

# Introduction to Photovoltaic Metrology

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# Outline

- Clean energy
- History of solar cells
- Global irradiation & photovoltaic power potential
- Solar cell efficiencies
- Photovoltaic metrology
- Experimental setup of MRI
- Uncertainty analysis
- References

# Clean energy

- Fossil fuels: 75% of global greenhouse gas emissions and ~90% of all carbon dioxide emissions
- Emissions need to be reduced by almost half by 2030 and reach net-zero by 2050
- Alternative sources of energy (clean, accessible, affordable, sustainable and reliable)
- Fossil fuels account for more than 80% of global energy production
- ~29% of electricity currently comes from renewable sources

1. Renewable energy sources are all around us

2. Renewable energy is cheaper

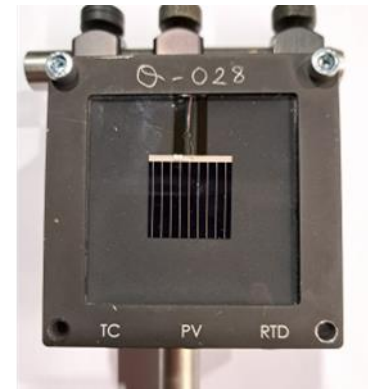
3. Renewable energy is healthier

4. Renewable energy creates jobs

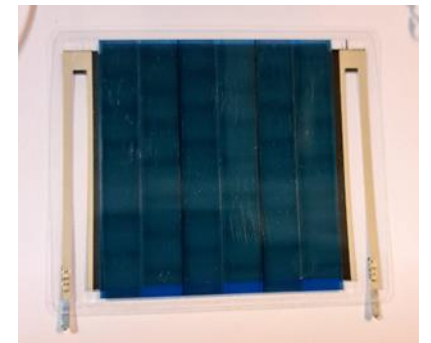


# History of solar cells

- Photovoltaic effect → reported in 1839 by *Becquerel*, who observed a light-dependent voltage between electrodes immersed in an electrolyte
- Observed in an all-solid-state system in 1876 for the case of selenium → development of photocells based on Se and cuprous oxide
- 1941: a silicon cell was reported
- 1954: the forerunner of present silicon cells was announced (the first photovoltaic structure with reasonable efficiency)
- 1958: power sources in spacecrafts
- Early 1960s: the design of cells for space use had stabilized (major application until next decade)
- 1970s: reawakening of interest in terrestrial use of these devices → terrestrial use outstripped the space use
- 1980s: significant reduction in solar cell costs, newer device technologies
- A continual expansion of the range of commercial applications



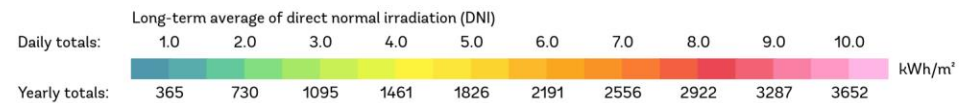
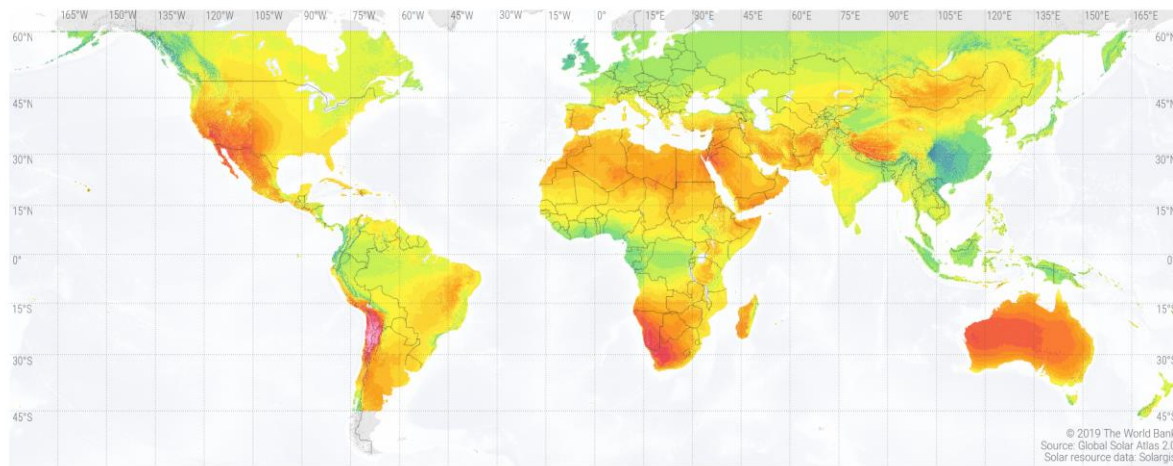
Crystalline silicon solar cell



Organic solar cell

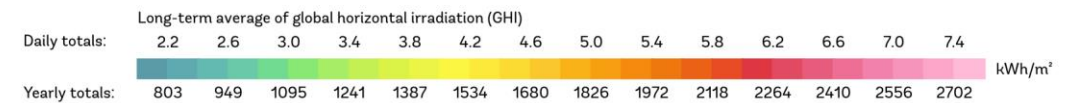
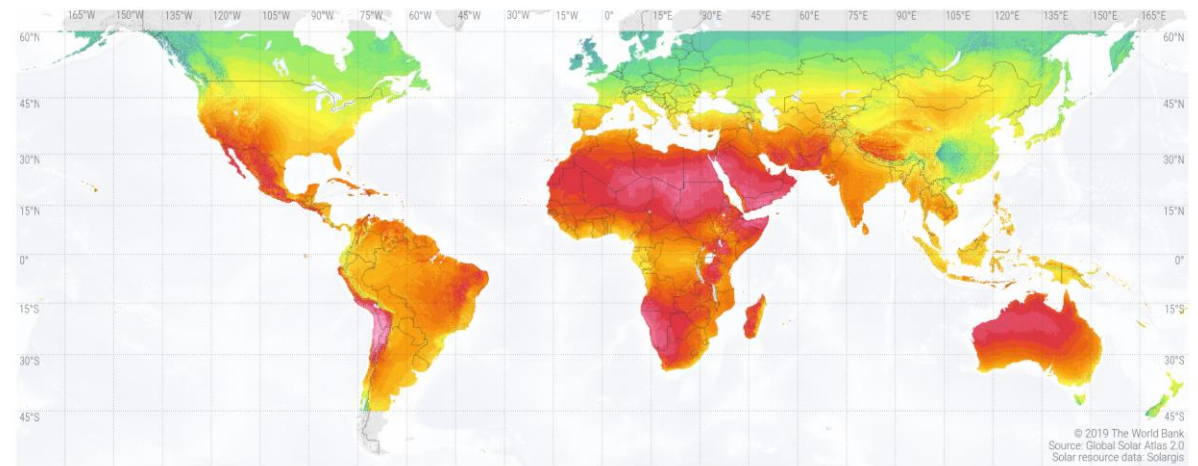
# Global irradiation

## SOLAR RESOURCE MAP DIRECT NORMAL IRRADIATION



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## SOLAR RESOURCE MAP GLOBAL HORIZONTAL IRRADIATION

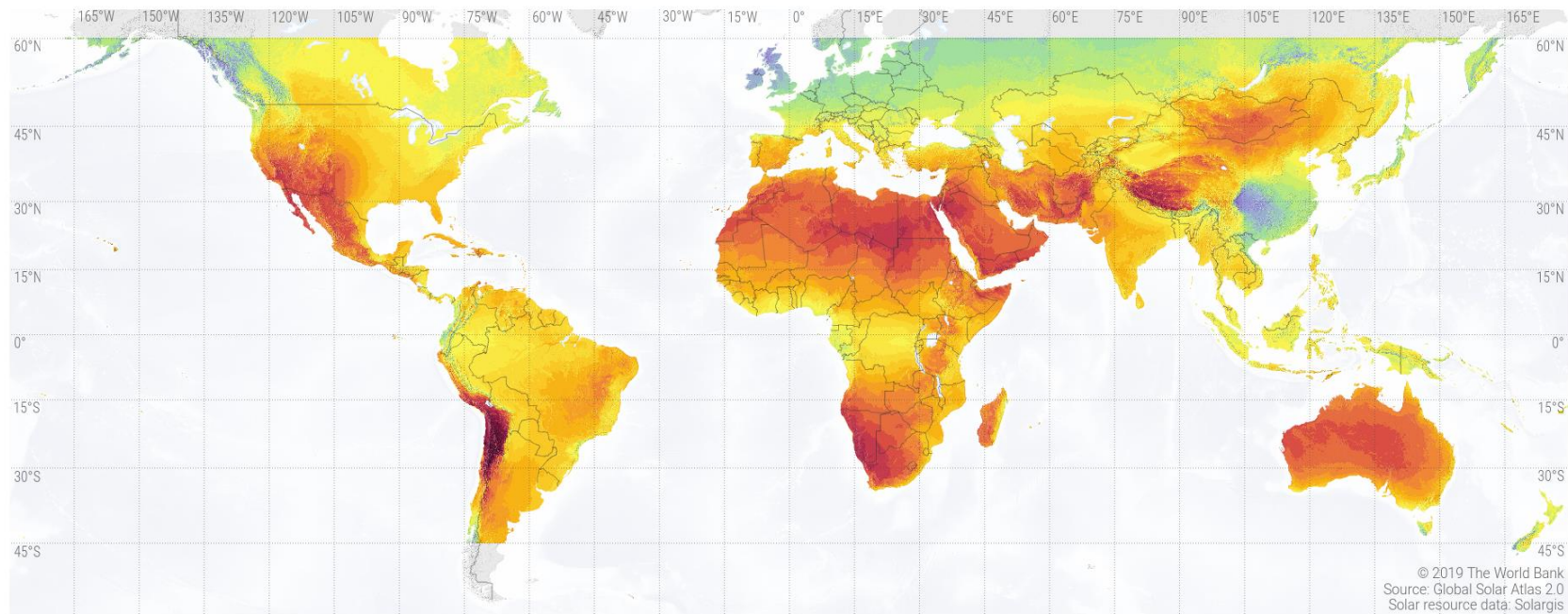


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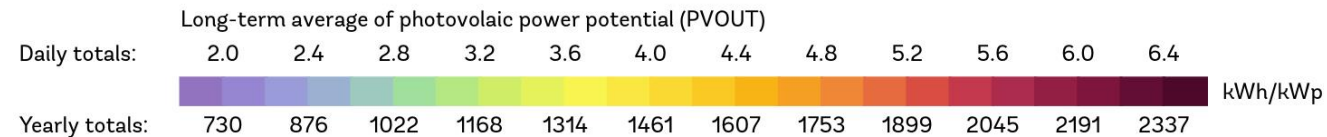
# World photovoltaic power potential

SOLAR RESOURCE MAP

## PHOTOVOLTAIC POWER POTENTIAL



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Source: Global Solar Atlas 2.0  
Solar resource data: Solargis



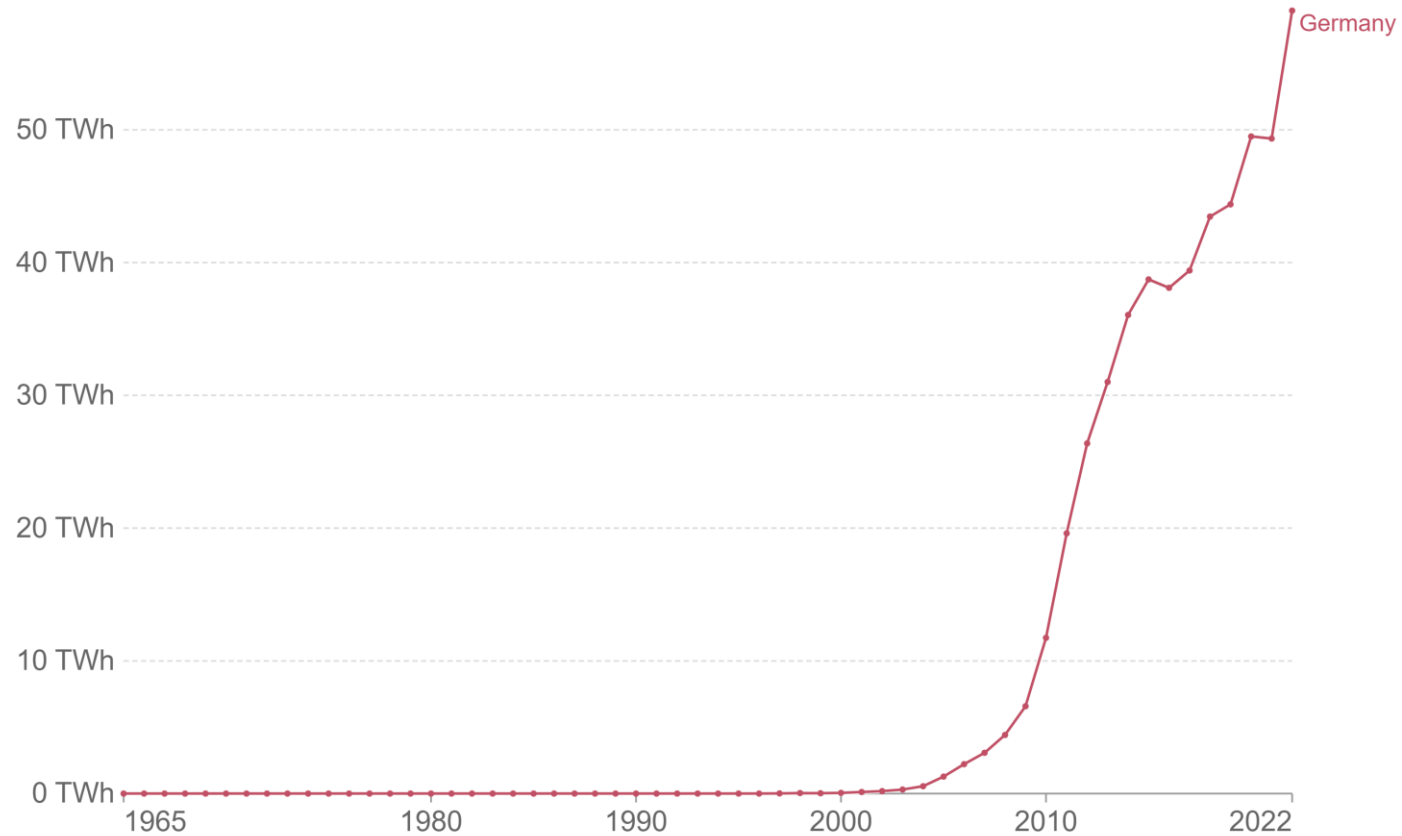
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# Solar power generation

## Solar power generation

Electricity generation from solar, measured in terawatt-hours (TWh) per year.

Our World  
in Data



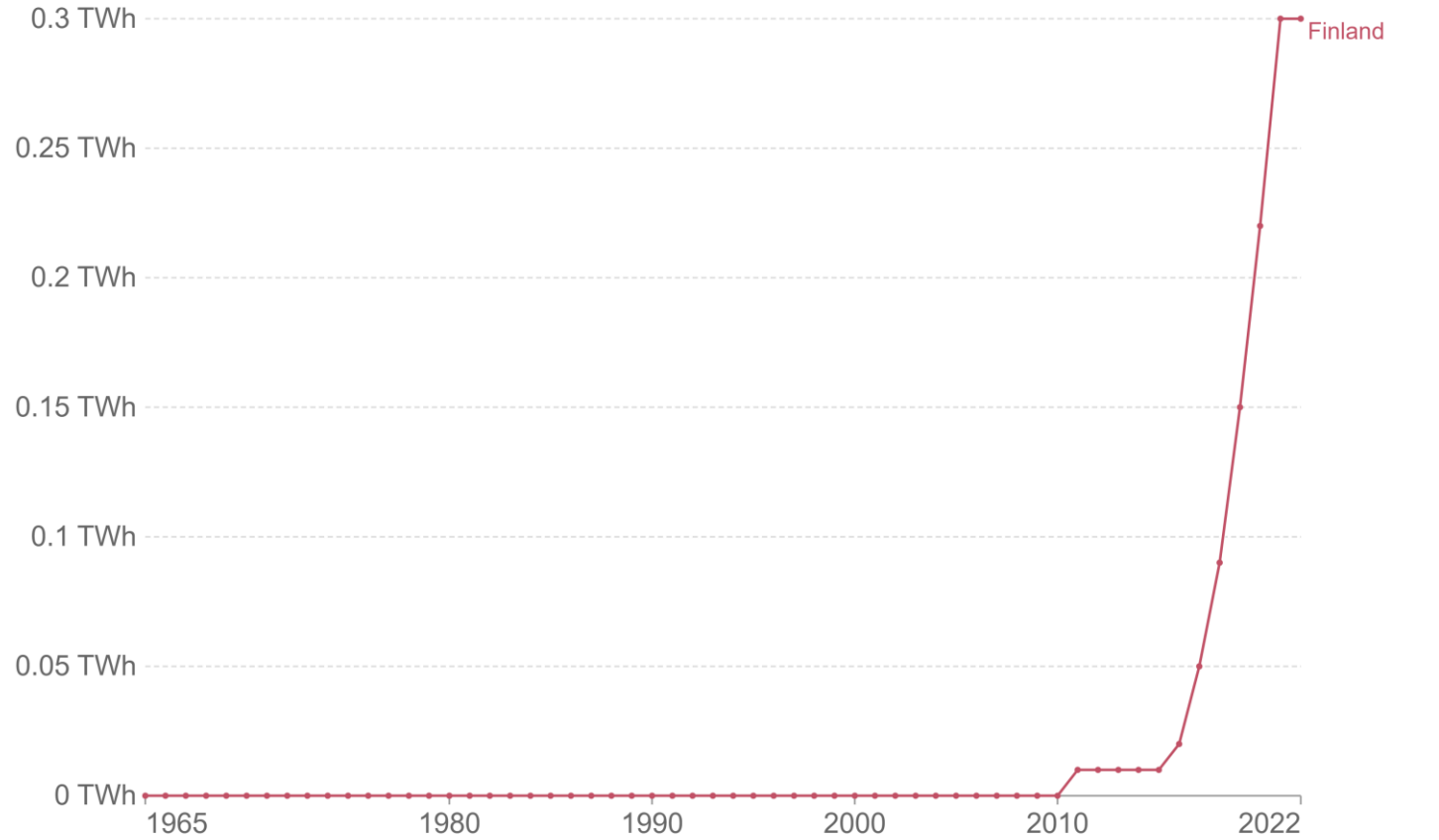
Source: Our World in Data based on BP Statistical Review of World Energy; Ember

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# Solar power generation

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Electricity generation from solar, measured in terawatt-hours (TWh) per year.

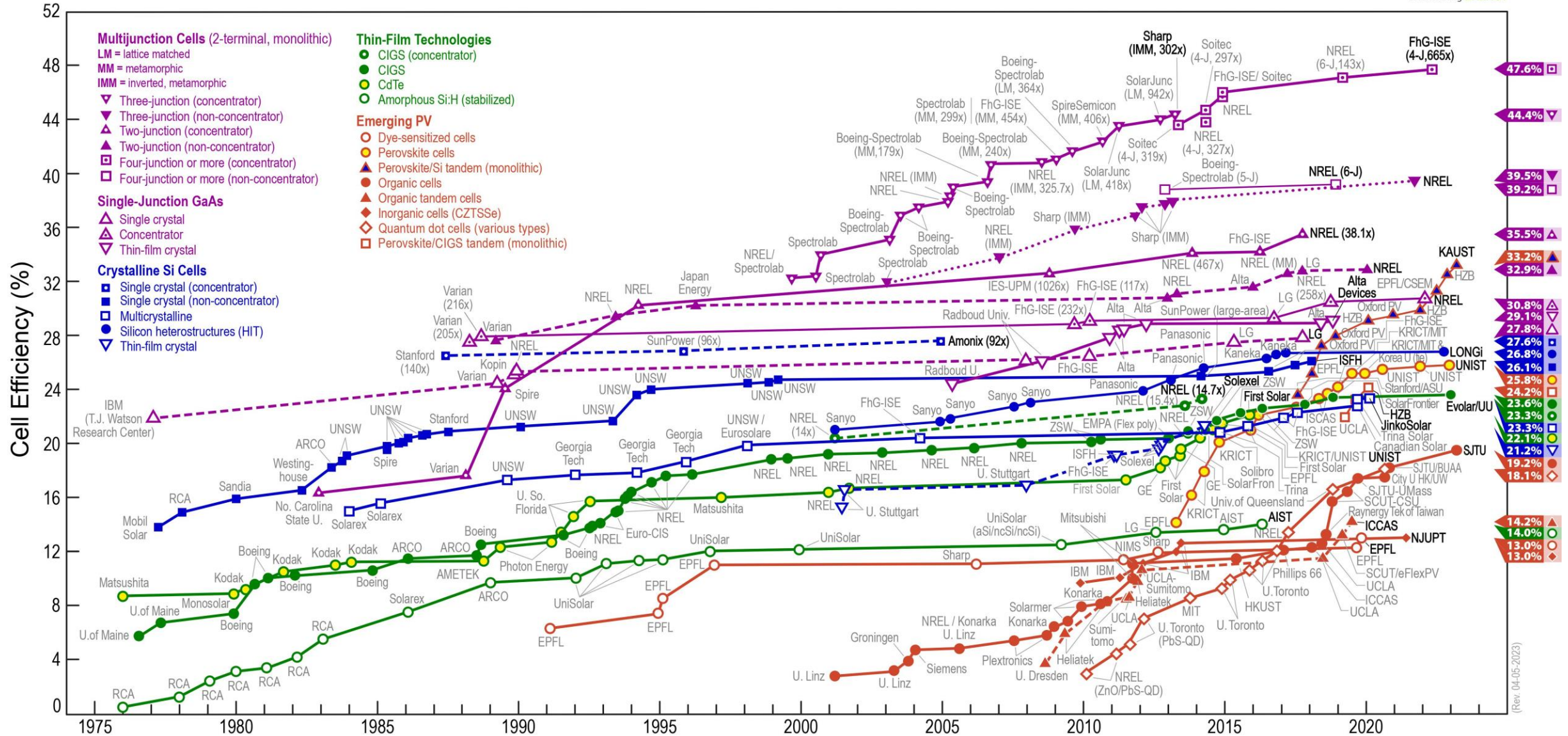


Source: Our World in Data based on BP Statistical Review of World Energy; Ember

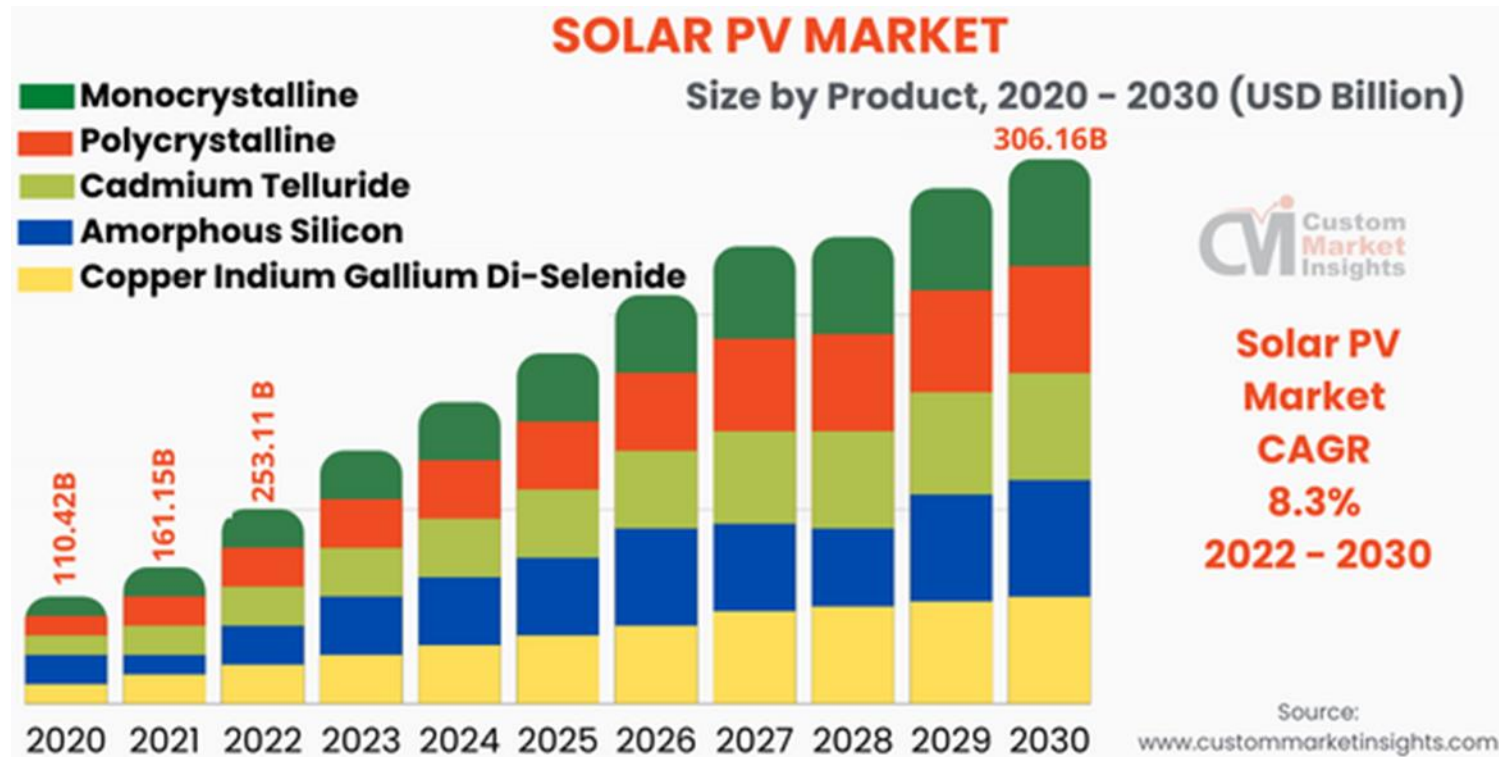
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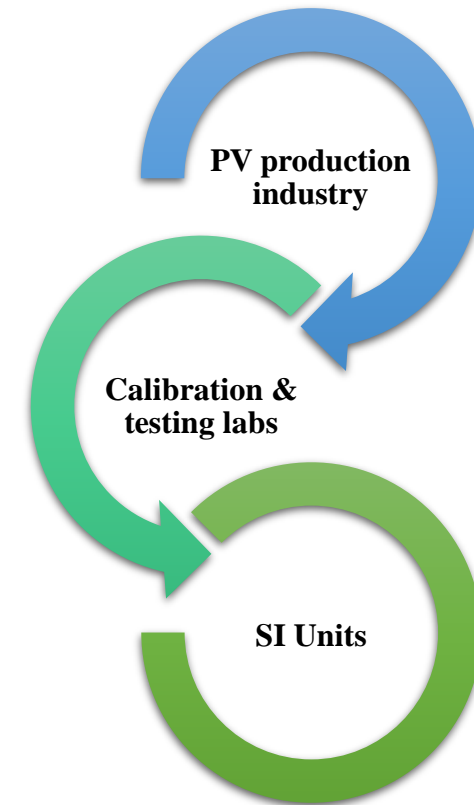
# Best Research-Cell Efficiencies



# Photovoltaic market



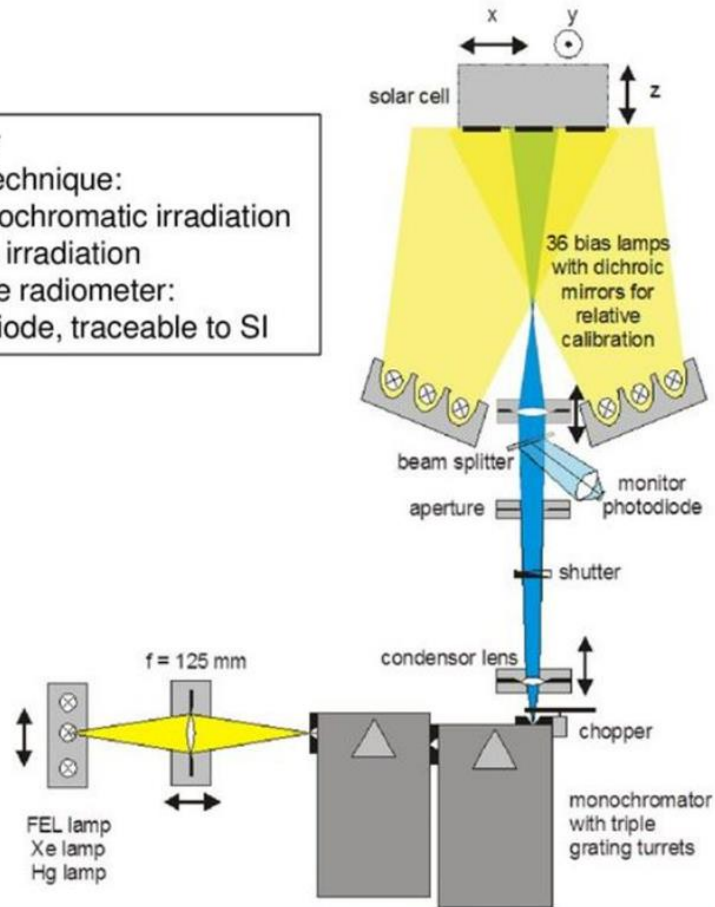
**Traceability**



# Photovoltaic metrology

## DSR- facility

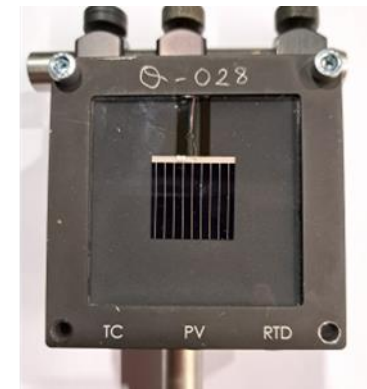
- 2 beam technique:
  - monochromatic irradiation
  - Bias irradiation
- Reference radiometer:
  - Photodiode, traceable to SI



Differential spectral responsivity (DSR) setup

$$\tilde{s}_{DUT}(\lambda, I_{bias}) = \frac{I_{DUT}(\lambda, I_{bias})/I_{MD,DUT}(\lambda)}{I_{Ref}(\lambda)/I_{MD,Ref}(\lambda)} \cdot \tilde{s}_{Ref}(\lambda)$$

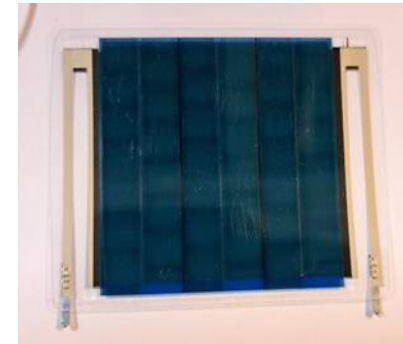
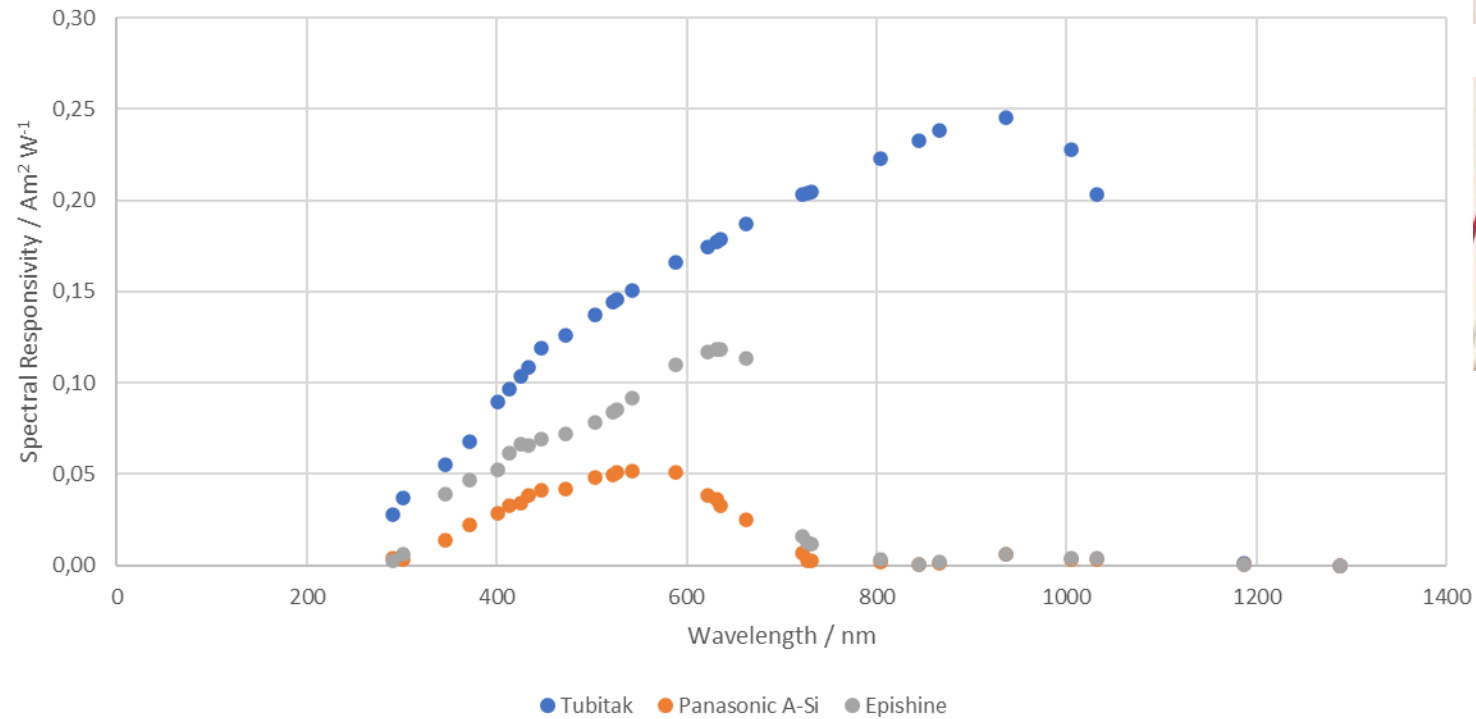
$$\tilde{s}_{AMx}(I_{bias}(E_b)) = \frac{\int_0^\infty \tilde{s}(\lambda, I_{bias}(E_b)) \cdot E_{\lambda,AMx}(\lambda) d\lambda}{\int_0^\infty E_{\lambda,AMx}(\lambda) d\lambda}$$



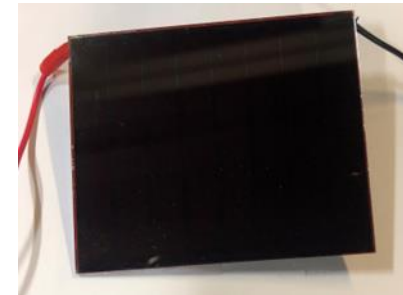
World photovoltaic scale (WPVS) solar cell

# Differential spectral responsivities

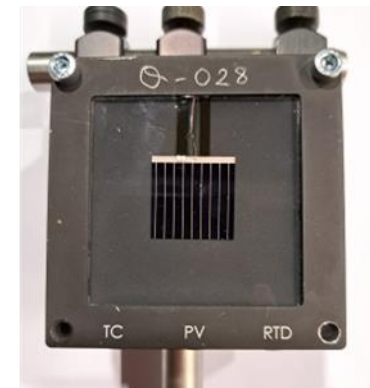
Spectral responsivity of solar cells at bias light 700 lx



Epishine organic indoor solar cell  
 Area: 50 x 50 mm<sup>2</sup>  
 Flexible, Thickness: 0,2 mm  
 6 cells,  $V_{oc} = 3,8$  V



Amorphous silicon solar cell  
 Panasonic AM-1815CA  
 Area: 48,5 x 58,3 mm<sup>2</sup>  
 Thickness: 1,3 mm  
 8 cells,  $V_{oc} = 4,9$  V



Tubitak reference cell  
 Area: 20 x 20 mm<sup>2</sup>

# Uncertainty analysis

Uncertainty contributors	Uncertainty range
The reference detector	$u(s_{\text{ref}}(600 \text{ nm}))=0,035\%$ up to $u(s_{\text{ref}}(1180 \text{ nm}))=3,6\%$
Aperture	$u=0,03\%$
Non-uniformity of spectral irradiance	$u<0,02\%$
Measurement electronics	$u(\text{lock-in})<0,01\%$ , $u(\text{TIA})<0,07\%$
Reference plane	$u<0,07\%$
Bias spectrum	$u<0,1\%$
Bandwidth	$u<0,001\%$ to $0,2\%$
Wavelength	$u<0,03\%$
Reproducibility/Noise	$u<0,08\%$
Temperature	$u<0,01\%$

# References

- I. Kröger, D. Friedrich, and S. Winter, “Calibration of solar cells beyond STC using the DSR method,” in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)*.
- Martin A. Green, *Solar cells operating principles technology and system applications*. Prentice Hall, 1982.
- [www.nrel.gov](http://www.nrel.gov)
- [globalsolaratlas.info](http://globalsolaratlas.info)

*Thank you*