Renewable Energy & Hydroelectric Works

8th semester, School of Civil Engineering

2nd semester, Master's Programme "Water Resources Science & Technology"

Solar energy

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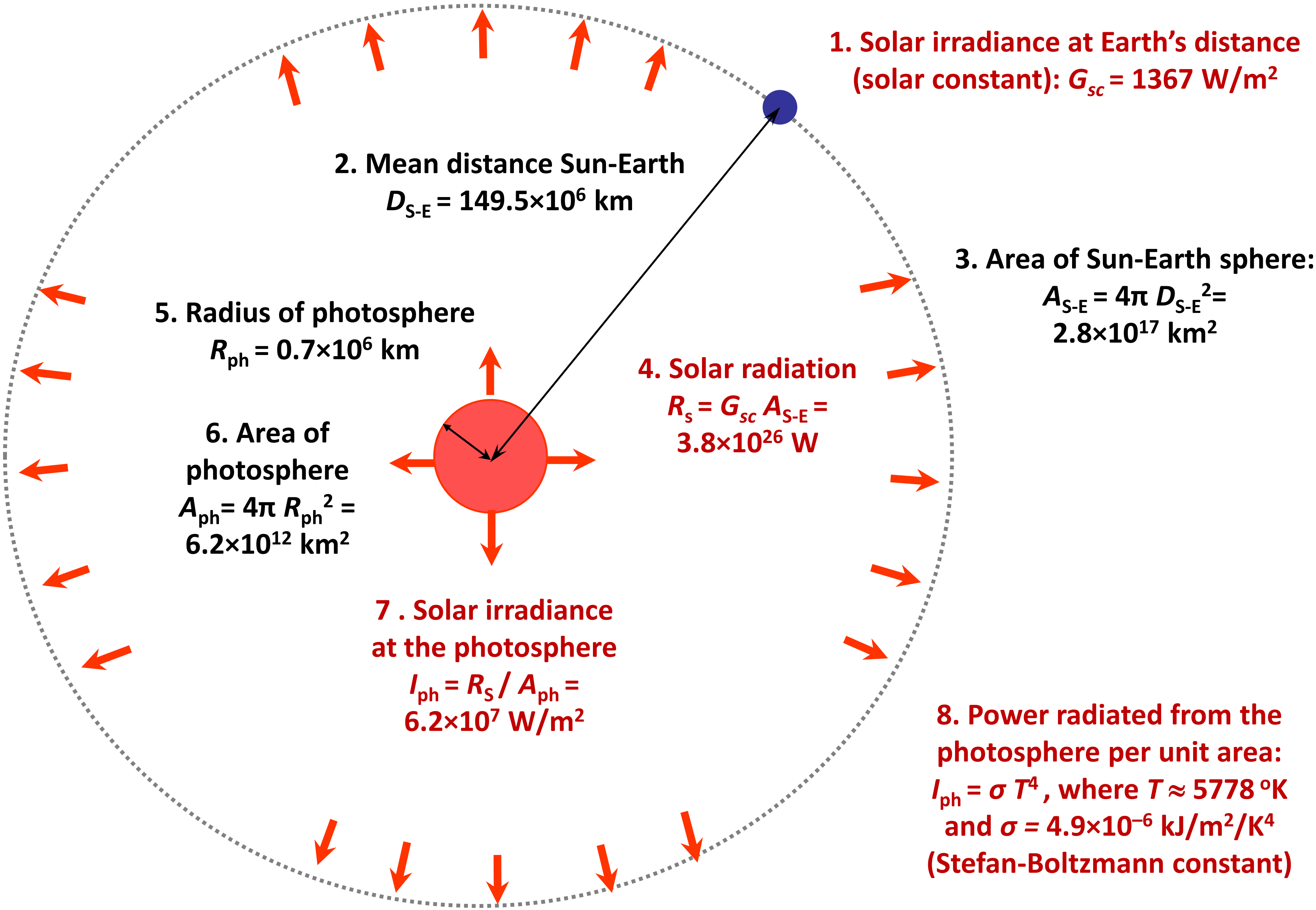
Solar physics: concepts and quantities

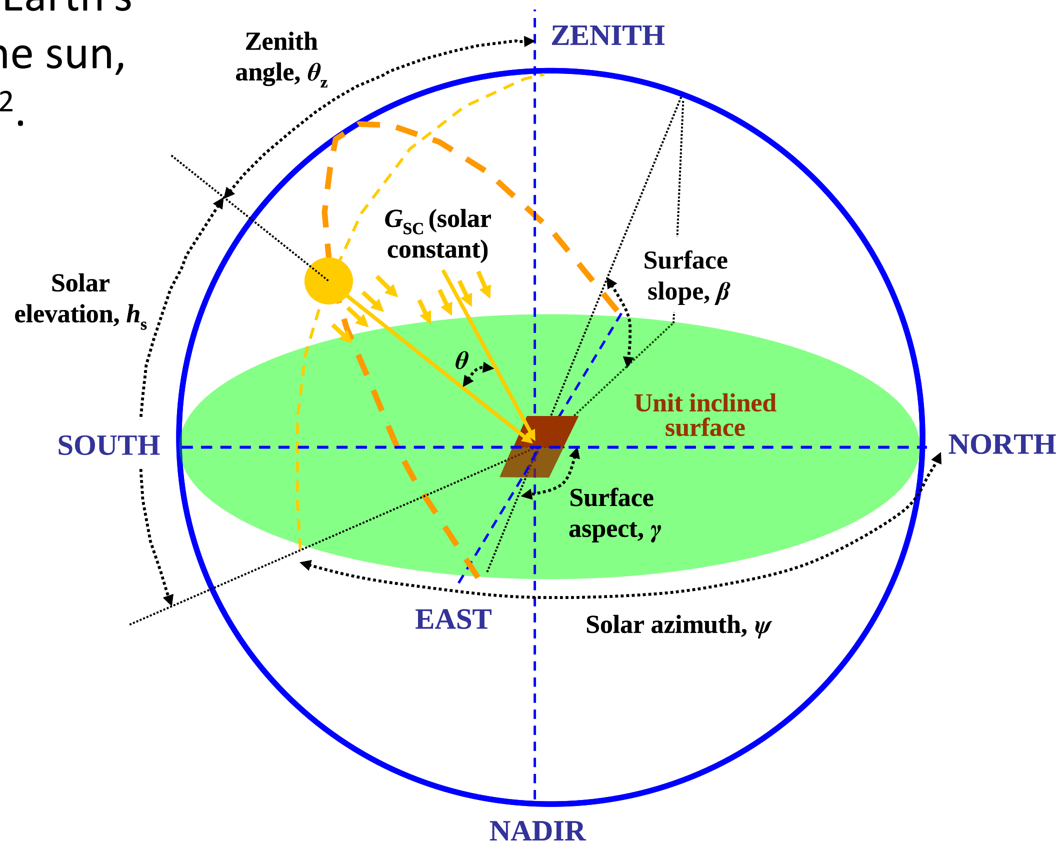


Extraterrestrial radiation: calculations

- The solar radiation received by **the top of the Earth's atmosphere above** a **horizontal surface** is called the **extraterrestrial** (solar) radiation, R_a, which is expressed in W/m^2.
- On **daily basis**, the extraterrestrial radiation is estimated by multiplying the solar constant G_{sc}, the eccentricity coefficient d_r, and the zenith angle ϑ_z, i.e.

$$R_a = G_{sc}\, d_r \cos(\vartheta_z)$$

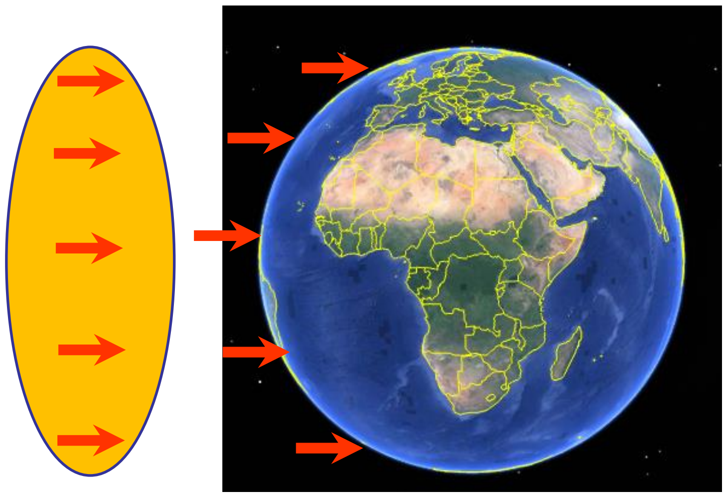
- The **solar constant** denotes the average density of solar radiation outside the Earth's atmosphere at mean distance from the sun, and is approximately $G_{sc} = 1367\ W/m^2$.
- The **eccentricity coefficient** d_r and the **zenith angle** ϑ_z depend on the **solar declination** and the **sunset hour angle**; the former is function of the day of the year, while the latter is also function of the latitude.
- For **hourly or shorter periods**, the solar time angle at the beginning and end of the specific period should be also considered in the calculations.



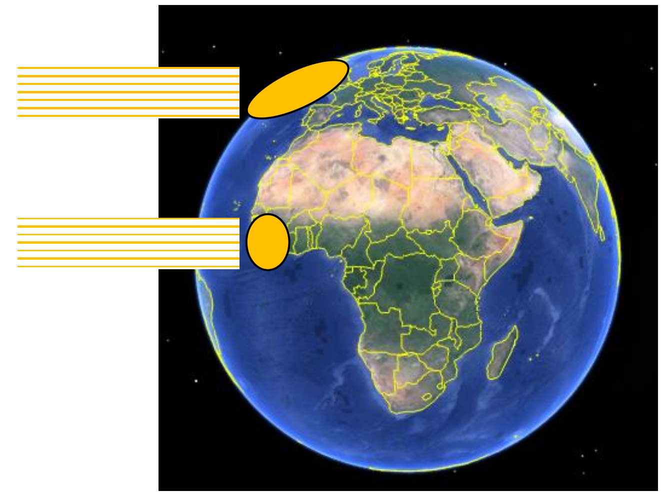
Extraterrestrial radiation: spatial variability

The solar constant (1367 W/m^2) only affects part of the Earth that corresponds to an area of πR^2

Since the total area of Earth is $4\pi R^2$, the average solar irradiance in Earth is equal to 25% of the solar constant

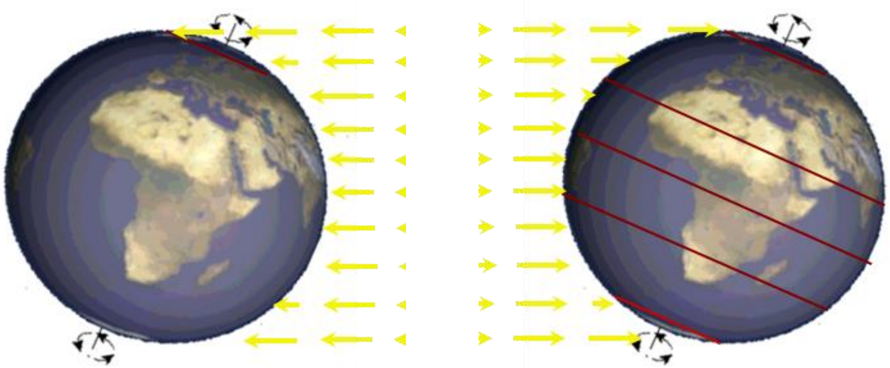


The spatial variation of solar radiation depends on the latitude, as the same irradiance affects areas with different sizes



With respect to the equator, the area at 45° latitude is 40% larger, it is double at 60° and it is six times larger at 80°

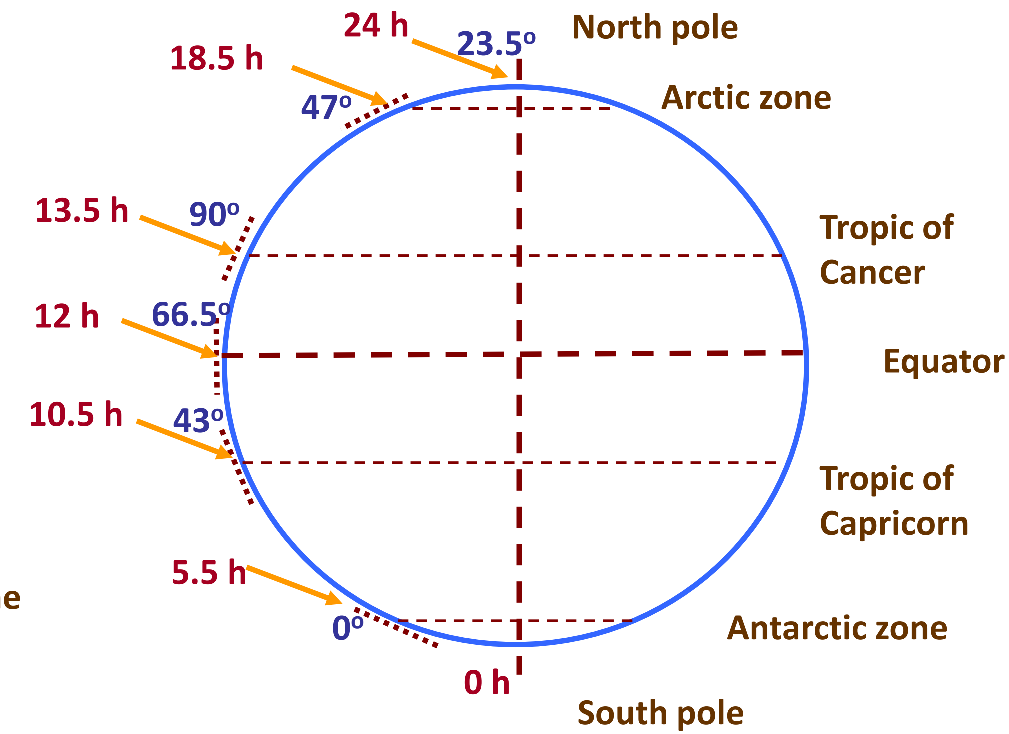
22/6 **Solstices** **22/12**



Equinoxes

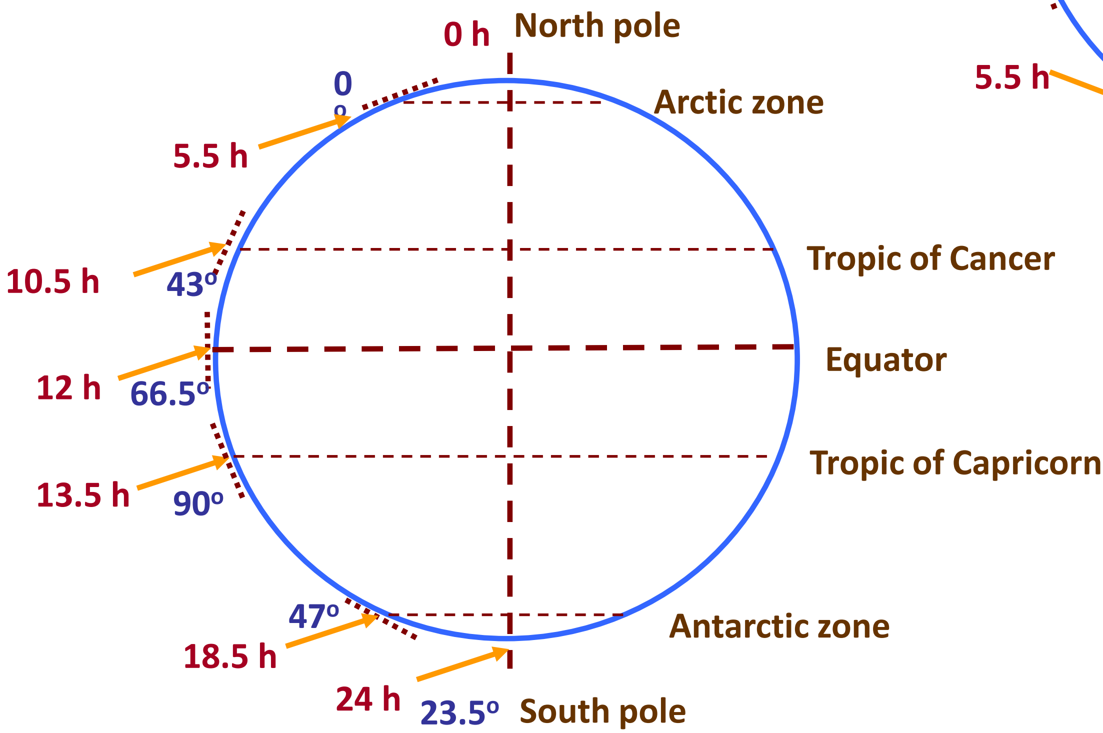
Extraterrestrial radiation: temporal variability

Angle of incidence of solar beam at noon and potential daily sunshine duration (h)

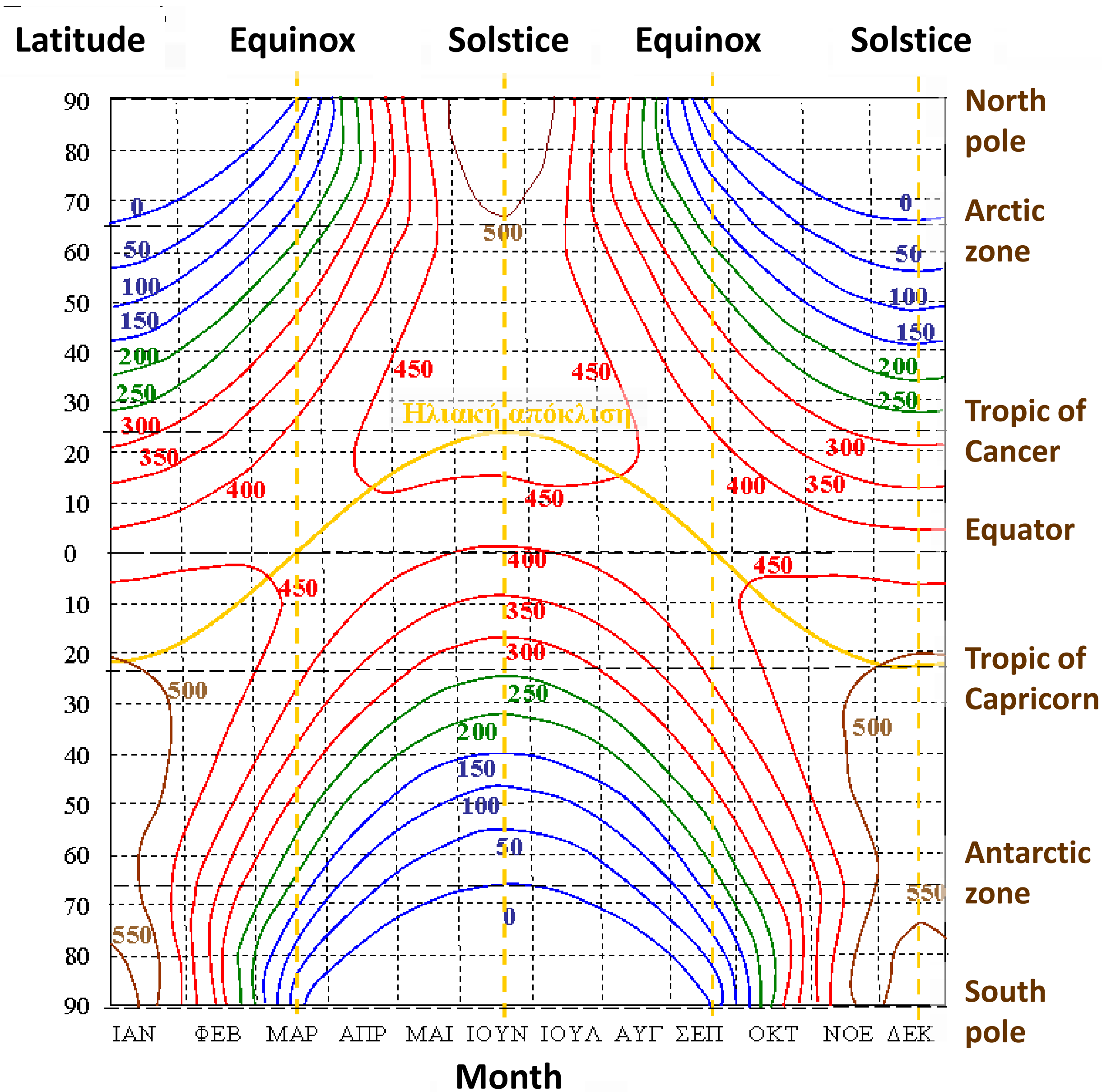


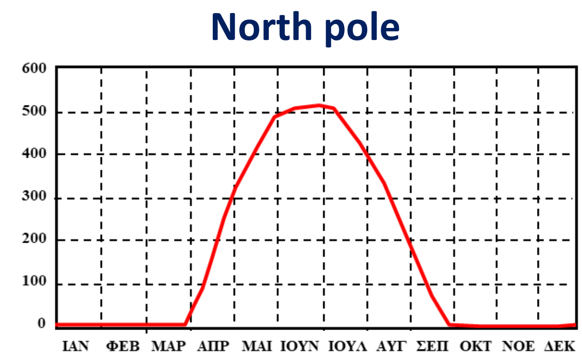
Summer equinox (22 June)

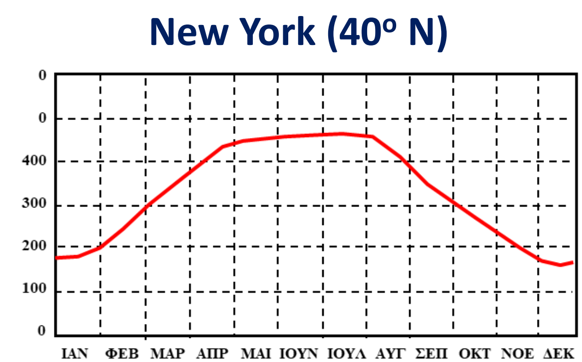
Winter equinox (22 December)

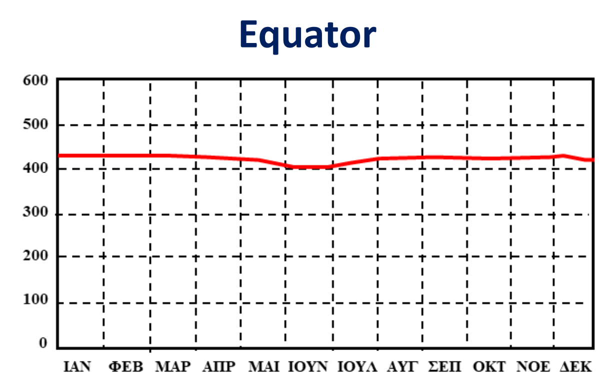


Extraterrestrial radiation: typical values (W/m^2)









Source: Christopherson, 2000

Solar/shortwave/global radiation and its components

- As the radiation penetrates the atmosphere, part of it is **scattered**, **reflected** or **absorbed** due to the **transmittance of the atmosphere** in the shortwave bands, which depends on the thickness of the atmosphere, the water vapour content, the concentrations of gases, solid particles, etc.
- The **amount of radiation actually reaching a horizontal plane** is known as **solar or shortwave radiation**, R_s. The term "shortwave" derives from the fact that the sun emits energy by means of electromagnetic waves that are characterized by short wavelengths.
- It is also known as **global radiation**, given that it is the sum of:
  - **direct shortwave radiation** from the sun, also referred to as **beam radiation**, R_b
  - **diffuse sky radiation** from all directions, R_d
- The distribution between direct and diffuse radiation depends on the **atmospheric conditions** (humidity, dust, etc.) and the **solar declination**, which is continuous function of time, although, normally, a unique value is considered for every day of the year.
- Under **clear sky conditions**, the diffuse solar radiation is about 15% or more of the total solar radiation received by a horizontal surface, while on **inclined surfaces facing away from the sun**, the proportion of diffuse to total solar radiation may be much higher.
- On a **cloudy day**, the radiation is scattered in the atmosphere, but even under extremely dense cloud cover (when direct radiation tends to zero), about 25% of the extraterrestrial radiation reaches the earth's surface as diffuse sky radiation.

Solar radiation: measurement & empirical estimations

- The global radiation is measured by **pyranometers**, **radiometers** or **solarimeters**. These instruments contain a sensor installed on a horizontal surface that measures the intensity of the total solar radiation, i.e., **both direct and diffuse radiation from cloudy conditions**.
- In the absence of measurements, solar radiation is estimated through empirical approaches, such as the Angström formula:

$$R_s = R_a\,(a_s + b_s\, n / N)$$

Either provided directly (sunshine values) or in terms of **cloud cover**

where n is the **actual sunshine duration**, N is the **maximum potential daylight hours** (function of **latitude** and **solar declination**), a_s is a regression constant, expressing the fraction of R_a reaching the earth on **overcast days**, when $n = 0$, and $a_s + b_s$ is the fraction of R_a ideally reaching the earth under **clear-sky conditions**, when $n = N$.

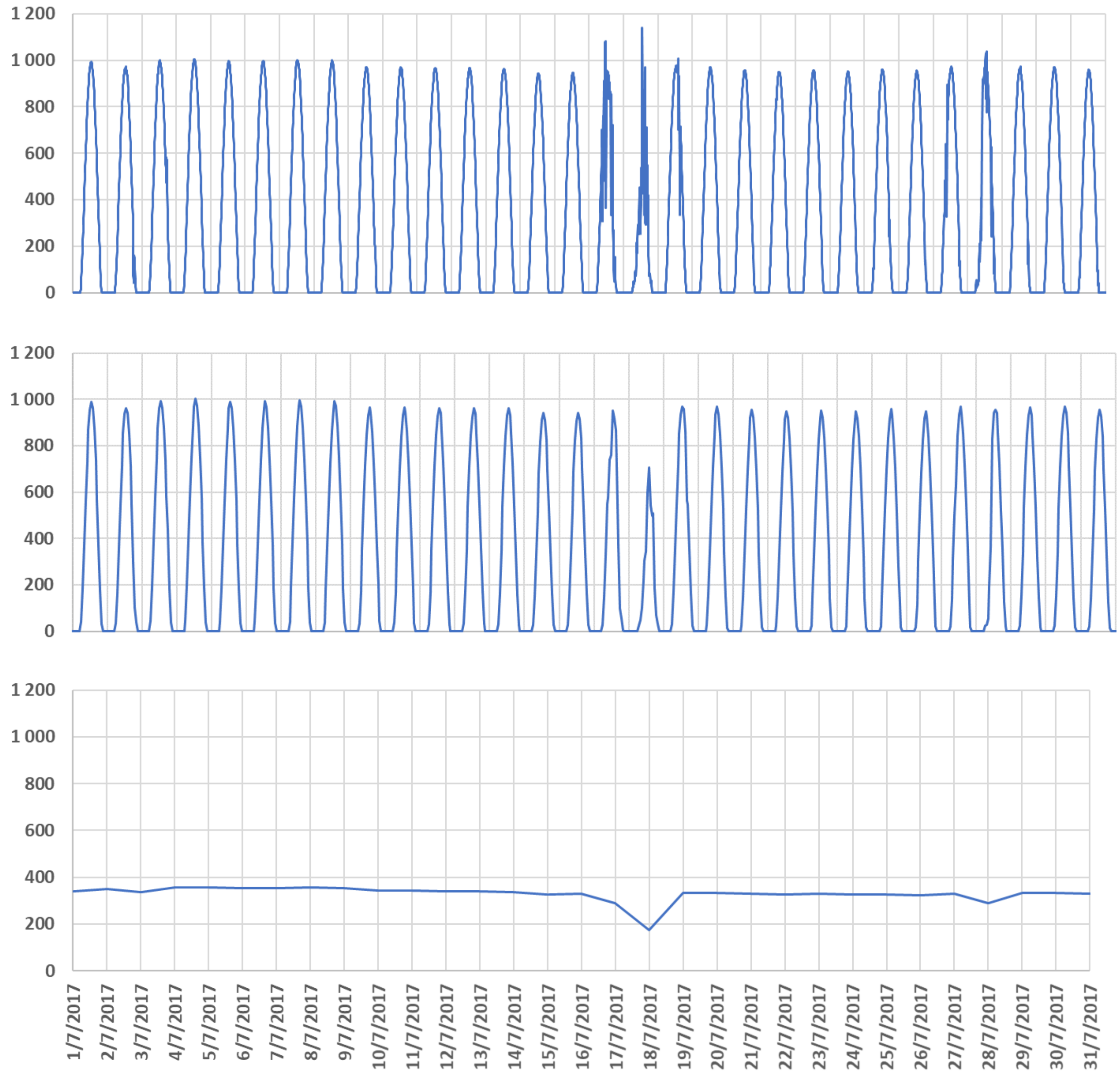
- Parameters a_s and b_s depend on the **location**, the **season** and the **state of the atmosphere** and they are related to the distribution of direct and diffuse radiation; if no actual solar radiation data are available for their calibration against local observations, the use of typical values $\boldsymbol{a_s}$ **= 0.25 and** $\boldsymbol{b_s}$ **= 0.50** are recommended.

φ (°)	36	38	40	42	44	46
Ιαν	9.8	9.7	9.5	9.3	9.1	8.9
Φεβ	10.6	10.5	10.4	10.3	10.2	10.1
Μαρ	11.7	11.7	11.7	11.7	11.6	11.6
Απρ	12.9	13.0	13.0	13.1	13.2	13.3
Μαϊ	13.9	14.0	14.2	14.4	14.5	14.7
Ιουν	14.4	14.6	14.8	15.0	15.2	15.5

φ (°)	36	38	40	42	44	46
Ιουλ	14.2	14.4	14.5	14.7	14.9	15.2
Αυγ	13.4	13.5	13.6	13.7	13.8	13.9
Σεπ	12.2	12.2	12.3	12.3	12.3	12.3
Οκτ	11.1	11.0	10.9	10.8	10.7	10.7
Νοε	10.1	9.9	9.8	9.6	9.4	9.2
Δεκ	9.6	9.4	9.2	9.0	8.8	8.5

Monthly average potential daylight hours, N, for latitudes φ = 36°-46° at the Northern Hemisphere (Source: Koutsoyiannis & Xanthopoulos, 1997, p. 173)

Variability of solar radiation (W/m^2) across scales



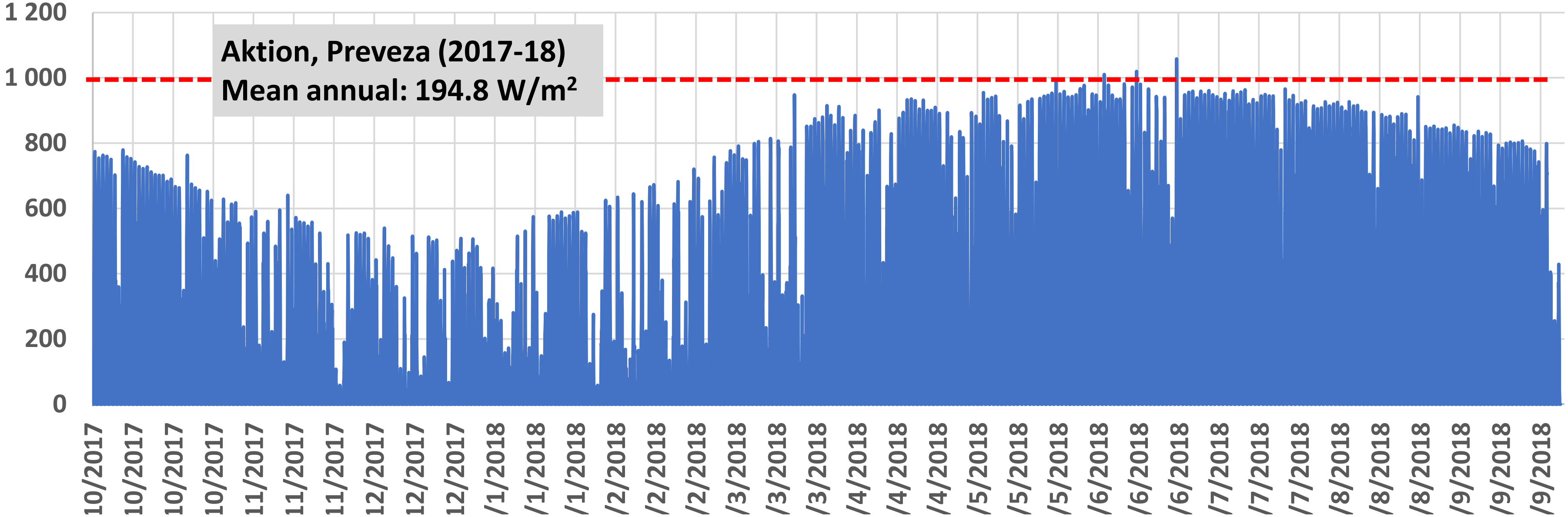
10 min solar radiation data at Aktion (July 2017)

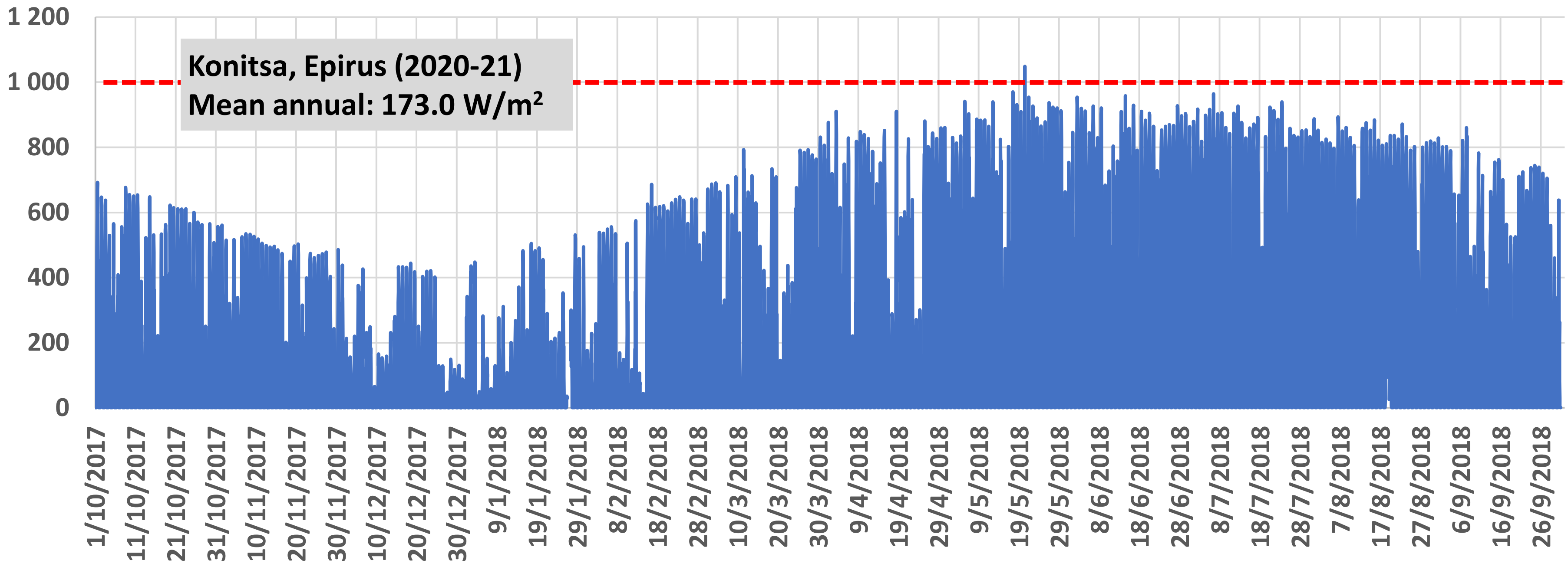
Mean hourly solar radiation data at Aktion (July 2017)

Mean daily solar radiation data at Aktion (July 2017)

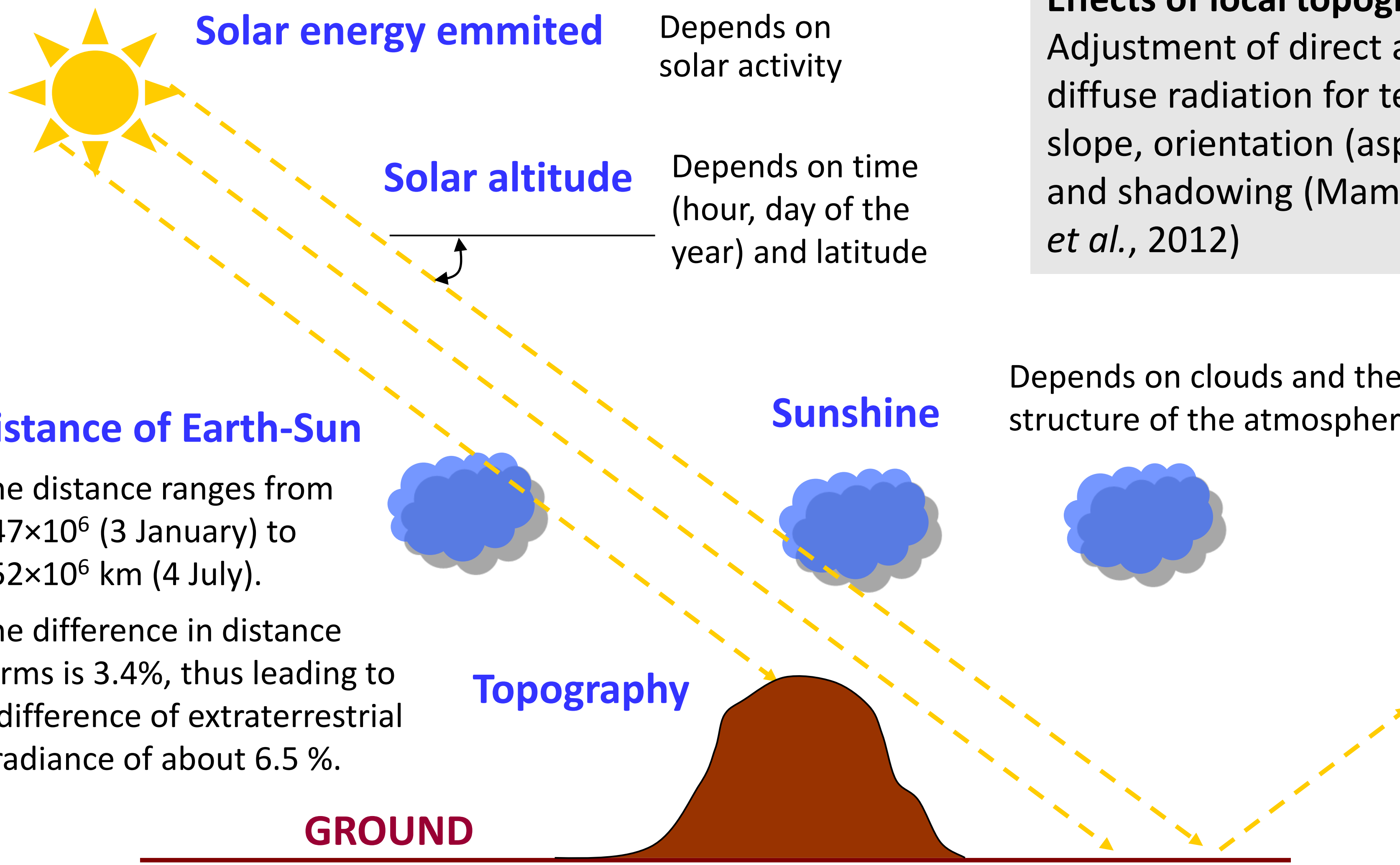
Source: https://system.openhi.net/stations/1427/

Spatiotemporal distribution





Factors that influence the ground solar radiation



Solar energy emmited

Depends on solar activity

Solar altitude

Depends on time (hour, day of the year) and latitude

Effects of local topography: Adjustment of direct and diffuse radiation for terrain slope, orientation (aspect) and shadowing (Mamassis *et al.*, 2012)

Distance of Earth-Sun

The distance ranges from 147×10^6 (3 January) to 152×10^6 km (4 July).

The difference in distance terms is 3.4%, thus leading to a difference of extraterrestrial irradiance of about 6.5 %.

Sunshine

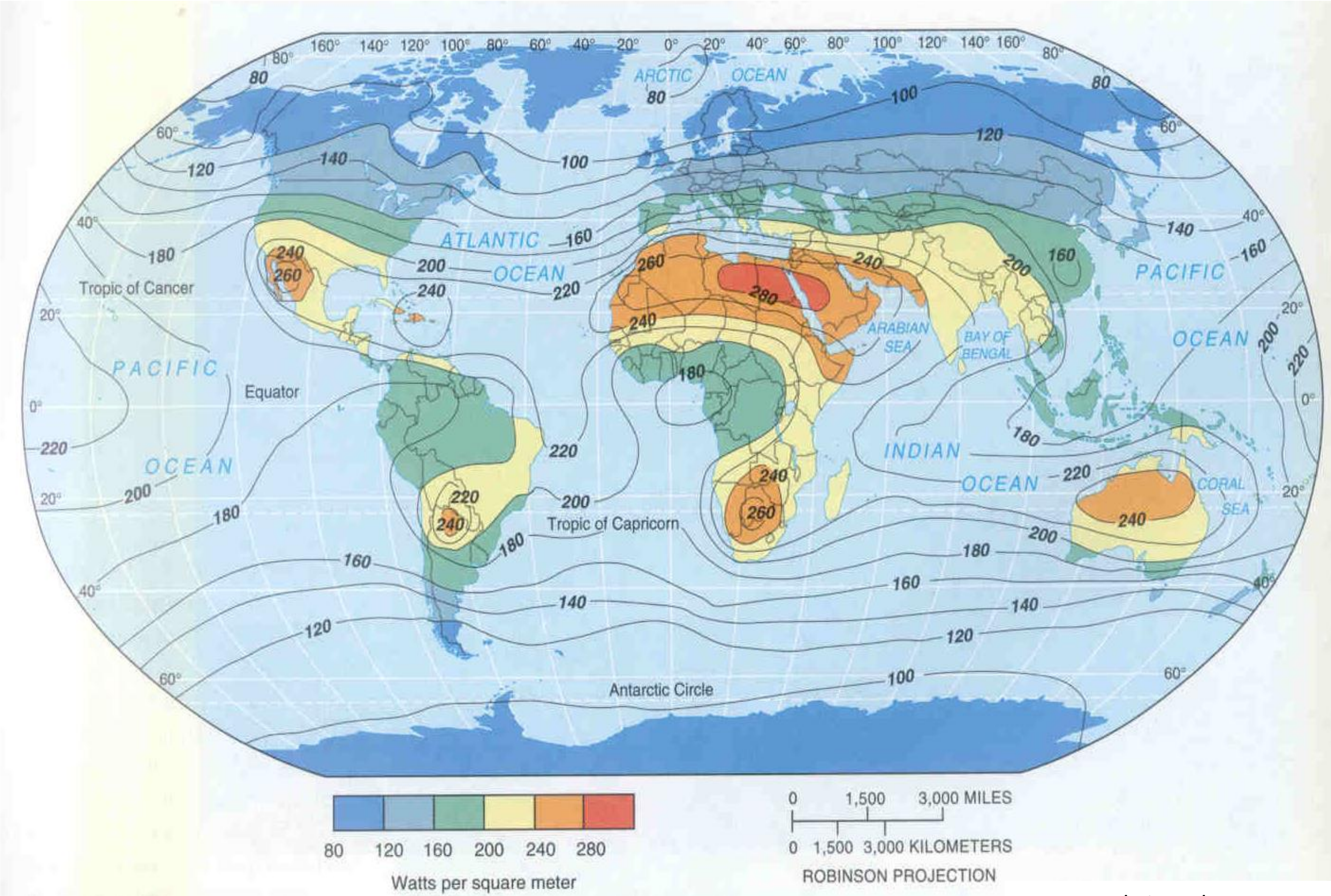
Depends on clouds and the structure of the atmosphere

Topography

Surface albedo

Depends on surface properties. Indicative values: water: 0.06, ground: 0.25, snow: 0.95

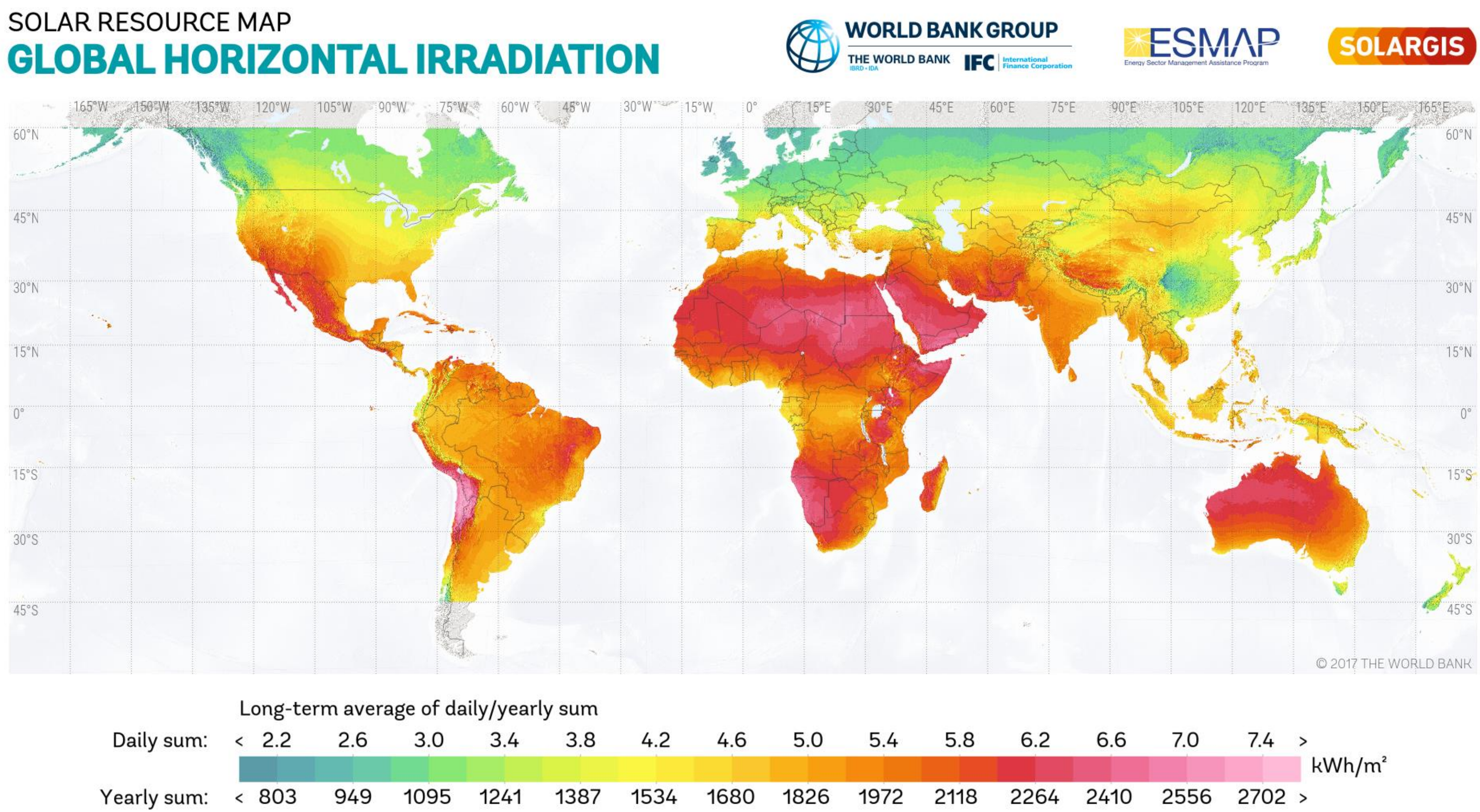
Mean annual solar radiation at ground level (W/m^2)



Source: Christopherson, 2000

Global map of horizontal irradiance (kWh/m²)

Global Horizontal Irradiance: Total irradiance from the sun on a horizontal surface on Earth, as the sum of **direct irradiance** (after accounting for the solar zenith angle of the sun) and **diffuse horizontal irradiance**.



Source: World Bank, *Global Solar Atlas*, 2017 (https://globalsolaratlas.info)

Solar (PV) energy in Greece

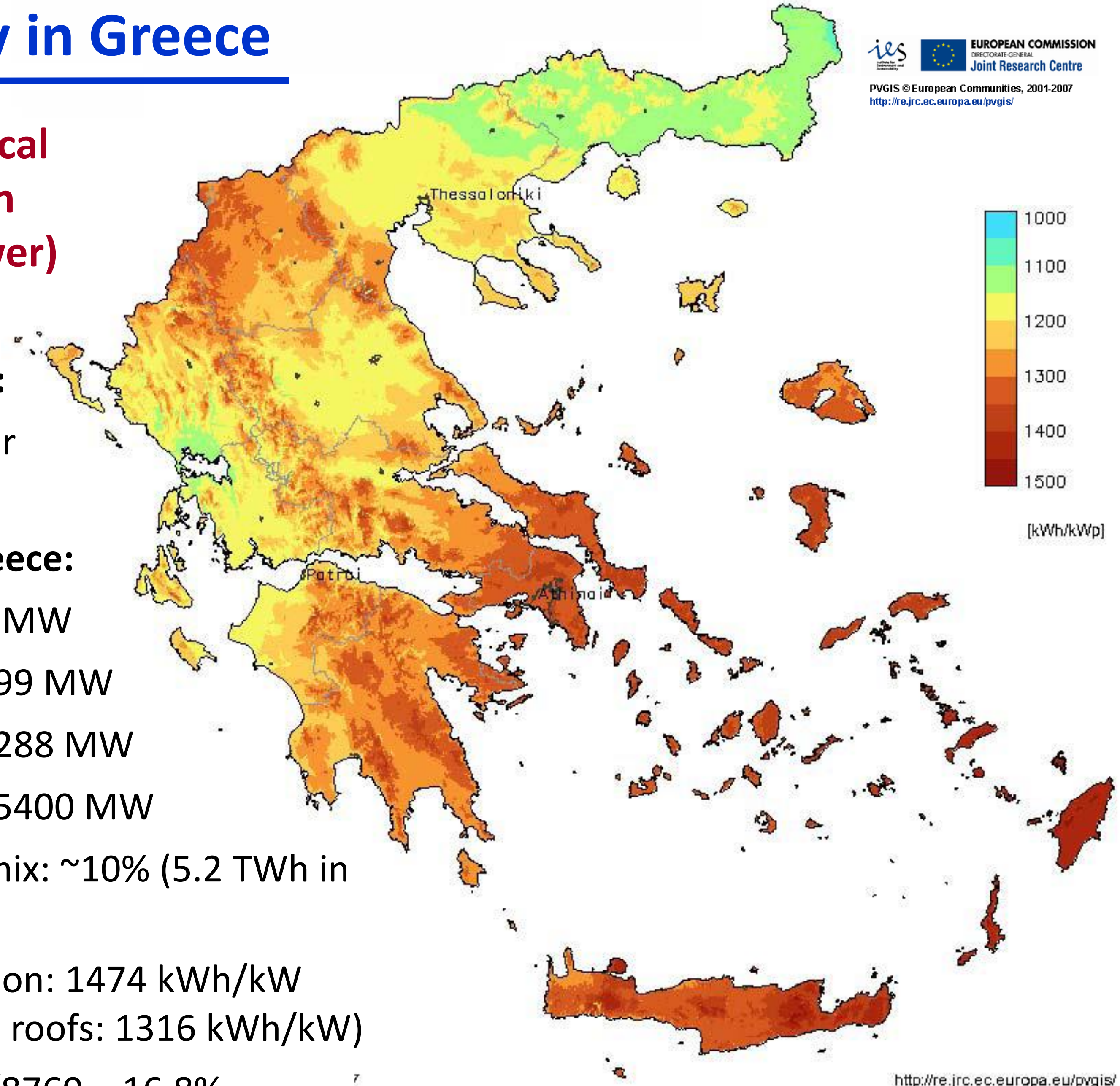
Expected annual electrical energy production (kWh per kW of installed power)

Useful link for fast assessment of PV systems:

https://selasenergy.gr/solar-calculator-main.php

Photovoltaic energy in Greece:

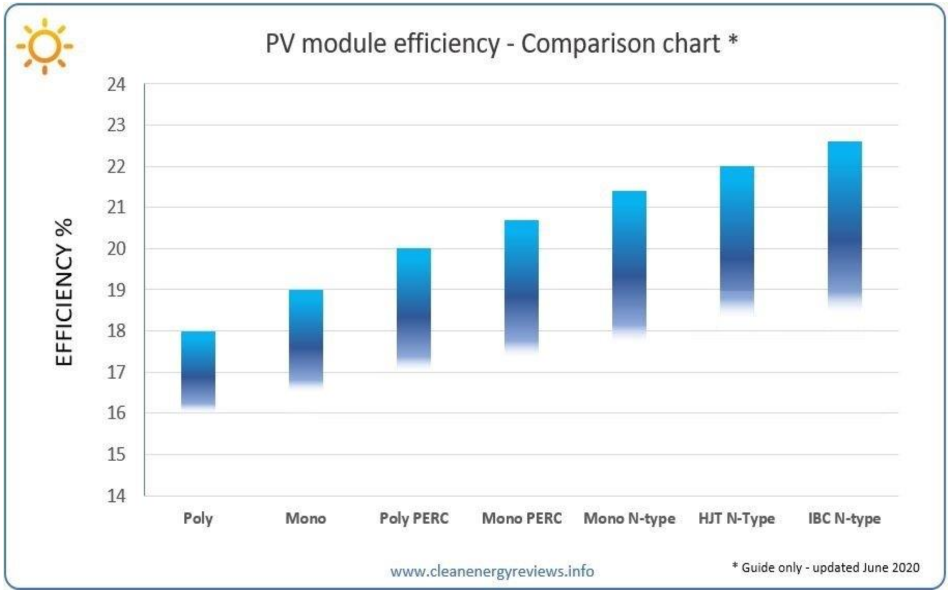
- Total capacity 2007: 2 MW
- Total capacity 2010: 199 MW
- Total capacity 2020: 3288 MW
- Total capacity 2022: >5400 MW
- Sharing in electricity mix: ~10% (5.2 TWh in 2021)
- Mean annual production: 1474 kWh/kW (parks: 1500 kWh/kW, roofs: 1316 kWh/kW)
- Capacity factor: 1474/8760 = 16.8%



Source: https://helapco.gr/wp-content/uploads/Greek_PV_Market_Snapshot_HELAPCO_23Nov2022-1.pdf

Remarks on PV efficiency (1)

- Efficiency of first commercial panels (1990): 10-11%
- Over last decade, the average panel conversion efficiency has increased from 15% to over 20%, which resulted in the power rating of a standard size panel (156 × 156 mm) to increase from 250 up to 400 W (Maxeon 3, power capacity 400 W, efficiency 22.6%).
- Solar panel efficiency is determined by:
  - the **photovoltaic cell efficiency**, depending on the cell design and silicon type;
  - the **total panel efficiency**, based on the cell layout, configuration, panel size and the color of protective backsheet (black backsheets absorb more heat).
- The total panel efficiency is measured under **Standard Test Conditions** (STC), based on a cell temperature of 25°C, solar irradiance of 1000 W/m^2 and air mass of 1.5, for 2.74 hours.
- The effect of deviation from STC (25°C) is accounted for by applying a **power temperature coefficient** (%/°C).
- Typical values: -0.38%/°C and -0.40%/°C, for mono- and polycrystalline panels.
- Cell temperature is 20-30°C higher than the ambient air temperature, resulting to 8-12% reduction in power output.
- PV efficiency drops significantly with time!



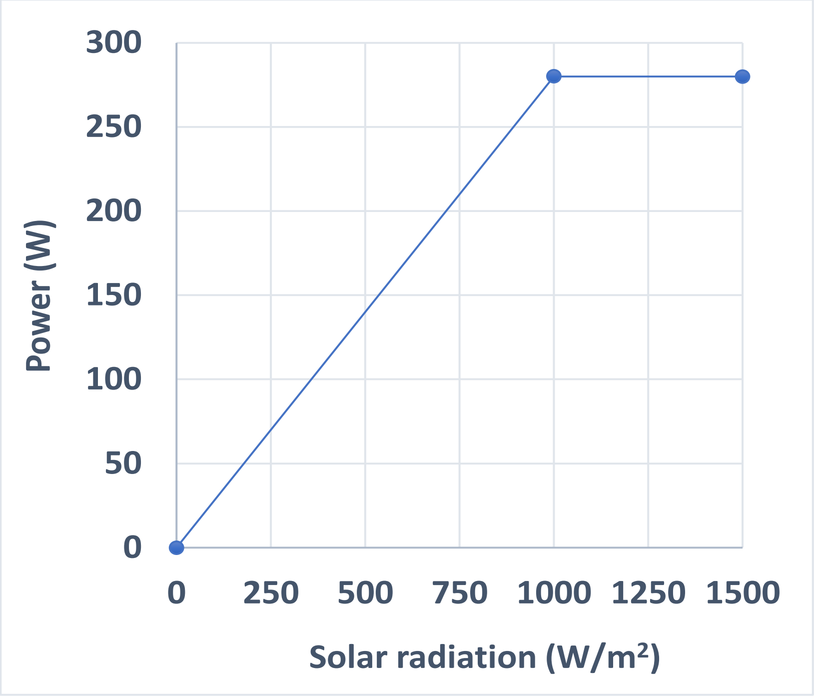
Remarks on PV efficiency (2)

Example panel

- Installed power: 280 W
- Dimensions: 1640 × 990 × 46 mm
- Nominal power achieved at 1000 W/m^2

Calculation of efficiency

- Panel area: 1.64 × 0.99 = 1.624 m^2
- For 1000 W/m^2 of incoming solar radiation each panel receives 1624 W and produces 280 W of electric power
- Efficiency: 280/1624 = 17.2%



- **Solar module tracking systems** are motorized mechanical racking systems that orient panels so that light strikes perpendicular to the surface of the panels, by tuning the angle at which panels receive solar radiation.
- Increase of energy output from 20-30%, yet substantially higher **installation and maintenance costs** over static solar plants.

Epilogue: PVs vs. arable land & win-win case of agrovoltaics