# 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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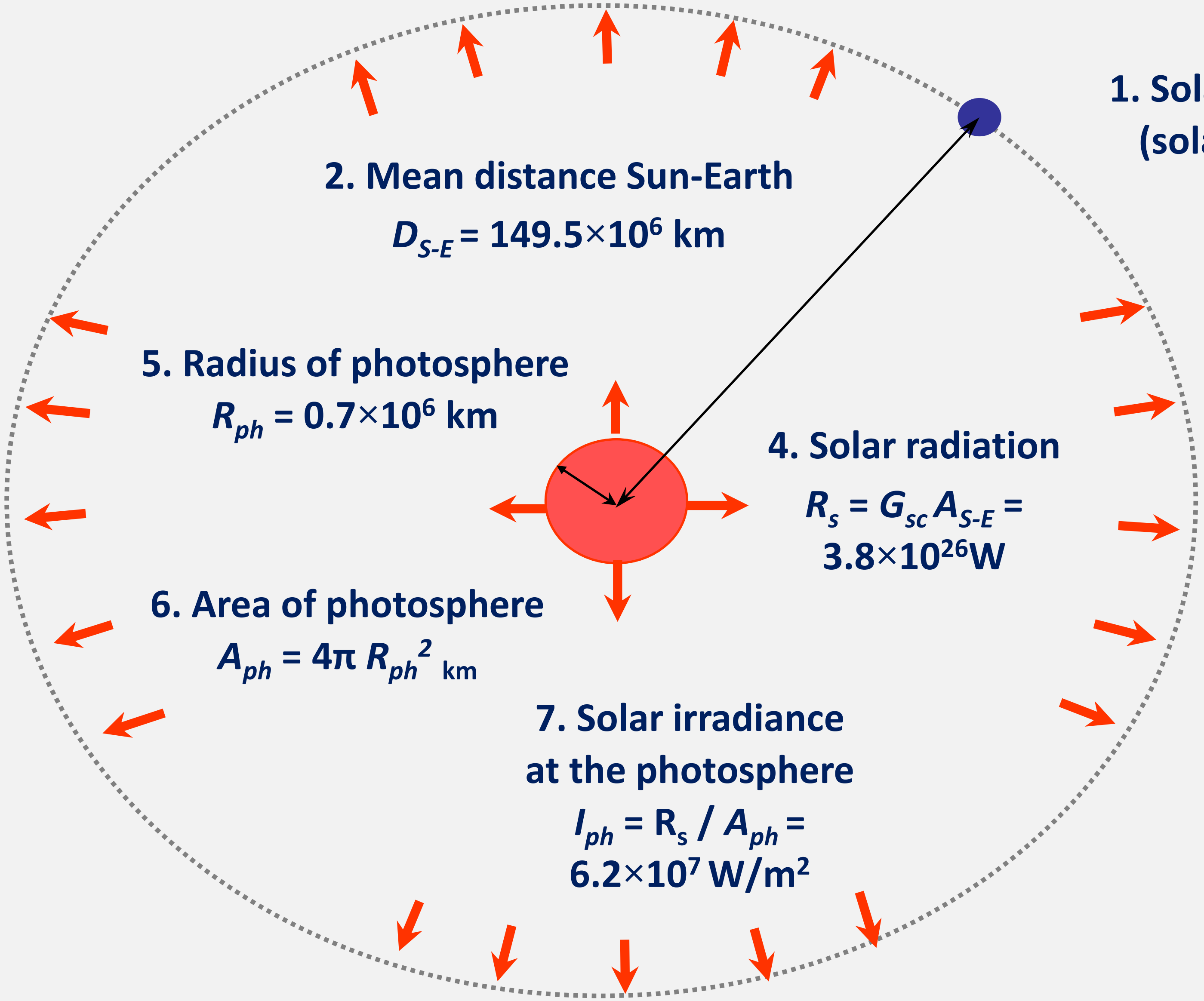
# Solar physics: concepts and quantities



1. Solar irradiance at Earth's distance (solar constant): $G_{sc}$ = 1367 W/m$^2$

2. Mean distance Sun-Earth $D_{S\text{-}E}$ = 149.5×10$^6$ km

3. Area of Sun-Earth sphere: $A_{S\text{-}E} = 4\pi D_{S\text{-}E}^2 = 2.8\times10^{17}$ km$^2$

4. Solar radiation $R_s = G_{sc} A_{S\text{-}E} = 3.8\times10^{26}$W

5. Radius of photosphere $R_{ph}$ = 0.7×10$^6$ km

6. Area of photosphere $A_{ph} = 4\pi R_{ph}^2$ km

7. Solar irradiance at the photosphere $I_{ph} = R_s / A_{ph} = 6.2\times10^7$ W/m$^2$

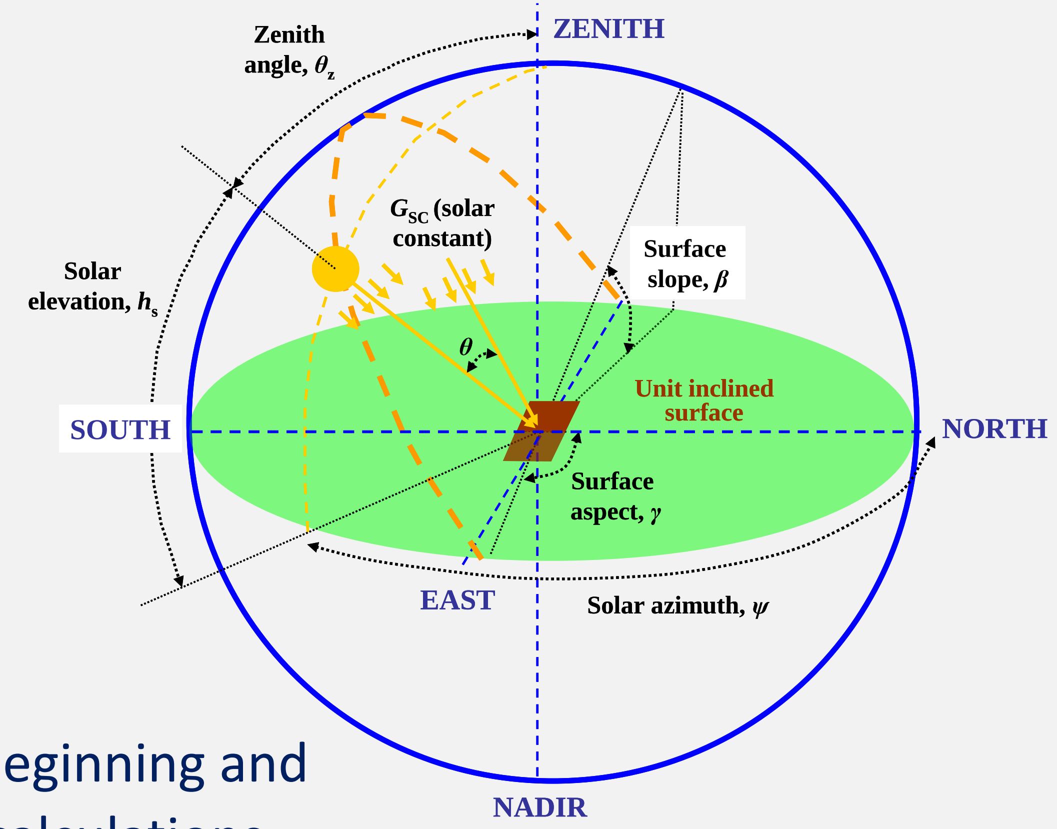
8. Power radiated from the photosphere per unit area: $I_{ph} = \sigma T^4$ , where $T \approx 5778$ °K and $\sigma = 4.9\times10^{-6}$ kJ/m$^2$/K$^4$ (Stefan-Boltzmann constant)

# 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 $\vartheta_z$, i.e.,

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

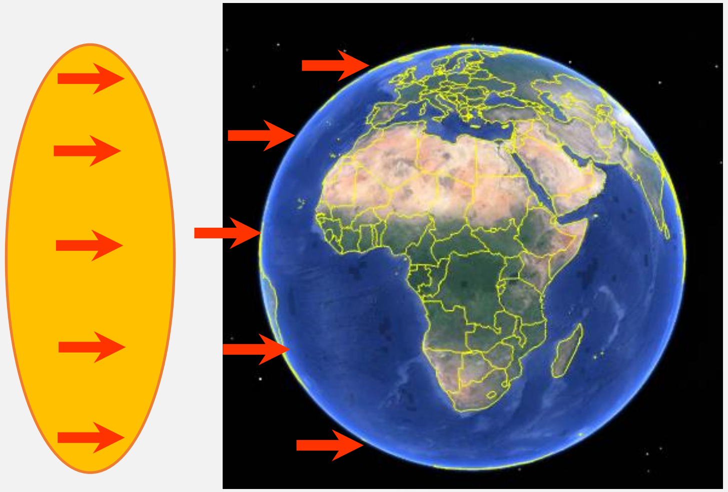
- The **solar constant** denotes the average density of solar radiation outside the Earth's atmosphere at mean distance from the sun and is approximately $G_{SC}$ = 1367 W/m$^2$.
- The **eccentricity coefficient** $d_r$ and the **zenith angle** $\vartheta_z$ depend on the **solar declination** and the **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 the end of the specific period should be considered in the calculations.



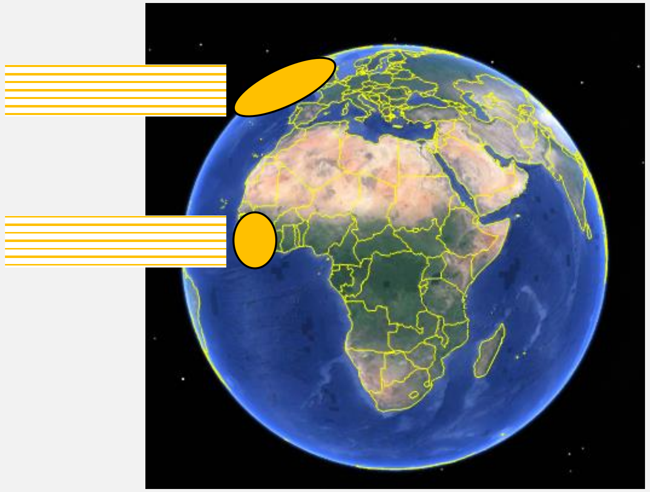
# Extraterrestrial radiation: spatial variability

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

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

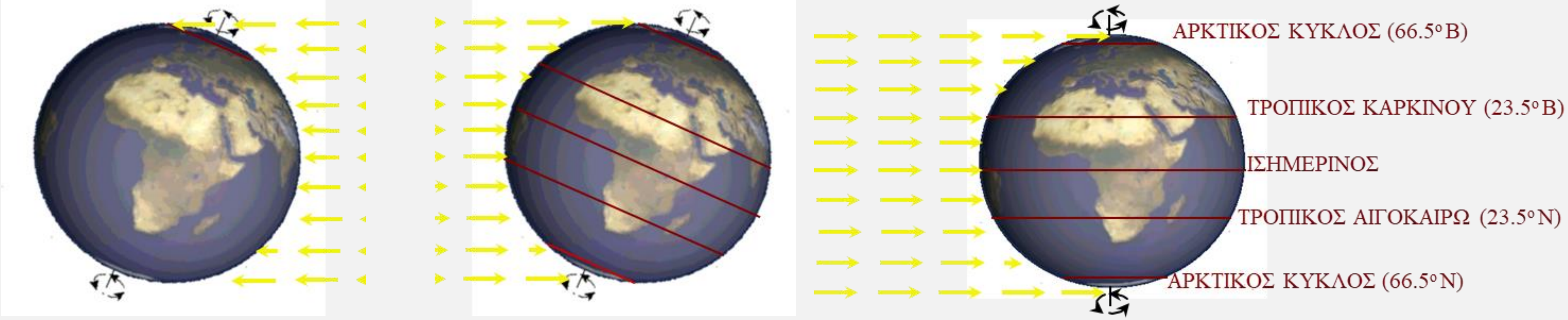


The spatial variation of solar radiation depends on the latitude, as the same irradiance affects areas with different sizes



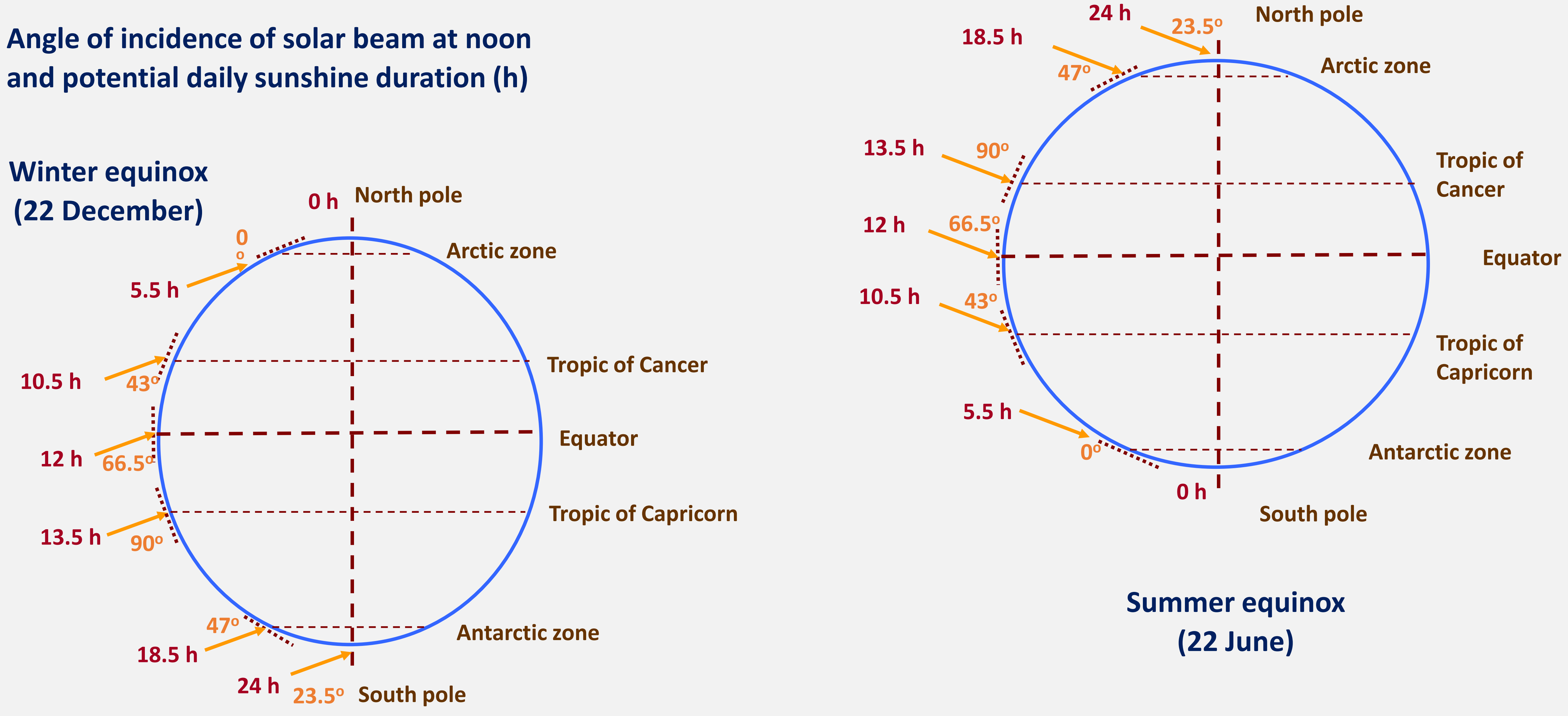
With respect to the equator, the area at 45° latitude is 40% larger, it is double at 60° and it is six times larger at 80°

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



# Extraterrestrial radiation: temporal variability

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



# 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 everyday 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 $n = N$.

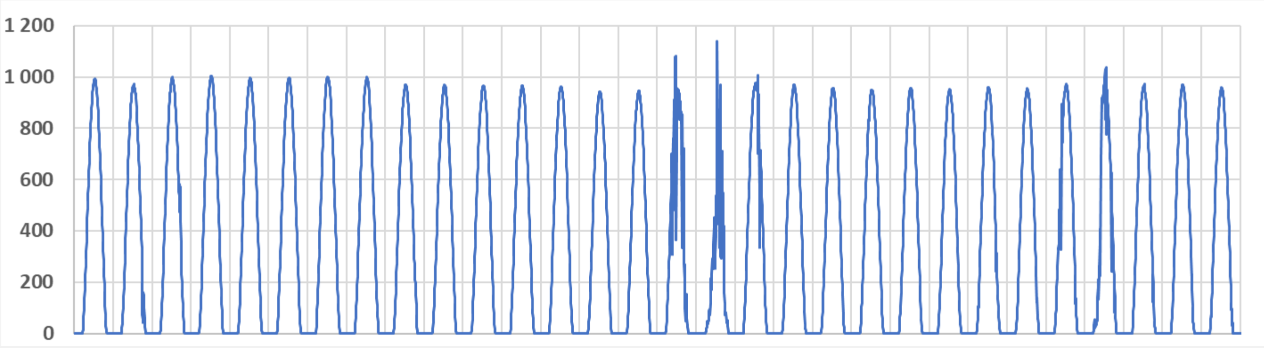
- Parameters $a_s$ and $b_s$ depend on the **location**, the **season** and the **state of the atmosphere** and they are related to the distribution of direct and diffuse radiation; if no actual solar radiation data are available for their calibration against local observations, the use of typical values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

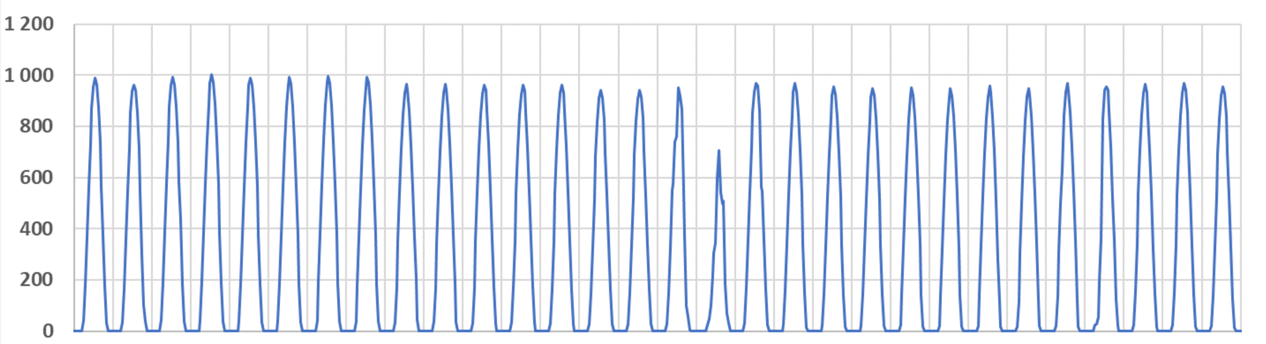
| φ (°) | 36 | 38 | 40 | 42 | 44 | 46 |
|---|---|---|---|---|---|---|
| Ιουλ | 14.2 | 14.4 | 14.5 | 14.7 | 14.9 | 15.2 |
| Αυγ | 13.4 | 13.5 | 13.6 | 13.7 | 13.8 | 13.9 |
| Σεπ | 12.2 | 12.2 | 12.3 | 12.3 | 12.3 | 12.3 |
| Οκτ | 11.1 | 11.0 | 10.9 | 10.8 | 10.7 | 10.7 |
| Νοε | 10.1 | 9.9 | 9.8 | 9.6 | 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 $\varphi$ = 36° - 46° at the Northern Hemisphere (Source: Koutsoyiannis & Xanthopoulos, 1997, p. 173)

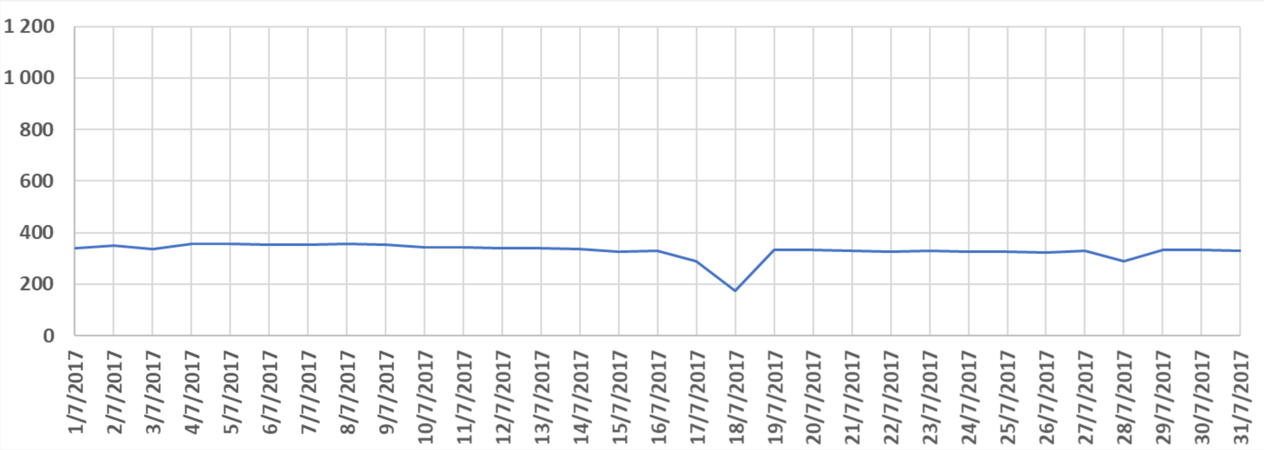
# Variability of solar radiation (W/m²) across scales




10-minute solar radiation at Aktion (July 2017)

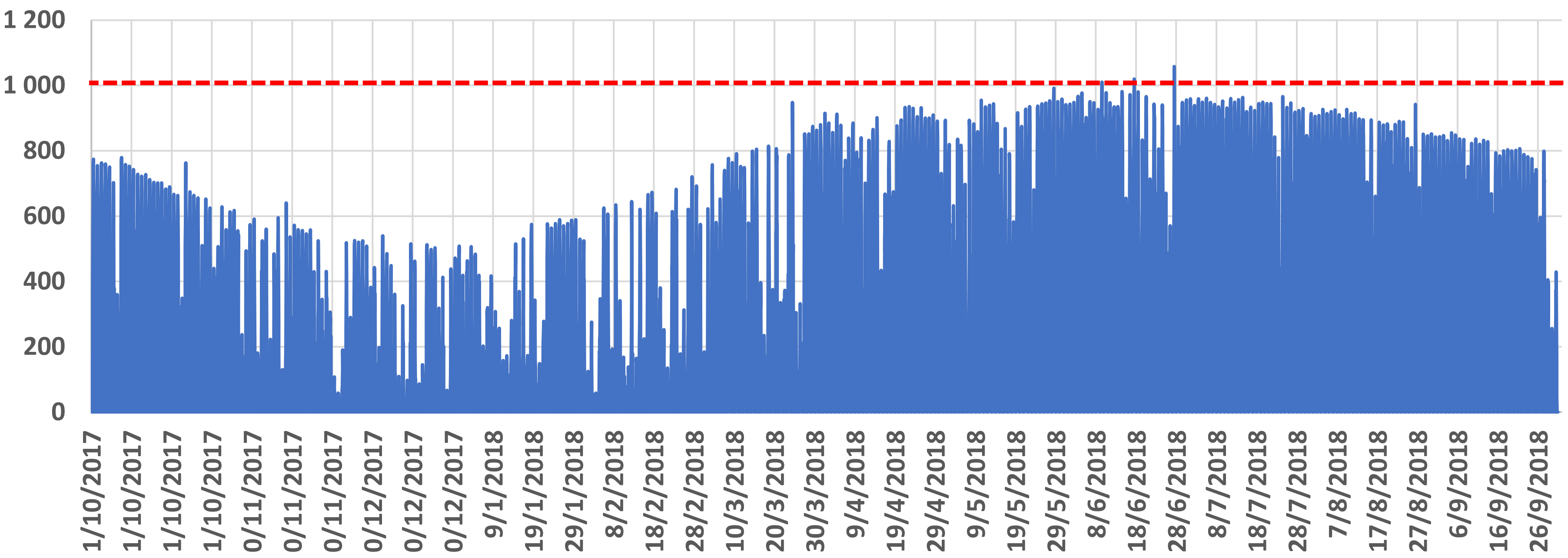



Mean hourly solar radiation at Aktion (July 2017)

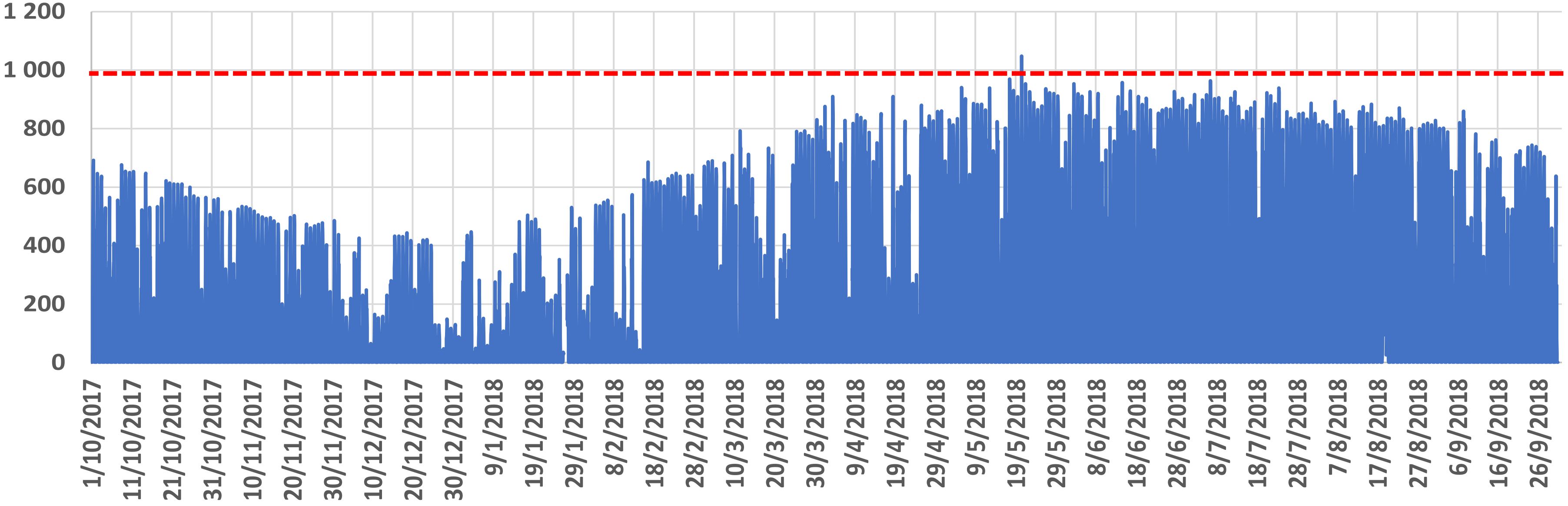



Mean daily solar radiation at Aktion (July 2017)

# Spatiotemporal distribution

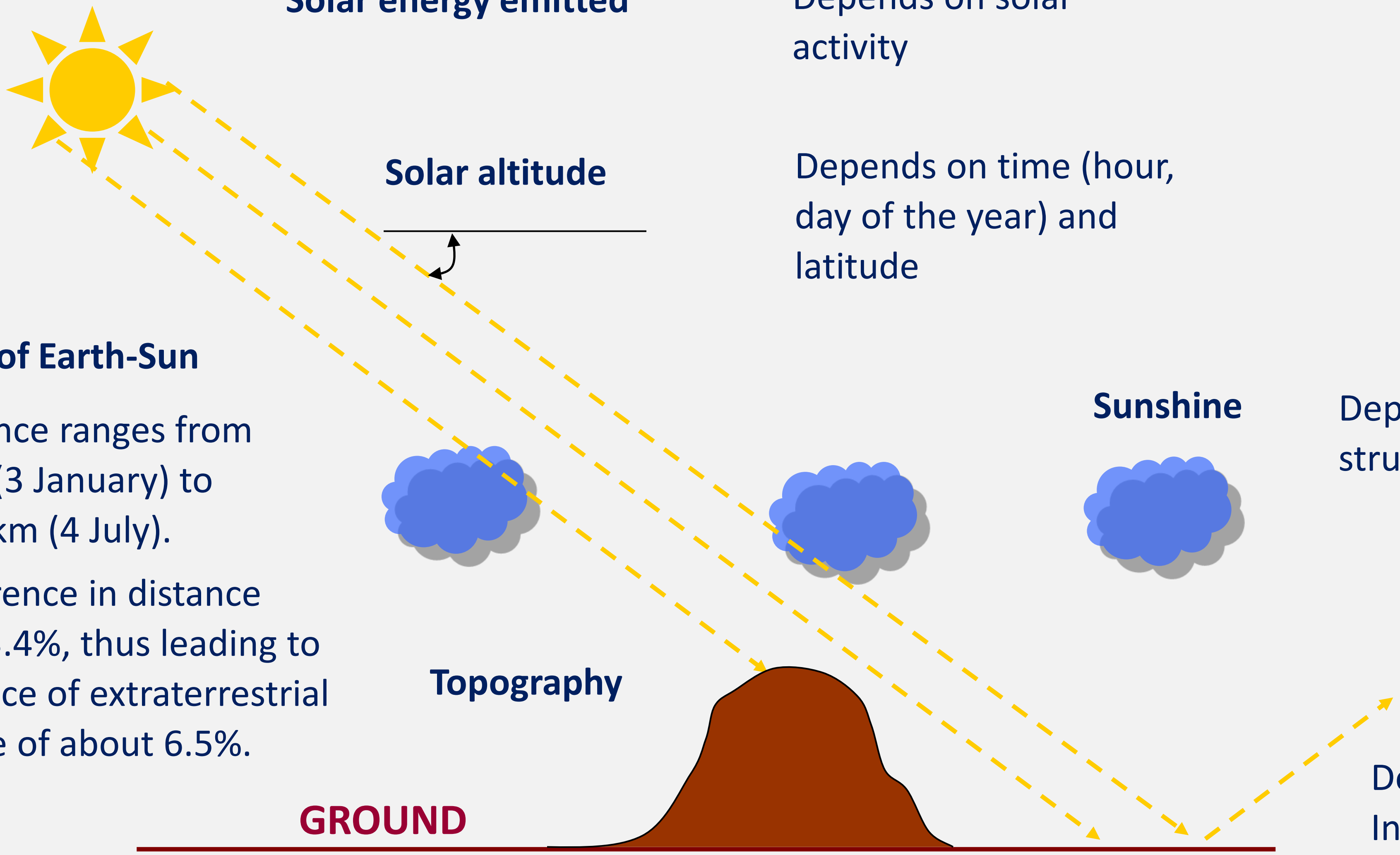



**Aktion, Preveza (2017-18)**
**Mean annual: 194.8 W/m²**




**Konitsa, Epirus (2020-21)**
**Mean annual: 173.0 W/m²**

# Factors that influence the ground solar radiation



**Solar energy emitted**

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 $147\times10^{6}$ (3 January) to $152\times10^{6}$ 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**

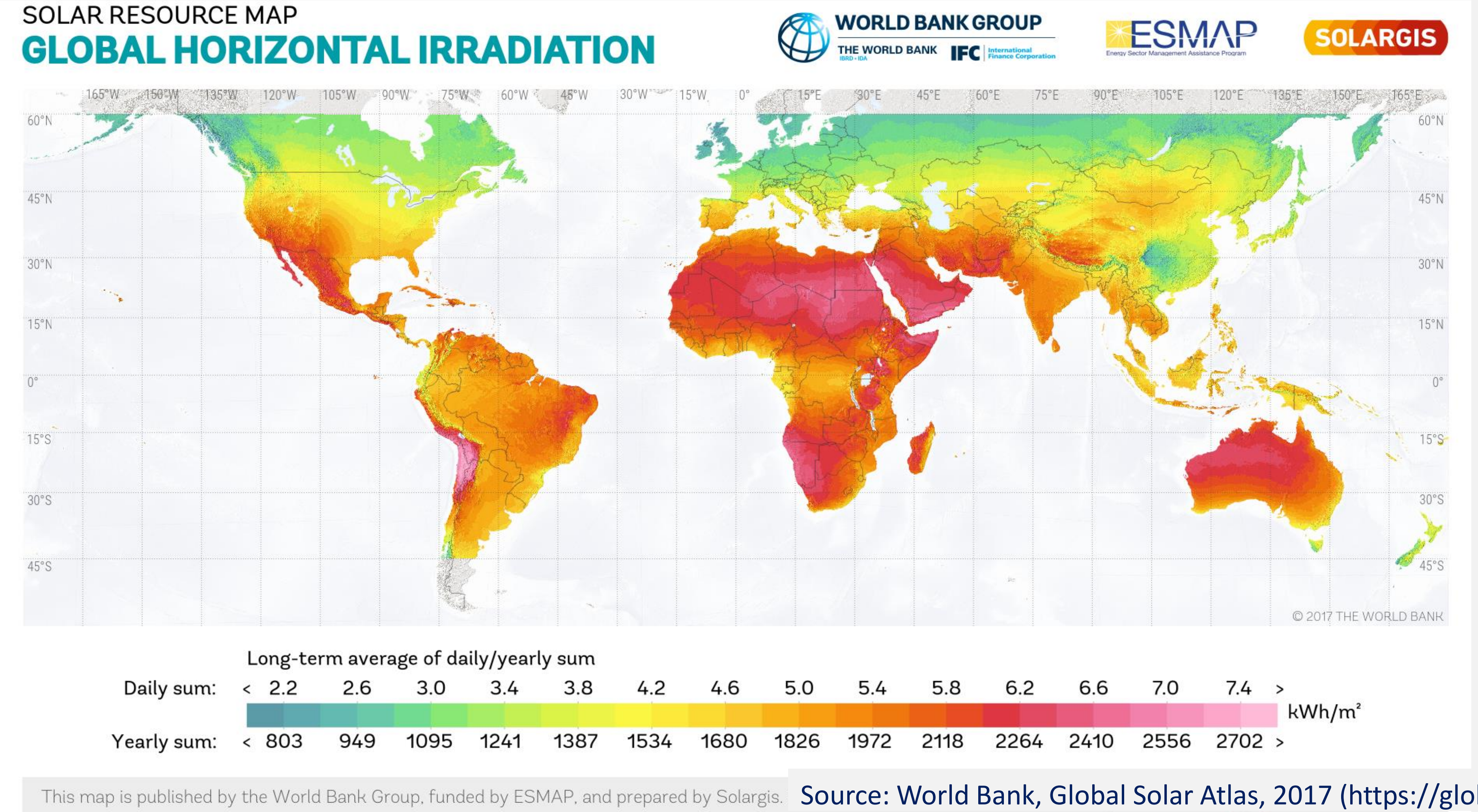
**GROUND**

**Surface albedo**

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

# 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)

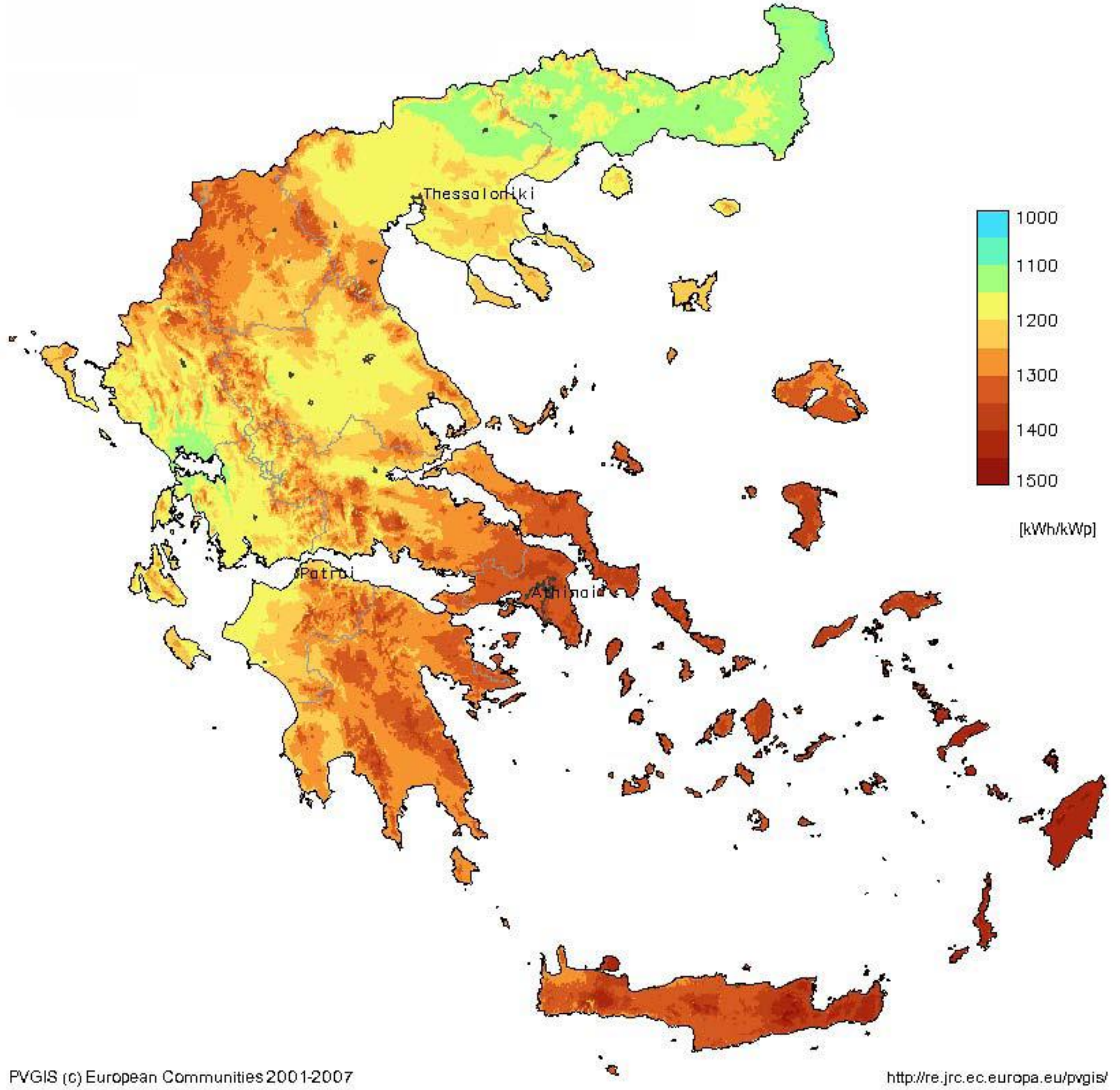
# Solar (PV) energy in Greece

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

**Photovoltaic energy in Greece:**

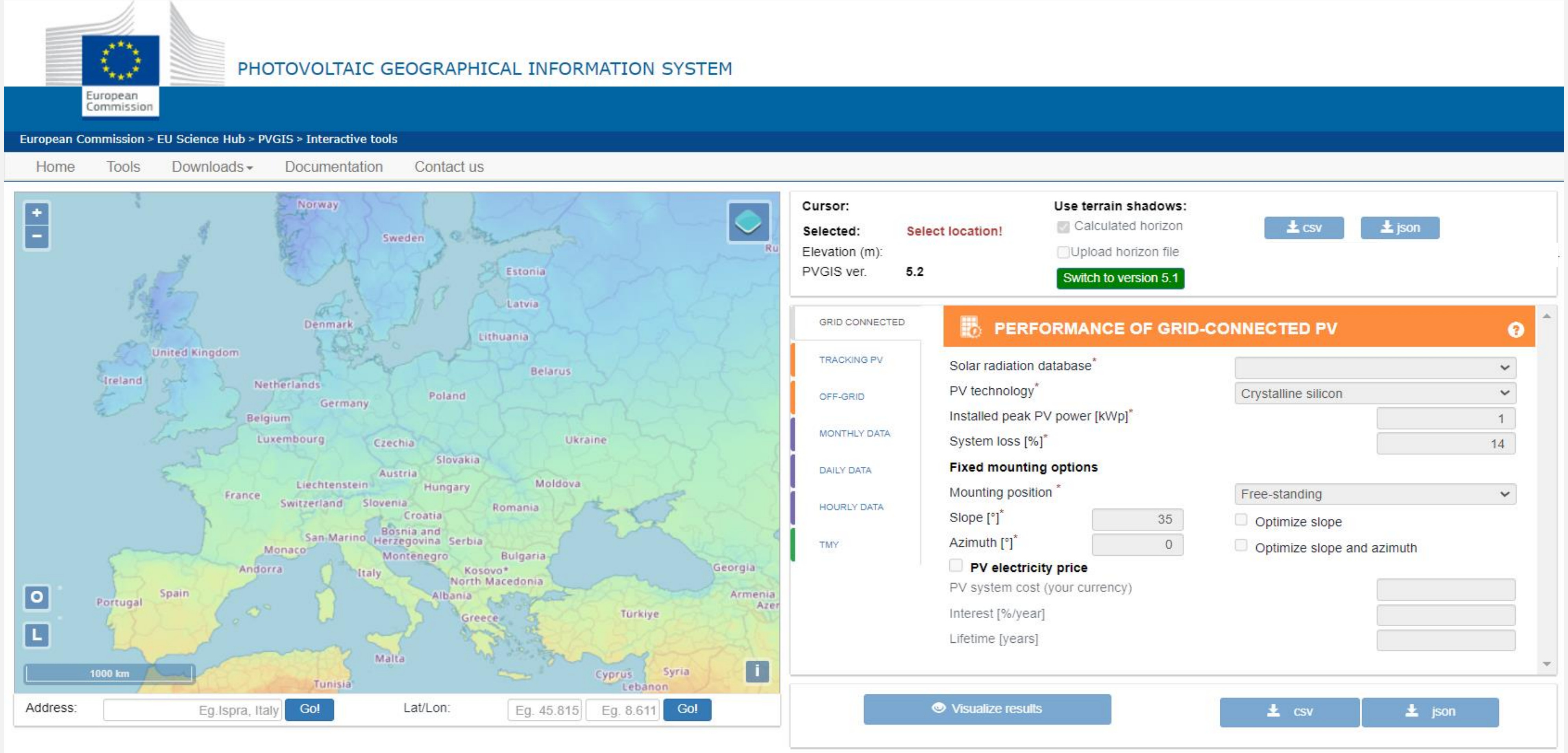
- Total capacity in 2007: 2 MW
- Total capacity in 2010: 199 MW
- Total capacity in 2020: 3288 MW
- Total capacity in 2022: 5273 MW
- Total capacity in 2023: 6369 MW
- Sharing in the electricity mix: 12.4% (6.50 TWh in 2022)
- Mean annual production: 1474 kWh/kW
  (parks 1500 kWh/kW, roofs: 1316 kWh/kW)
- Capacity factor: 1474/8760: 16.8%

**Global photovoltaic power potential by country:**
https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf



# In a world of restricted data, there is still hope

**PVGIS** is a web application that allows the user to get **data on solar radiation (monthly, daily, and hourly scale)** and **photovoltaic (PV) system energy production (based on mounting angle, slope and azimuth)**, at **any place in most parts of the world**. It is completely **free to use**, with no restrictions on what the results can be used for, and with no registration necessary.




**The PVGIS platform can be accessed here:**

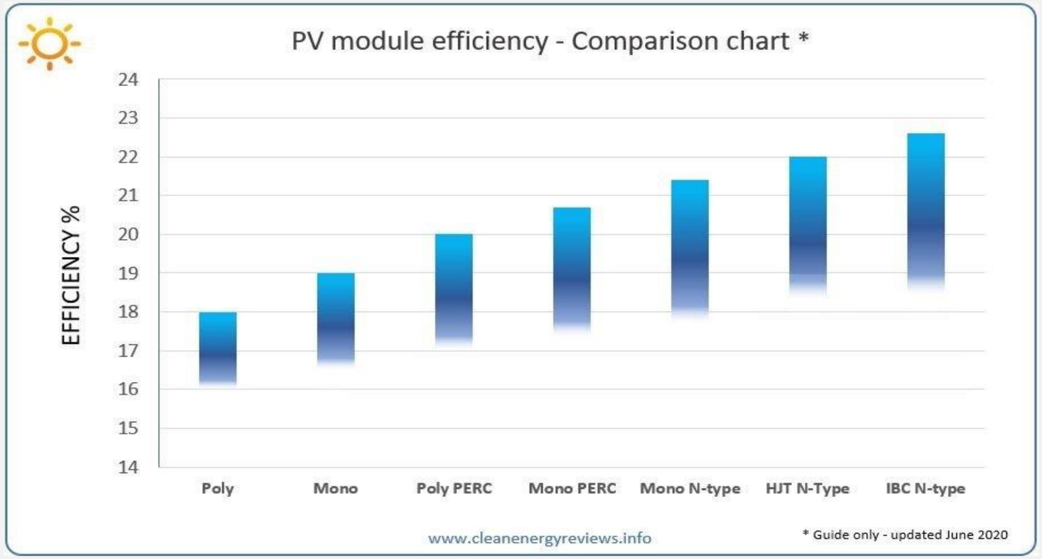
https://re.jrc.ec.europa.eu/pvg_tools/en/

**Information about the database and the processing of the satellite data can be found here:**

Huld, T.; Müller, R.; Gambardella, A. “A new solar radiation database for estimating PV performance in Europe and Africa.” Sol. Energy 2012, 86, 1803–1815, doi:10.1016/j.solener.2012.03.006

# 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).
- The coefficient usually ranges between -0.29 and -0.5 %/°C, meaning that **every 10 °C in excess results in a decrease in power of the module ranging between 2,9 and 5%**.
- Cell temperature is 20-30°C higher than the ambient air temperature, resulting to 8-12% reduction in power output.
- PV efficiency also significantly decreases over time.



# Remarks on PV efficiency (2)

- The **hourly power production** is calculated according to the following formula:

$$P_{hourly} = \frac{n_{act}}{n_{nom}} min[n_{nom} \cdot R \cdot A_{panel}, P_{nom}]$$

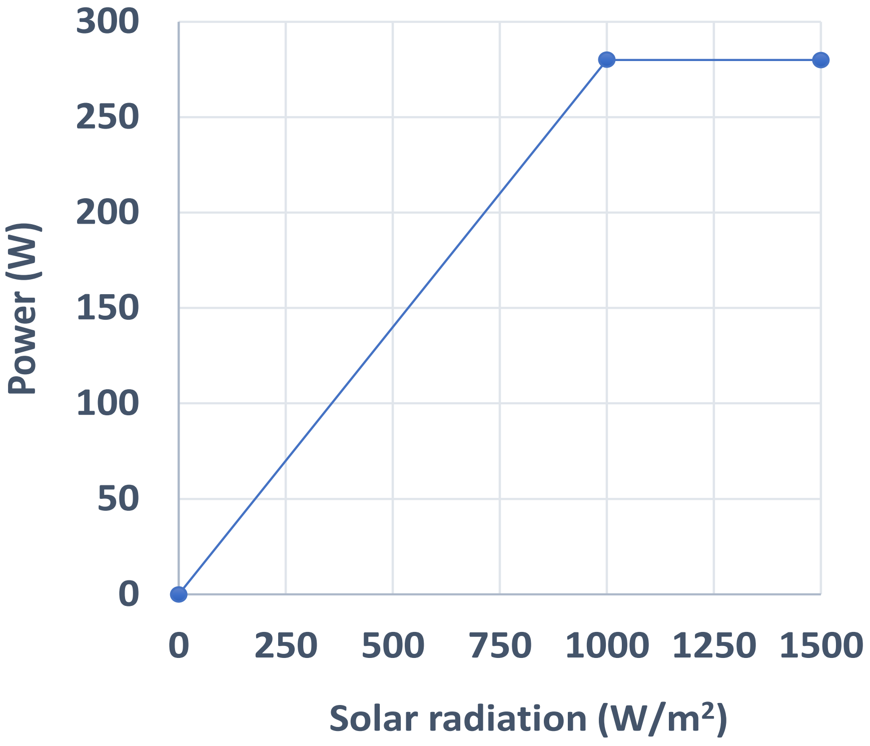
where $n_{act}$ is the adjusted PV efficiency against temperature effects, $n_{nom}$ is the nominal efficiency, $R$ (W/m$^2$) is the solar radiation and $T$ (°C) is the temperature $A_{panel}$ is the PV area, and $P_{nom}$ is the nominal power, which is achieved under the so-called Standard Test Conditions.

- The **adjustment of efficiency** is employed by the following formula that accounts for temperature effects:

$$n_{actual} = n_{nom} - a_T \cdot max(T - 25, 0)$$

where $a_T$ is a power temperature coefficient (%/°C), denoting the rate of PV efficiency decrease for every unit increase of temperature above 25°C

- **Solar PV tracking systems** are motorized mechanical tracking systems that orient panels so that light strikes perpendicular to the surface of the panels, by tuning the tilt angle, can lead to a 20-30% increase of energy output. However, they require significantly **higher installation** and **maintenance costs**.




**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 m2
- 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 PVs in the Water-Land-Energy-Food Nexus: Two prime applications

## Solar PVs in agriculture (Agrovoltaics)

## Solar PVs in mobile wastewater treatment units (Sewer Mining)