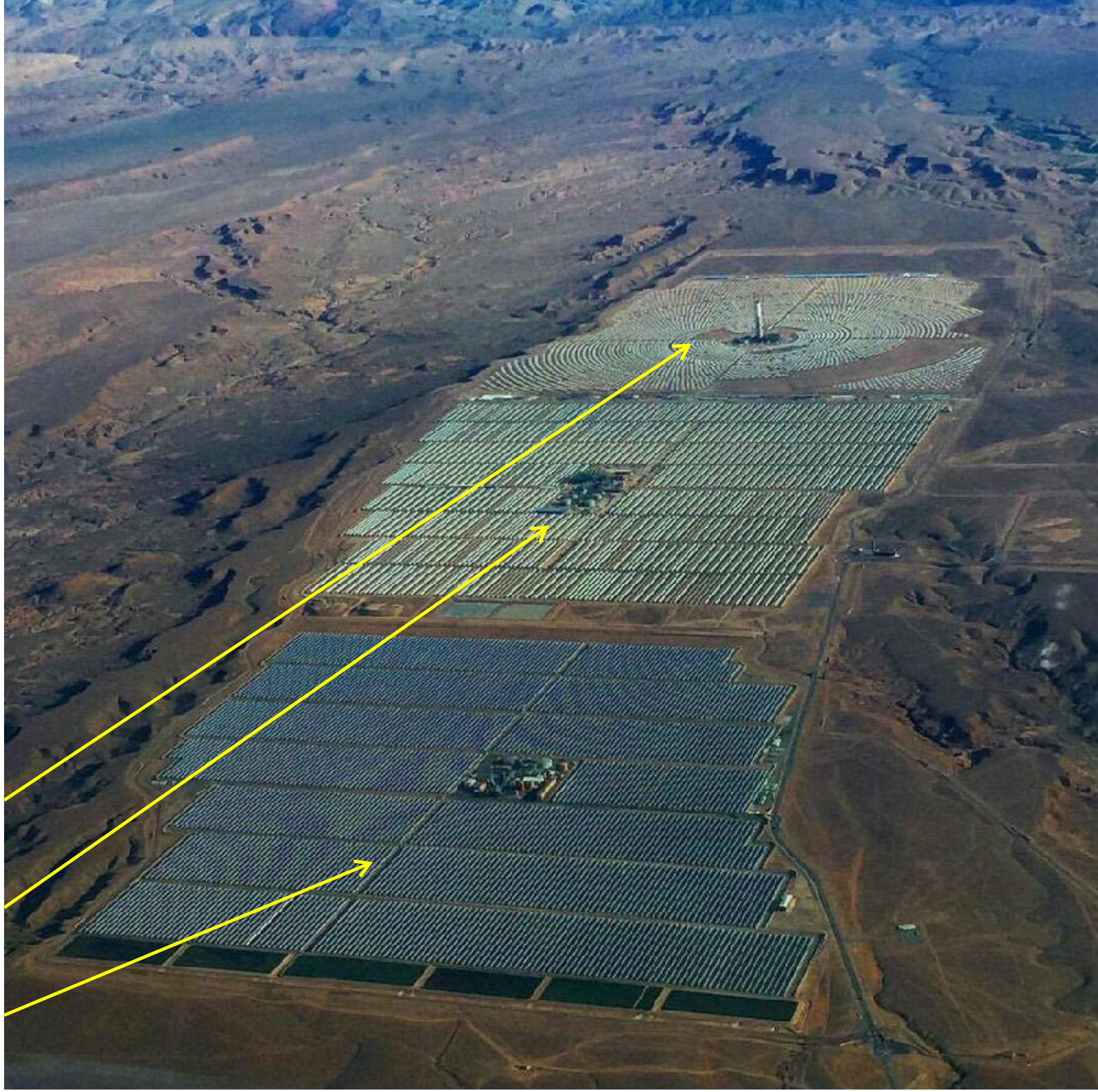
Solar Dish CSP



- Parabolic-shaped point focus concentrator in the form of a dish
- Reflects solar radiation onto a receiver mounted at the focal point.
- Mounted on a structure with a two-axis tracking system to follow the sun.
- The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure.
- Stirling and Brayton cycle engines are currently favoured for power conversion.
- Projects of modular systems have been realized with total capacities up to 5 MWe.
- The modules have maximum sizes of 50 kWe and have achieved peak efficiencies up to 30% net.

Concentrating Solar Power (CSP)

(2015)



Noor III: 135 MW Tower (2018): 15.0 c.kWh^{-1}

Noor II: 185 MW Trough (2018): 14.0 c.kWh^{-1}

Noor I: 145 MW Trough (2015): 18.9 c.kWh^{-1}

Sheikh Mohammed bin Rashid announces winning contract for world's largest CSP solar project

(2017)

The project will cost Dh14.2 billion and have a capacity of 700 megawatts

LeAnne Graves and John Everington
September 16, 2017
Updated: September 17, 2017 06:51 PM

1,511 shares

Dubai Electricity and Water Authority

September 2017

600 MW "Solar Trough" design, with storage

+

100 MW "Power Tower" design, with storage

PPA of 7.3 $c.kWh^{-1}$

PPA for adjacent PV farm of 2.99 $c.kWh^{-1}$

Concentrating Solar Power (CSP)

SolarReserve Bids CSP Under 5 Cents in Chilean Auction

October 29, 2017 By Susan Kraemer

Atacama desert in Chile

October 2017

"Power Tower" design, with storage

PPA of <5 $c.kWh^{-1}$

How Port Augusta Got the World's Cheapest Solar Thermal Power

August 30, 2017 By Susan Kraemer

South Australia

August 2017

"Power Tower" design, with storage

PPA of 6.1 $c.kWh^{-1}$

CSP capex costs fall by almost half as developers shift towards China and Middle East

Thermal Energy Storage

Apr 16, 2018

The cost of building new CSP plants has fallen significantly as developers have moved towards China and the Middle East and embraced tower technology with storage, New Energy Update has found.

Project	Country	$/kW	Capex (Y)	Capex ($M)	Size (MW)	TES (h)	Type
Qinghai Gonghe	China	3,910	1,222	196	50	6	Tower
Golden (Three Gorges)	China	4,000	2,500	400	100	8	Tower
Yumen Town East	China	4,304	1,345	215	50	9	PT
Aurora	Australia	4,333		650	150	8	Tower
Urat Middle Banner	China	4,480	2,800	448	100	10	PT
Zhongyang Zhanjiakou	China	4,500	1,800	288	64	16	PT
Shouhang Dunhuang	China	4,864	3,040	486	100	11	Tower
Hami	China	5,056	1,580	253	50	8	Tower
Dacheng Dunhuang	China	5,376	1,680	269	50	13	LF
DEWA Phase IV	UAE	5,529		3,870	700	11 (PT) & 15 (Tower)	PT (600 MW), Tower (100 MW)
Yumen	China	5,728	1,790	286	50	9	Tower
Huaqiang Zhaoyang Zhanjiakou	China	5,760	1,800	288	50	14	LF
Tamarugal	Chile	6,000		2,700	450	13	Tower
Likana	Chile	6,154		2,400	390	13	Tower
CGN Delingha	China	6,202	1,938	310	50	9	PT
Gansu Akesai	China	6,355	1,986	318	50	15	PT
Source: New Energy Update							

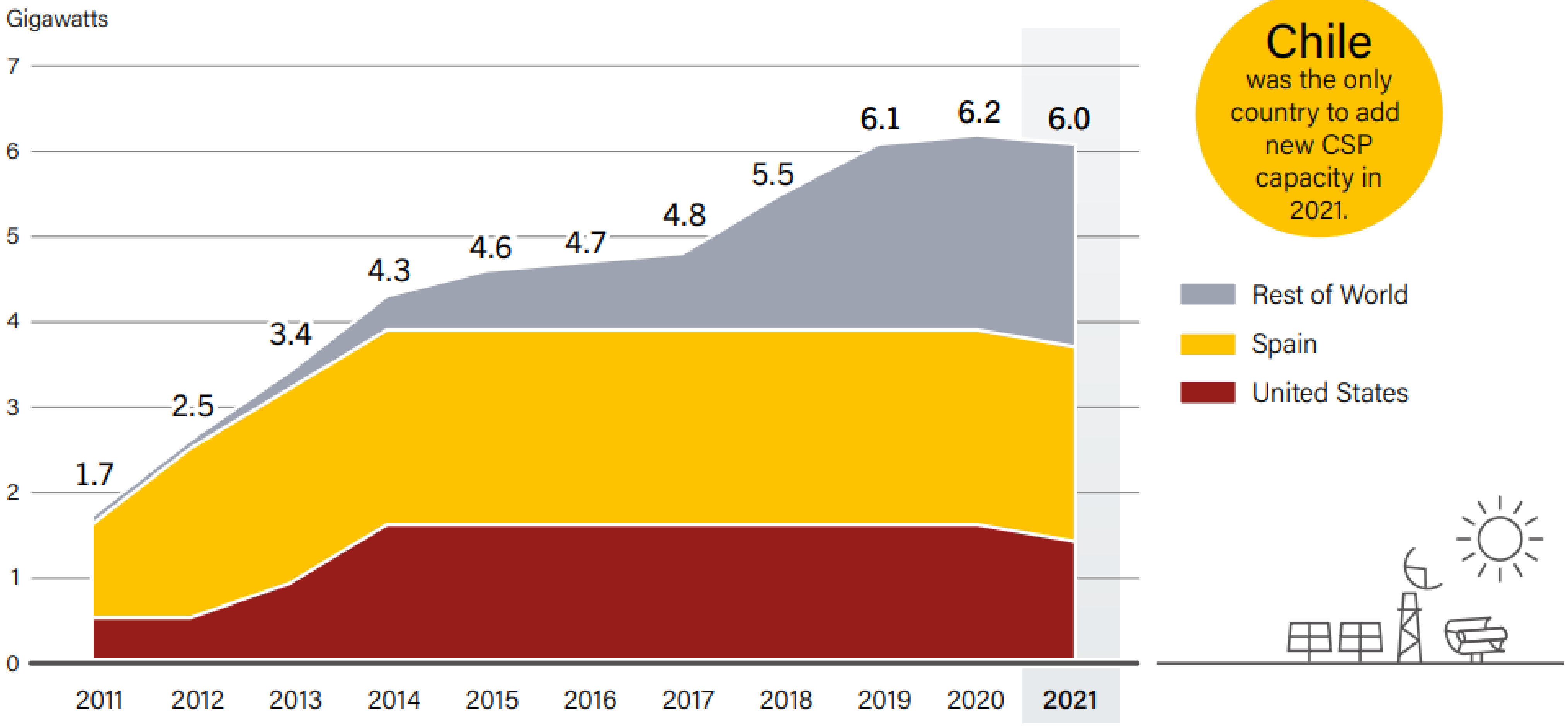
http://newenergyupdate.com/csp-today/csp-capex-costs-fall-almost-half-developers-shift-towards-china-and-middle-east

Concentrating Solar Power (CSP)

China Announces Another 1.3 GW of CSP with 12,000 MWh of Thermal Storage

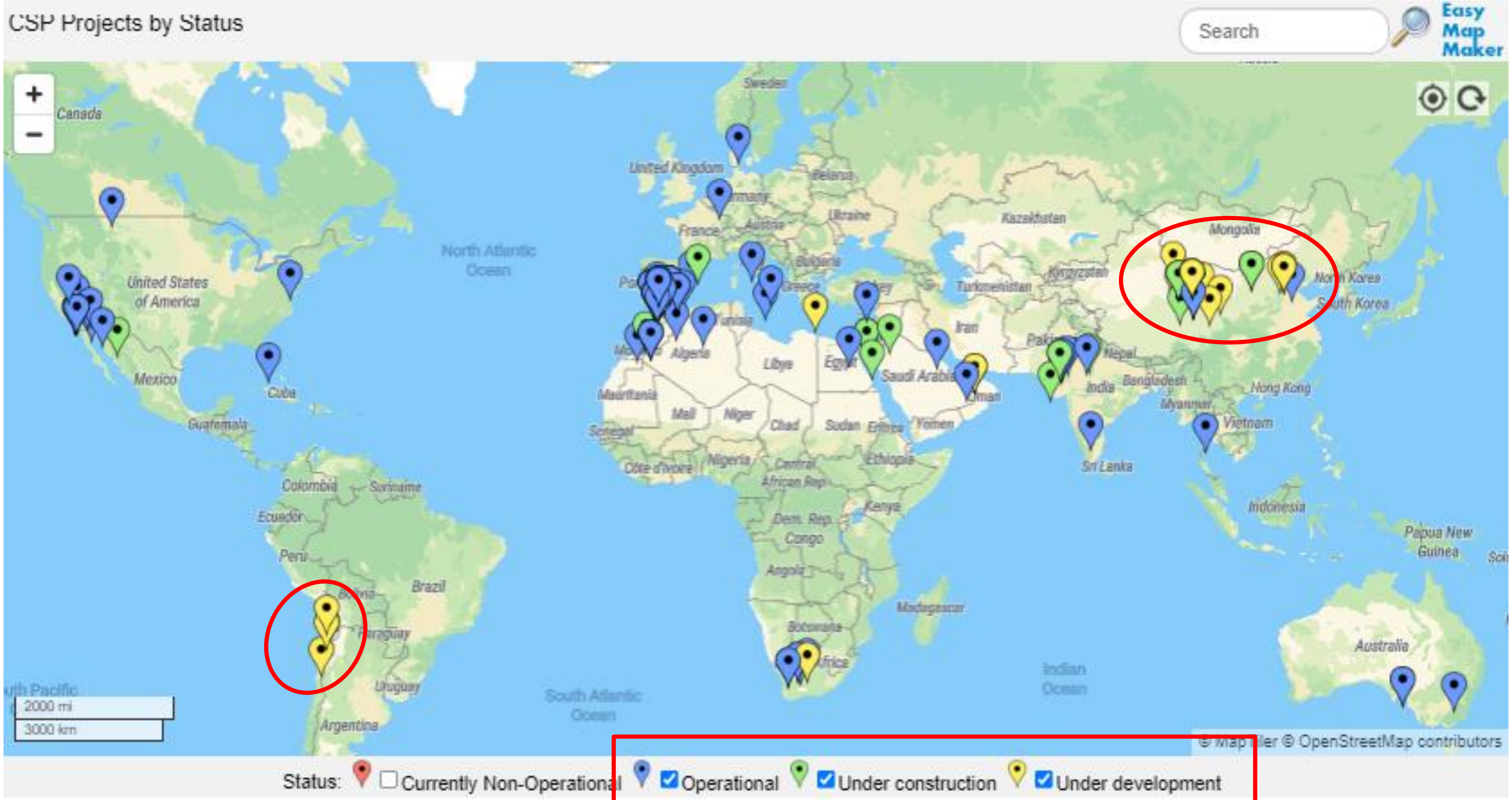
July 7, 2022 By Susan Kraemer

FIGURE 38.
Concentrating Solar Thermal Power Global Capacity, by Country and Region, 2006-2021



Source: REN21 (2022), "Renewables 2022: Global Status Report", Paris: REN21 Secretariat

Concentrating Solar Power (CSP)



Source: IEA TCP Solar Power and Chemical Energy Systems, https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/

Concentrating Solar Power (CSP)

Source: IEA TCP Solar Power and Chemical Energy Systems, https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/

Concentrating Solar Power (CSP)

Source: IEA TCP Solar Power and Chemical Energy Systems, https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/

Future developments in CSP

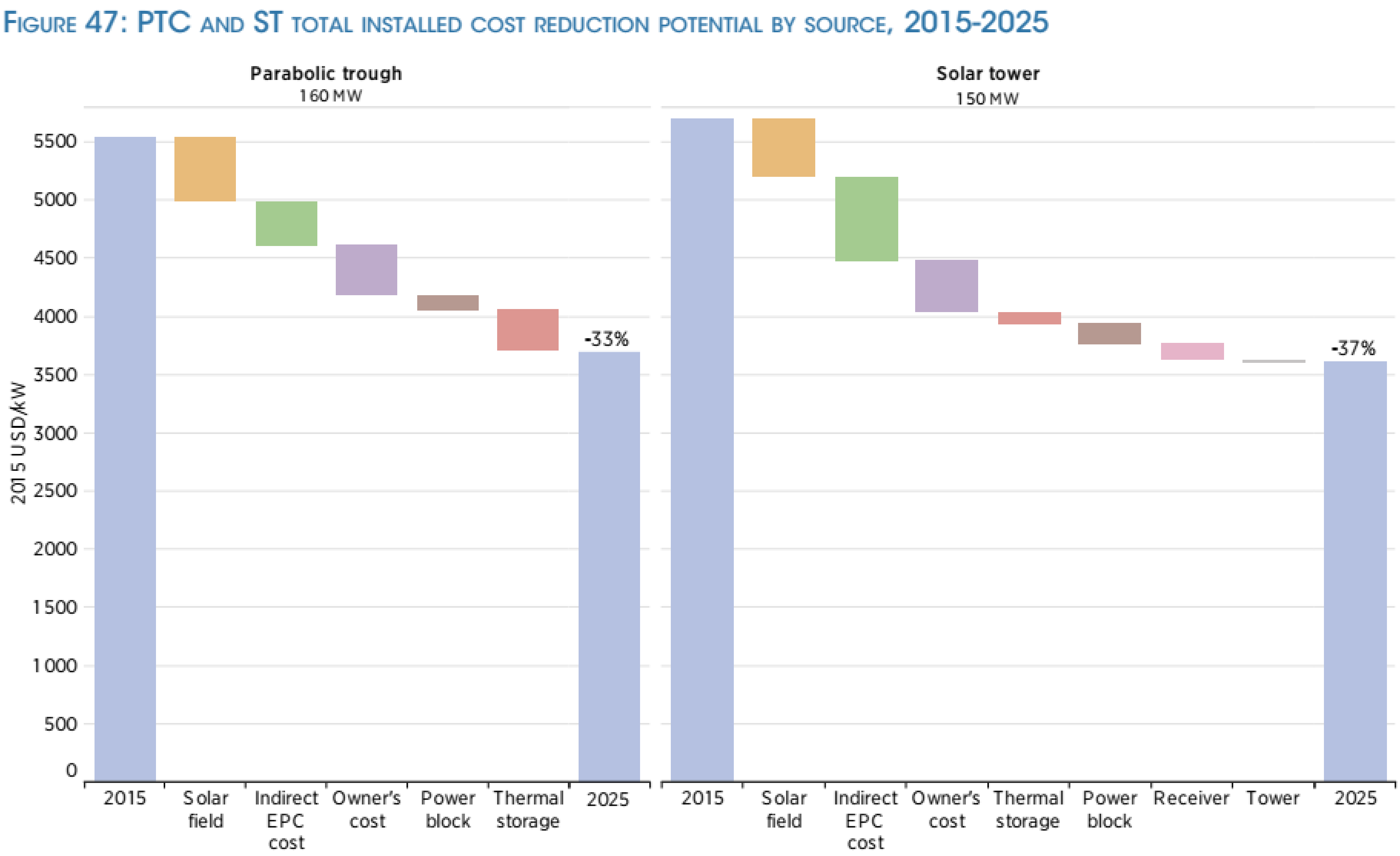
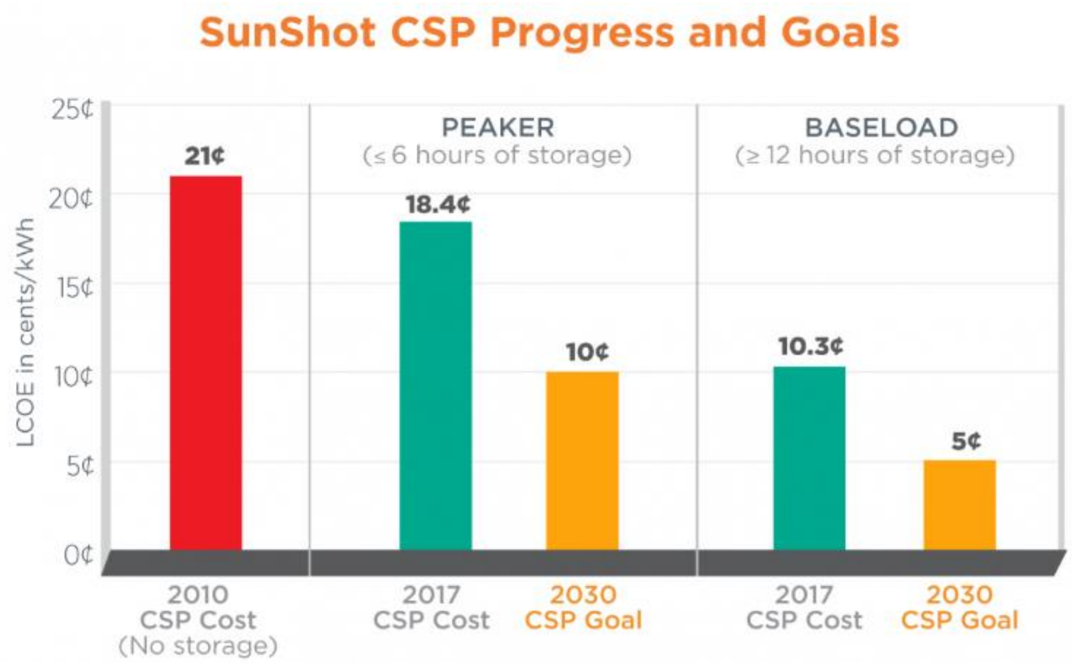


Image source: IRENA (2016), "The Power to Change: Solar and Wind cost reduction potential to 2025"

Future developments in CSP

U.S.:

- Switch from steam to supercritical CO_2 for Rankine cycle
  - Enables T_{max} to increase to 700 C → power cycle efficiency of ~50%
- Requires higher-temperature heat collection. 3 HTF being evaluated:
  - Solid (sand) – good for high temperatures, difficult to circulate
  - Liquid (molten Chloride salts) – familiar, but corrosive
  - Gas (supercritical CO_2) – easy to circulate, hard to capture and store heat



Source: *https://www.solarpaces.org/us-trial-novel-tech-reduce-solar-csp-cost/*

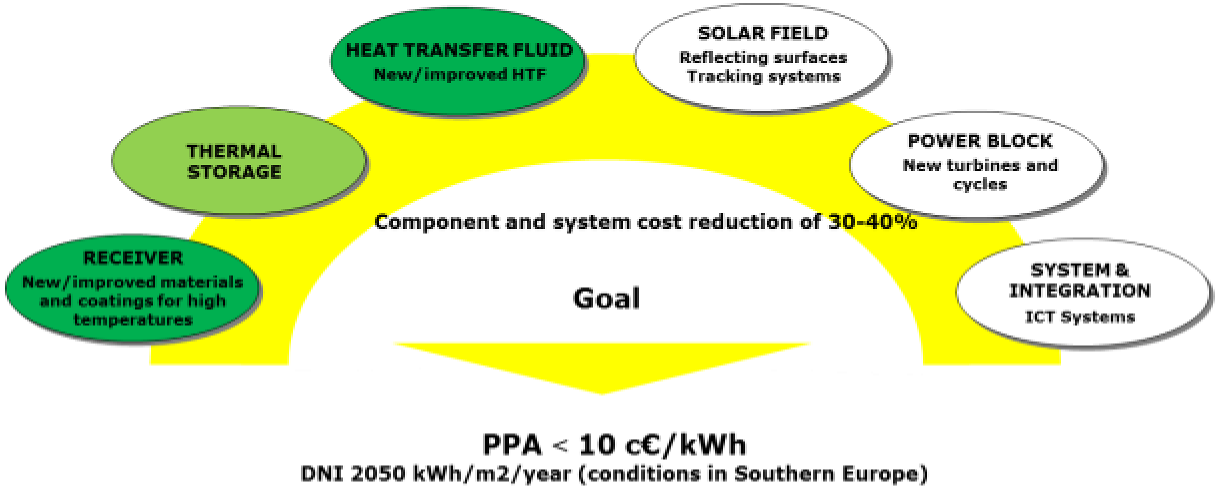
Future developments in CSP

E.U.:

- Short-term: > 40% cost reduction by 2020 (from 2013) translating into
  - supply price* < 10 c€/kWh for a radiation of 2,050 kWh.m^{-2}.yr^{-1} (conditions in Southern Europe)

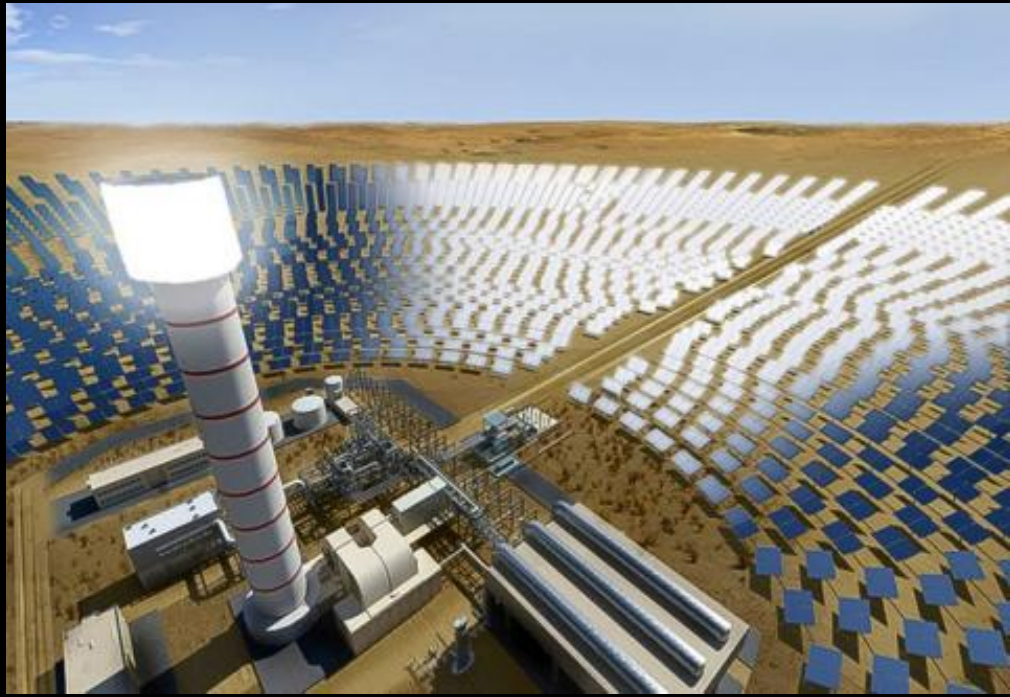
- Longer-term: develop the next generation of CSP/STE technology
  - new cycles (including supercritical ones)
  - first demonstrator by 2020,
  - achieve additional cost reductions and open new business opportunities.

* For a PPA with a duration of 25 years



Source: *http://www.solar-era.net/files/9315/2706/3908/SET_Plan_CSP_Implmentation_Plan_2017.pdf/*

versus



Summary of PV and CSP

Solar Power Plant Characteristics	
PV	**CSP**
No moving parts, low O&M costs	Complex cycle
Modular, down to very small powers	Needs to be 10s of MW
Rapidly-fluctuating output	Stable, controllable output
No “after dark” capability	After dark capability (with storage) - dispatchable
Cost-competitive with fossil fuels, under certain conditions.	More expensive than PV, but prices falling more rapidly.
Suitable for distributed generation and local consumption	Centralised, grid-connected, only.
Can use diffuse and/or normal radiation	Needs direct solar (beam) radiation

The global and regional contexts

1. The present global annual demand for primary energy arrives as solar energy in the deserts within 5.7 hours of sun shine.

2. Energy equivalent to the total known fossil reserves on Earth arrives in 47 days, and that in the expected total resources in 227 days in the deserts.

3. The total known and expected resources for nuclear energy are delivered as solar energy to the world's deserts within 13 days.

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