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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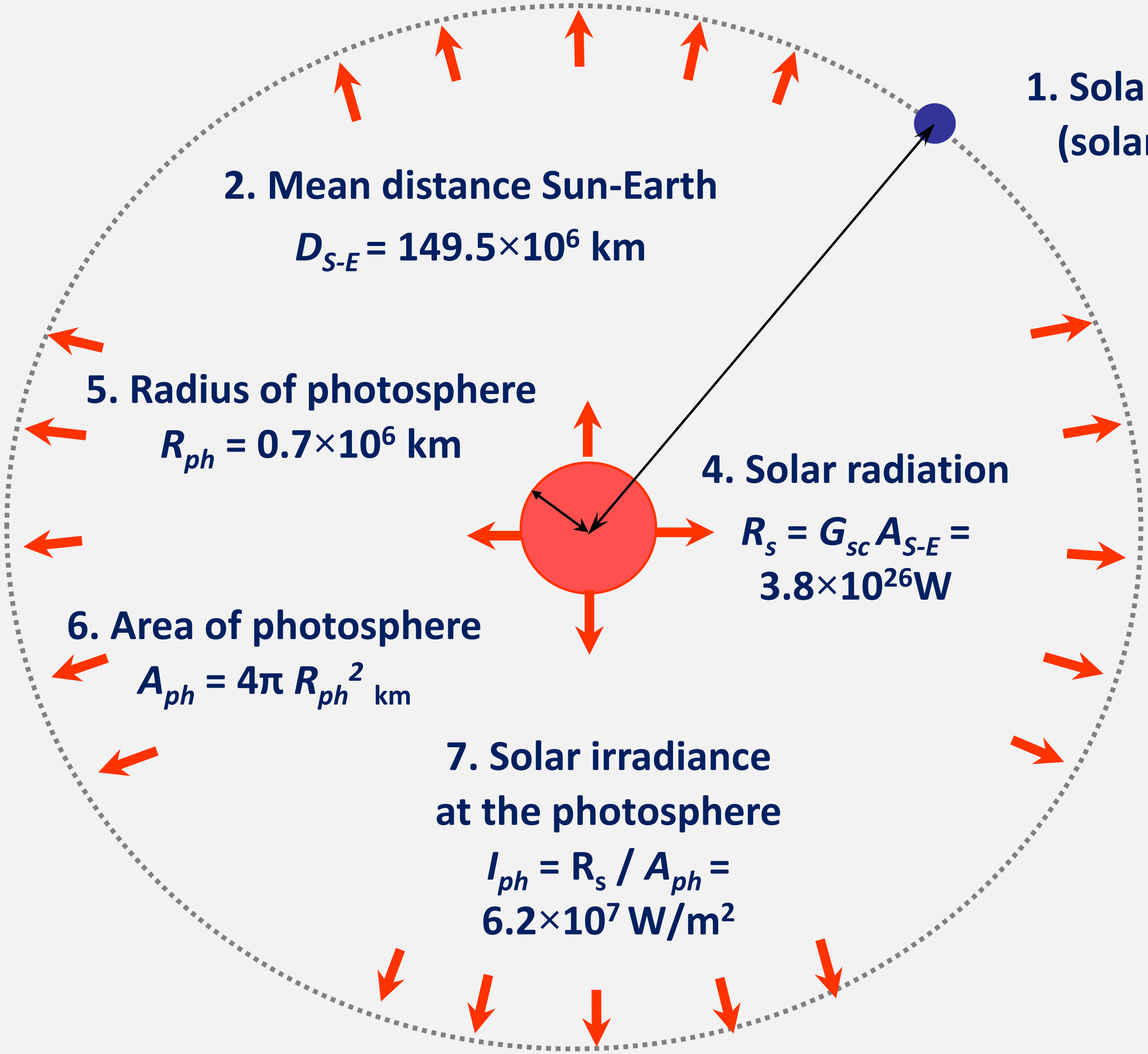
Academic year 2024-25

Solar physics: concepts and quantities



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

3. Area of Sun-Earth sphere: $A_{S\text{-}E} = 4\pi D_{S\text{-}E}^2 = 2.8 \times 10^{17}$ km^2

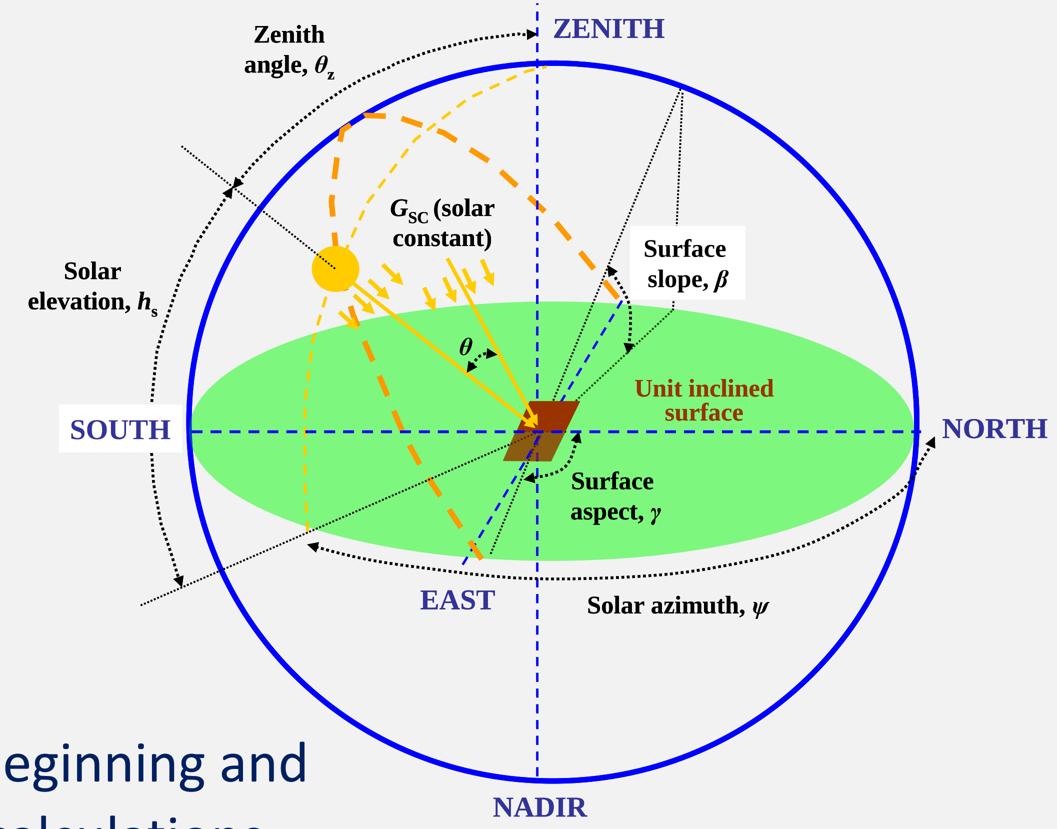
8. Power radiated from the photosphere per unit area: $I_{ph} = \sigma T^4$, where $T \approx 5778$ °K and $\sigma = 4.9 \times 10^{-6}$ kJ/m^2/K^4 (Stefan-Boltzmann constant)

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 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 the end of the specific period should be considered in the calculations.

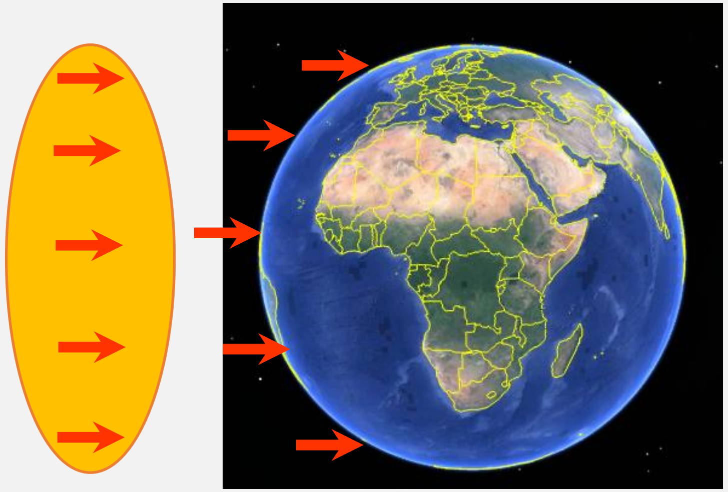


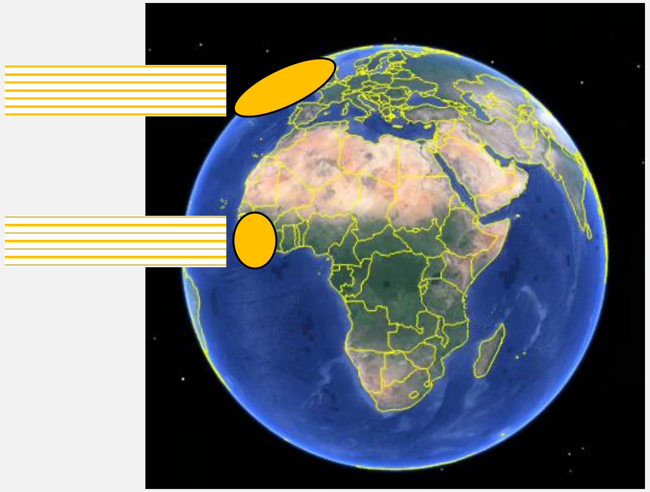
Extraterrestrial radiation: spatial variability

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

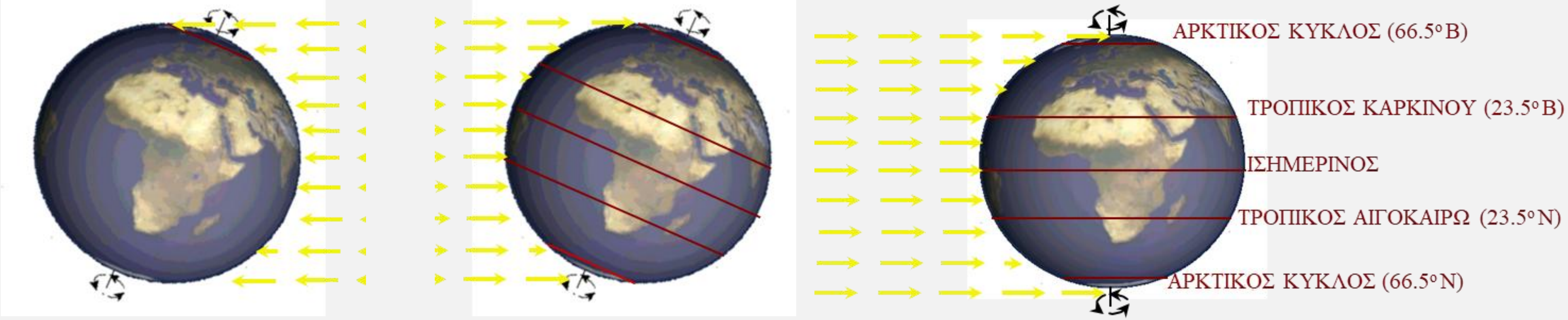
The solar constant (1367 W/m^2) only affects part of the Earth that corresponds to an area of πR^2





With respect to the equator (0°), the area at 45° latitude is 40% larger, it is double at 60° and it is six times larger at 80°

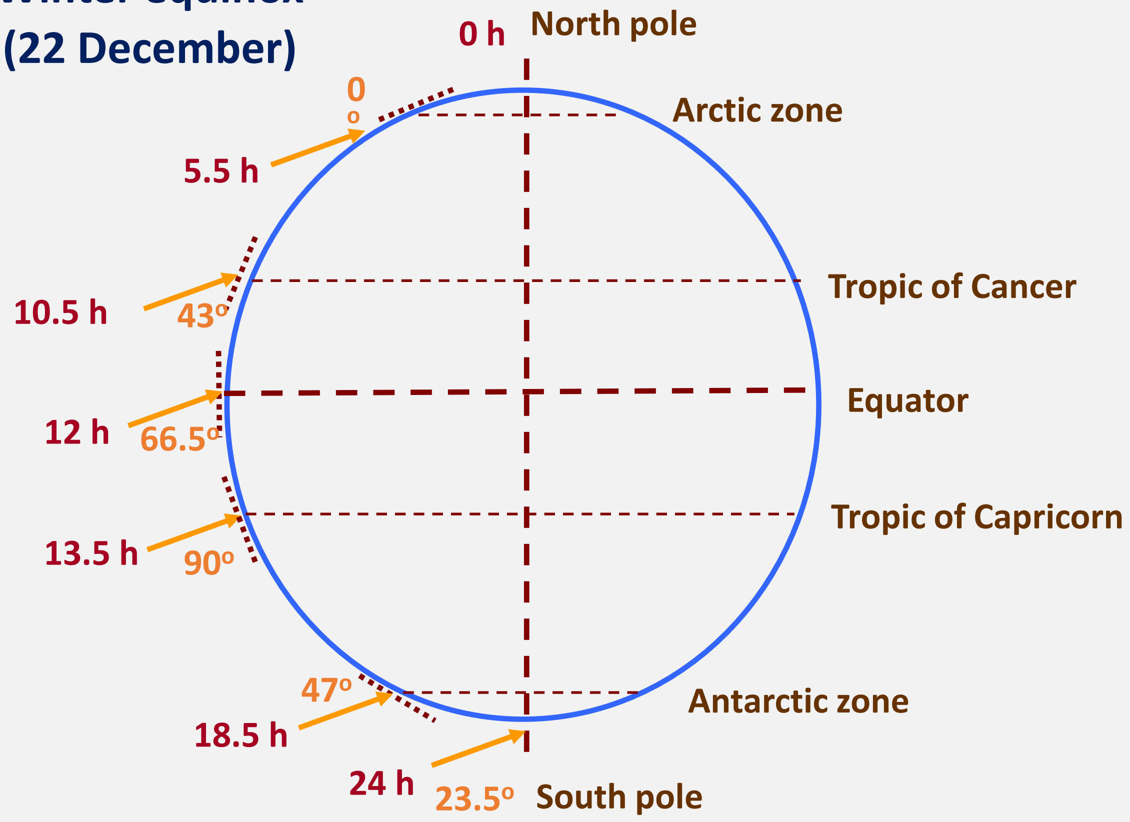
22/6 **Solstices** **22/12** **Equinoxes**

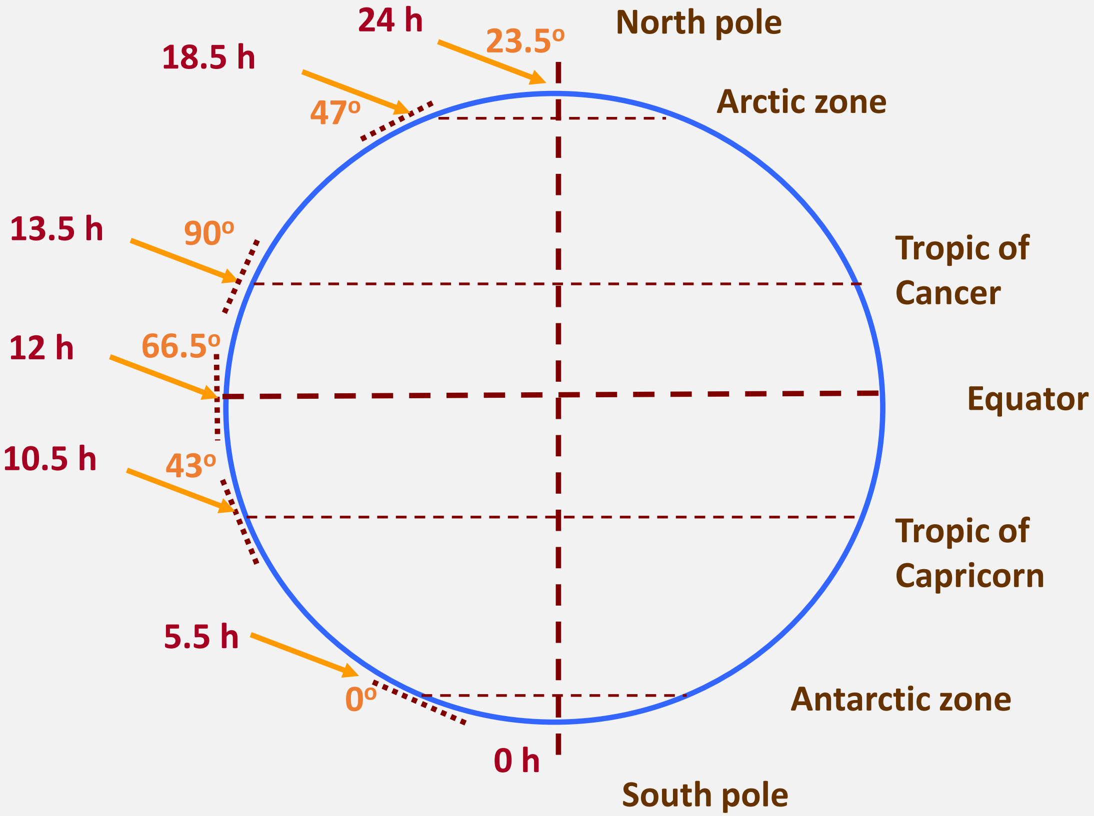


Extraterrestrial radiation: temporal variability

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

Winter equinox (22 December)





Summer equinox (22 June)

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 $n = N$.

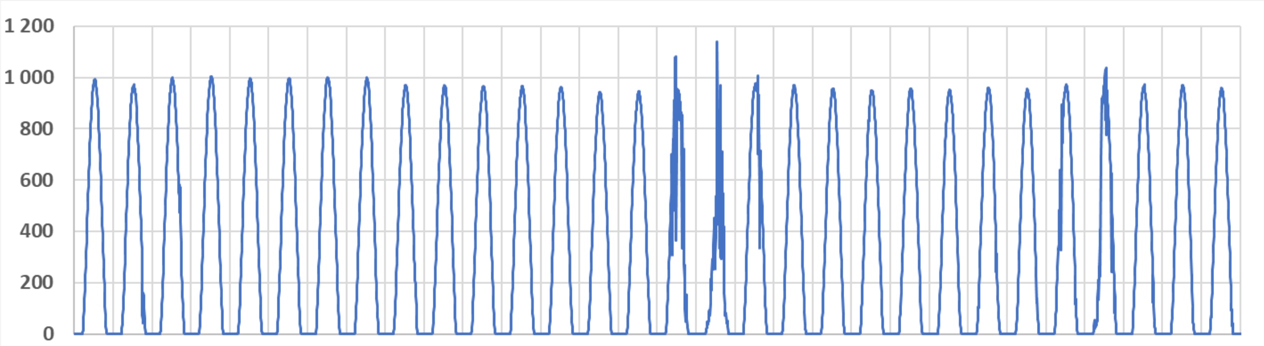
- Parameters a_s and b_s depend on the **location**, the **season** and the **state of the atmosphere** and they are related to the distribution of direct and diffuse radiation; if no actual solar radiation data are available for their calibration against local observations, the use of typical values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

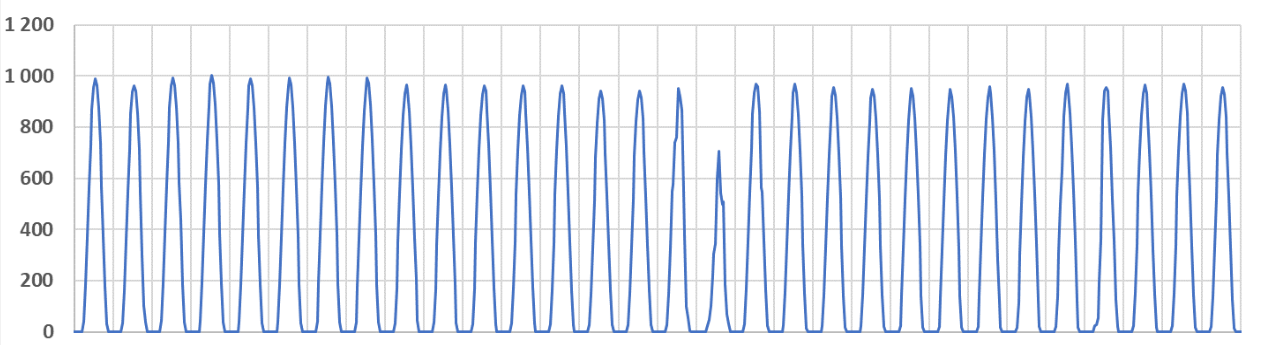
φ (°)	36	38	40	42	44	46
Ιουλ	14.2	14.4	14.5	14.7	14.9	15.2
Αυγ	13.4	13.5	13.6	13.7	13.8	13.9
Σεπ	12.2	12.2	12.3	12.3	12.3	12.3
Οκτ	11.1	11.0	10.9	10.8	10.7	10.7
Νοε	10.1	9.9	9.8	9.6	9.4	9.2
Δεκ	9.6	9.4	9.2	9.0	8.8	8.5

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

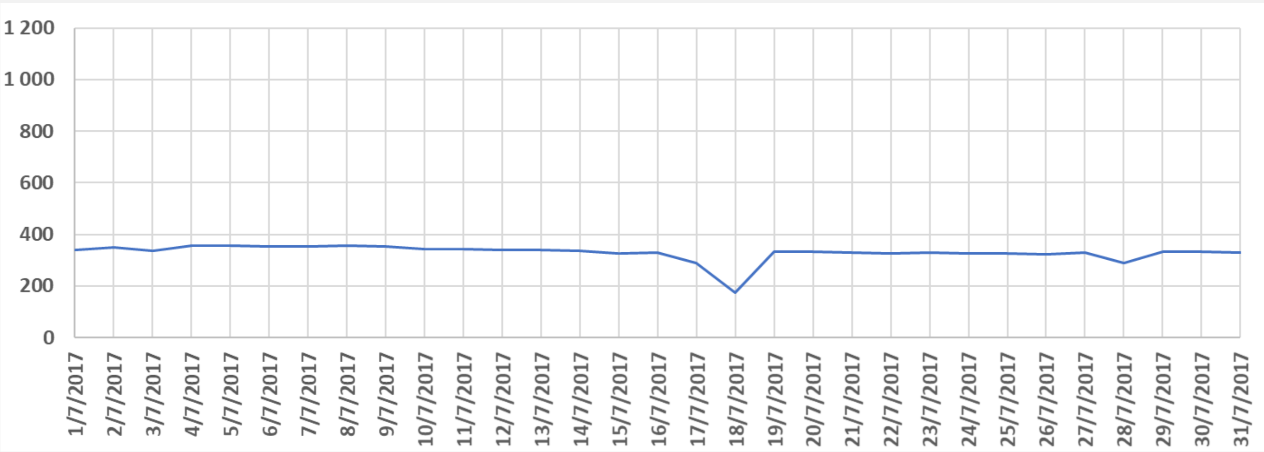
Variability of solar radiation (W/m^2) across scales



10-minute solar radiation at Aktion (July 2017)

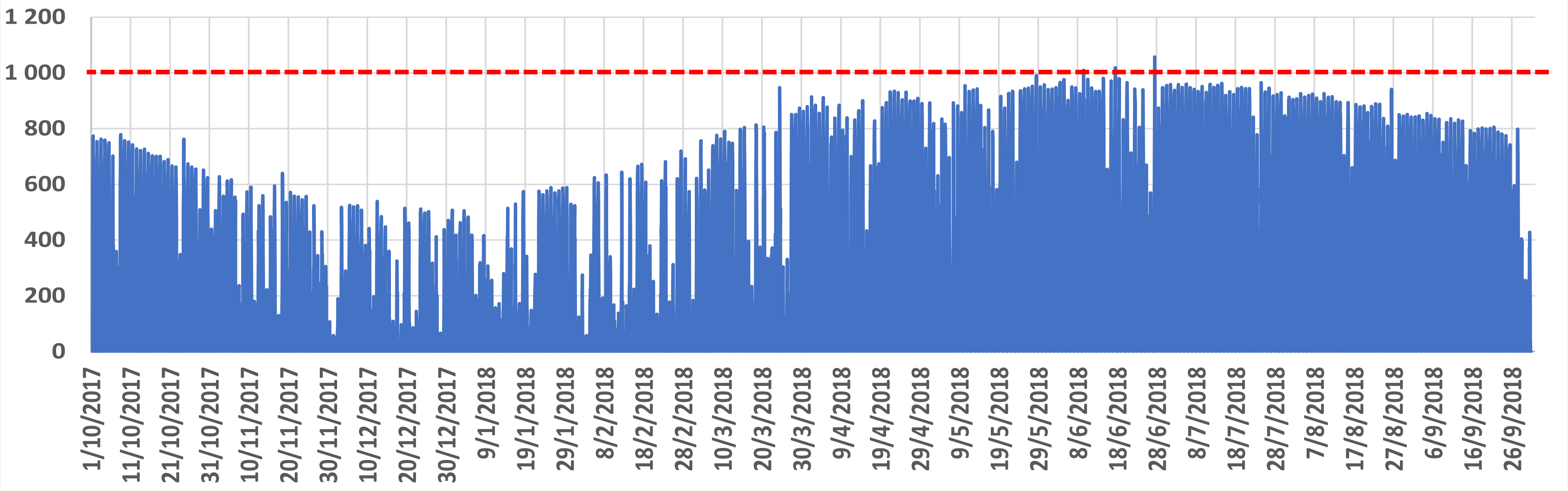


Mean hourly solar radiation at Aktion (July 2017)

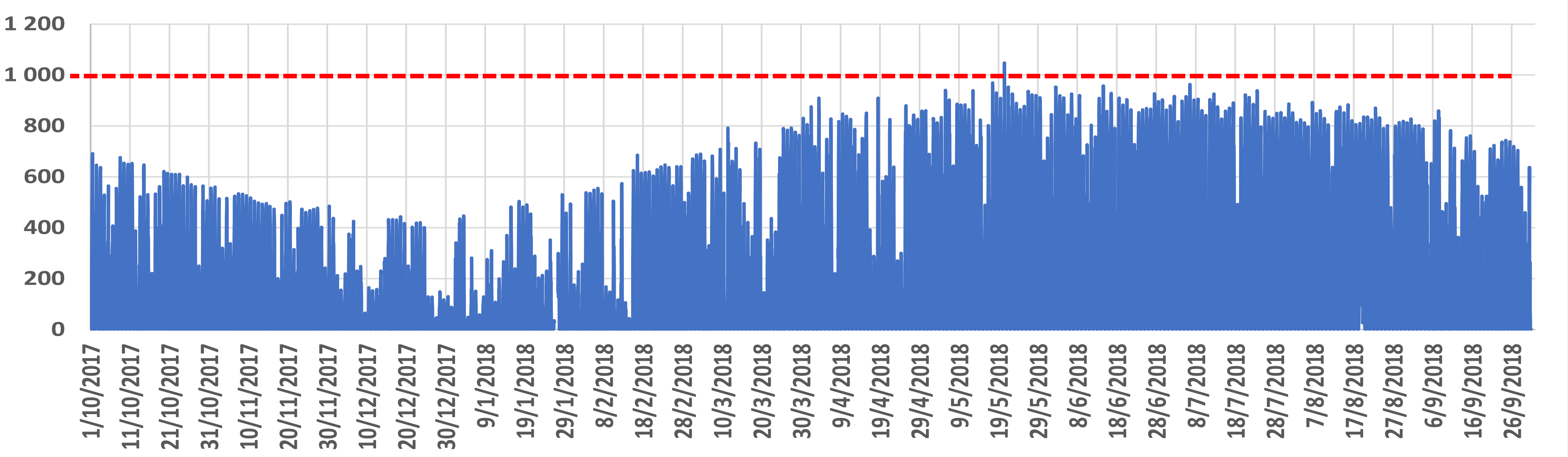


Mean daily solar radiation at Aktion (July 2017)

Spatiotemporal distribution

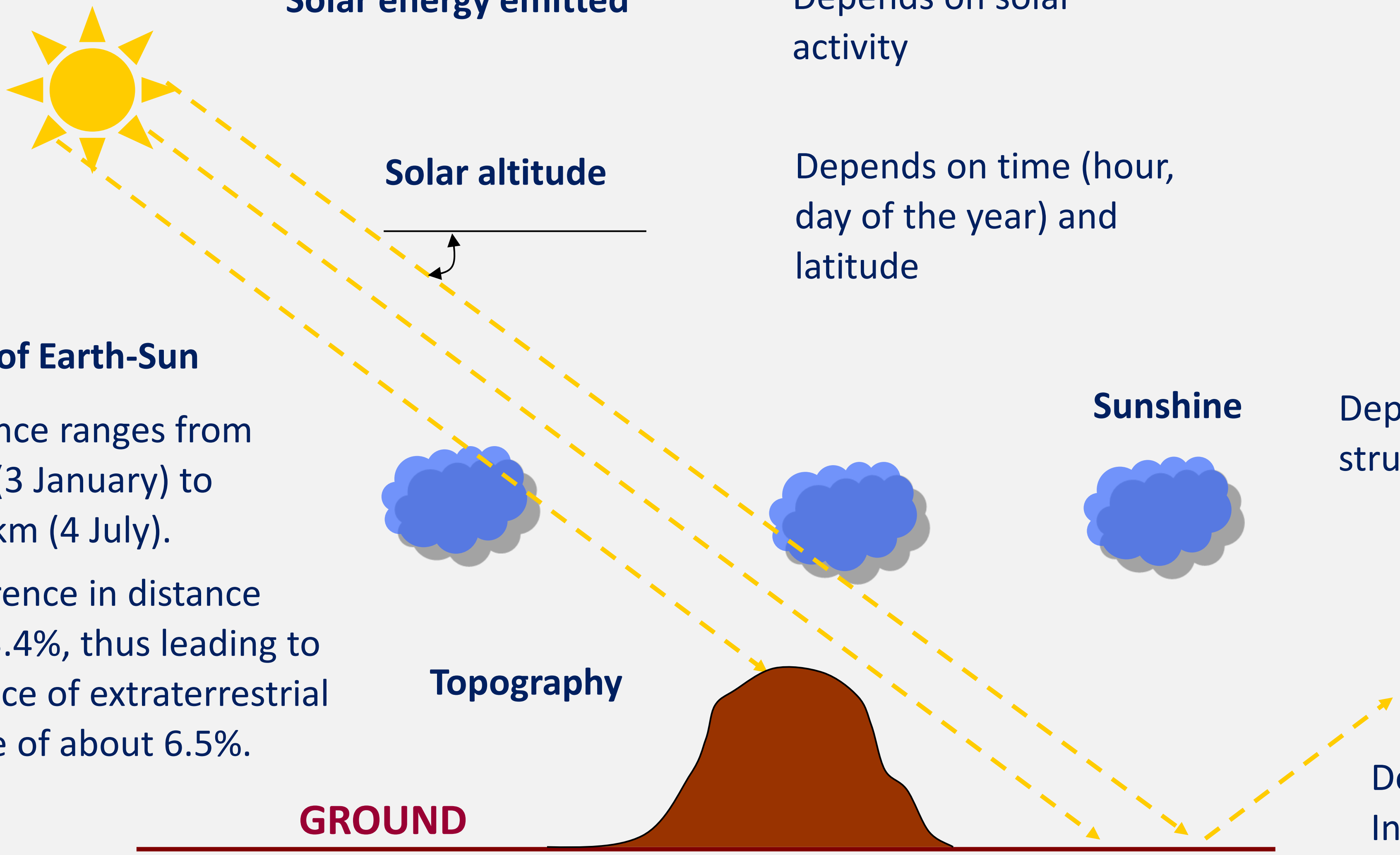


Aktion, Preveza (2017-18)
Mean annual: 194.8 W/m^2



Konitsa, Epirus (2020-21)
Mean annual: 173.0 W/m^2

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 147×10^6 (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

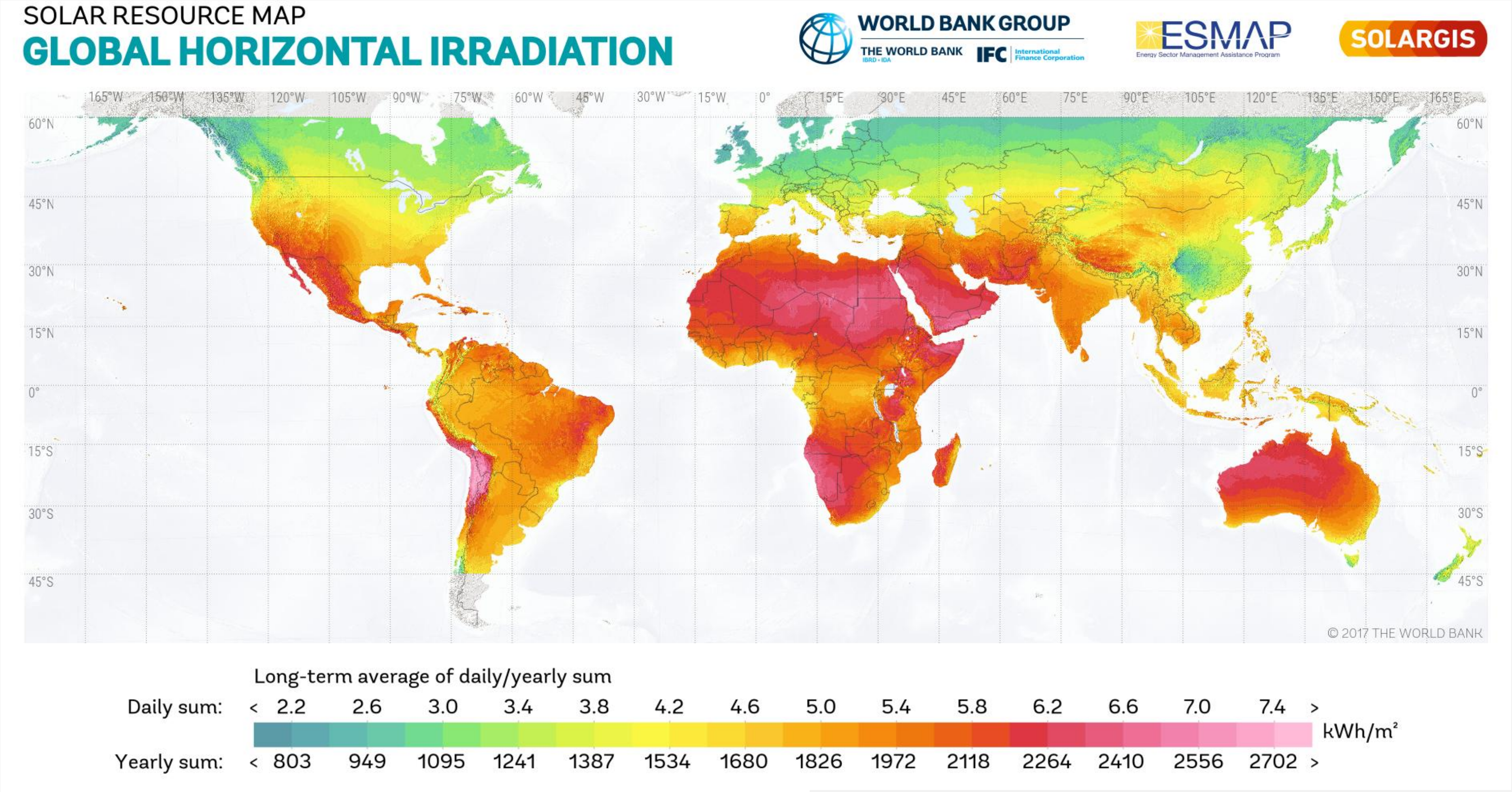
Topography

Surface albedo

Depends on 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**.



This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis.

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

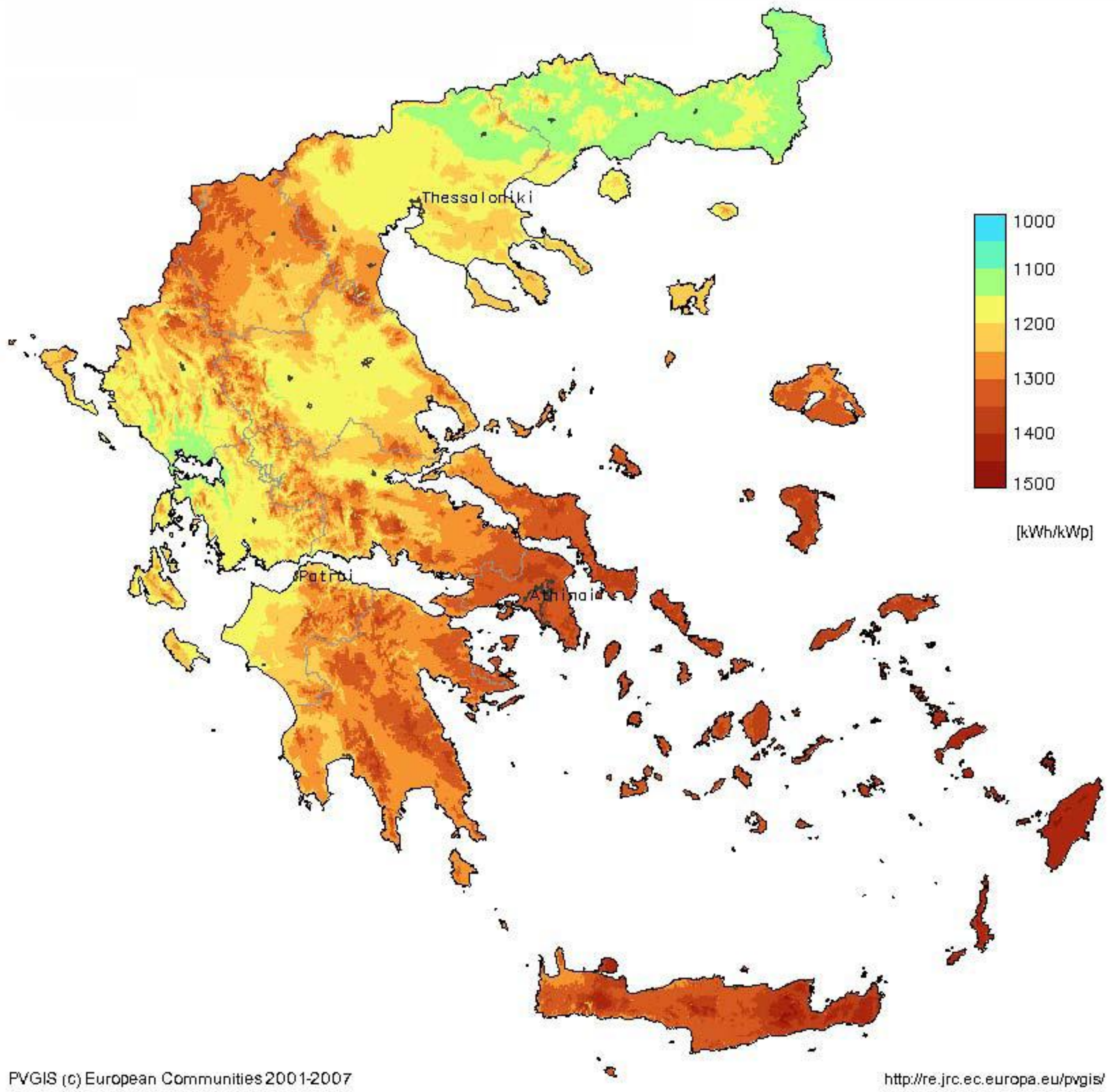
Solar (PV) energy in Greece

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

Photovoltaic energy in Greece*:**

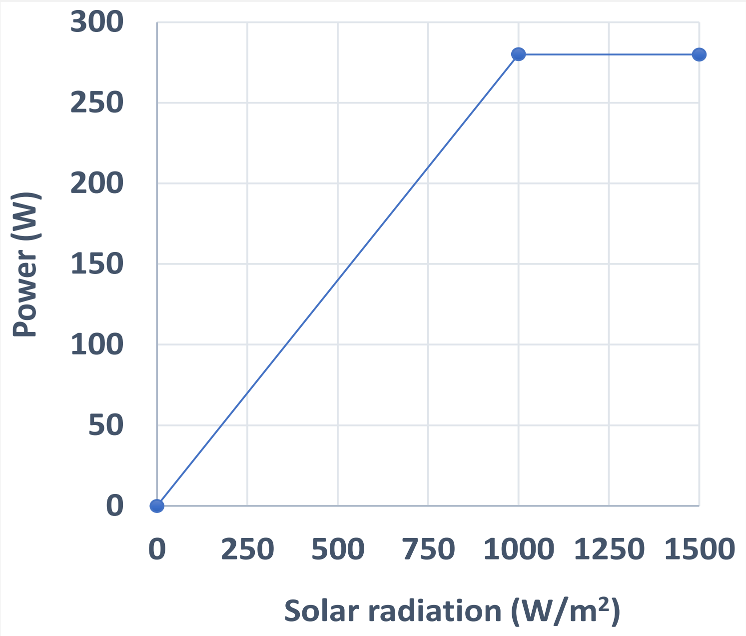
- Total capacity in 2007: 2 MW
- Total capacity in 2010: 199 MW
- Total capacity in 2020: 3288 MW
- Total capacity in 2022: 5273 MW
- Total capacity in 2023: 6369 MW
- Total capacity in 2024: 6768 MW
- Sharing in the electricity mix: 12.4% (6.50 TWh in 2022)
- Mean annual production: 1474 kWh/kW
  (parks 1500 kWh/kW, roofs: 1316 kWh/kW)
- Capacity factor: 1474/8760: 16.8%

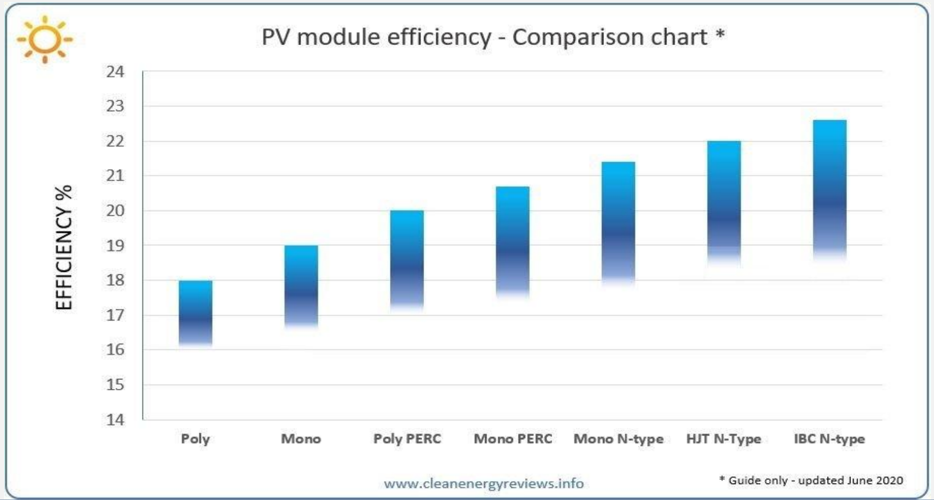
Global photovoltaic power potential by country:
https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf



Remarks on PV efficiency (1)

- Efficiency of first commercial panels (1990): 10-11%
- Over last decade, the average panel conversion efficiency increased from **15%** to over **20%**, resulting 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:
  - **photovoltaic cell efficiency**, depending on the cell design and silicon type;
  - **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), for temperature of 25°C, solar irradiance of 1000 W/m^2 and air mass of 1.5, for 2.74 h
- 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:

$$P_{hourly} = \begin{cases} n_{actual} \cdot G \cdot A_{panel}\,, & G < 1000\ W/\mathrm{m}^2 \\ \dfrac{n_{actual}}{n_{nom}} P_{nom}\,, & G \geq 1000\ W/\mathrm{m}^2 \end{cases}$$

where $\boldsymbol{n_{act}}$ is the adjusted PV efficiency against temperature effects, $\boldsymbol{n_{nom}}$ is the nominal efficiency, $\boldsymbol{G}$ (W/m^2) is the solar radiation and $\boldsymbol{T}$ (°C) is the temperature $\boldsymbol{A_{panel}}$ is the PV area (m^2), and $\boldsymbol{P_{nom}}$ 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:

$$n_{actual} = \begin{cases} n_{nom}\,, & T_c \leq T_{ref} \\ n_{nom}\left[1 - a_{\mathcal{T}} \cdot \left(T_c - T_{ref}\right)\right], & T_c > T_{ref} \end{cases}$$

where $\boldsymbol{a_T}$ is a power temperature coefficient (%/°C), denoting the rate of PV efficiency decrease for every unit increase in the ambient temperature above $\boldsymbol{T_{ref}}$ (usually considered 25 °C), and $\boldsymbol{T_c}$ refers to cell temperature calculated as follows:

$$T_c = T_{ambient} + \frac{NOCT - 20}{800} G$$

where $\boldsymbol{NOCT}$ is the nominal operating cell temperature, which is defined as the temperature of the cell in a standard reference environment (i.e., ambient temperature of 20 °C, solar irradiance of 800 W/m^2, and wind speed of 1 m/s).

Remarks on PV efficiency (3)

- PV efficiency is also influenced by several other local factors:
  - Humidity
  - Dust accumulation
  - Atmospheric particles (aerosols)
  - Ozone concentration
  - Water vapors

- **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, PV tracking systems require significantly **higher installation** and **maintenance costs**.

Example: Calculation of PV power production

- Installed power: 280 W
- Dimensions: 1640 × 990 × 46 mm
- Incident radiation: 1050 W/m^2
- Ambient temperature: 30 °C
- NOCT: 45 °C
- Temperature coefficient: 0.4 %/ °C

Calculation of efficiency

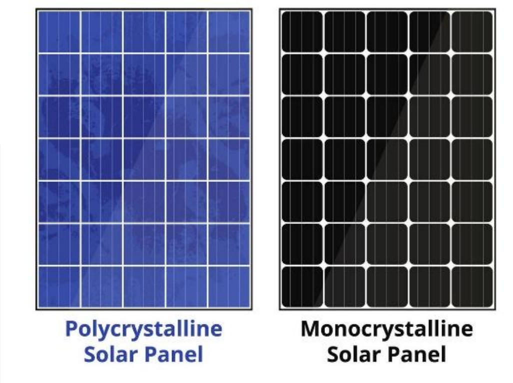
- Panel area: 1.64 × 0.99 = 1.624 m^2
- For 1000 W/m^2 of incoming solar radiation each panel receives 1624 W and produces 280 W of electric power
- Efficiency: 280/1624 = 17.2%

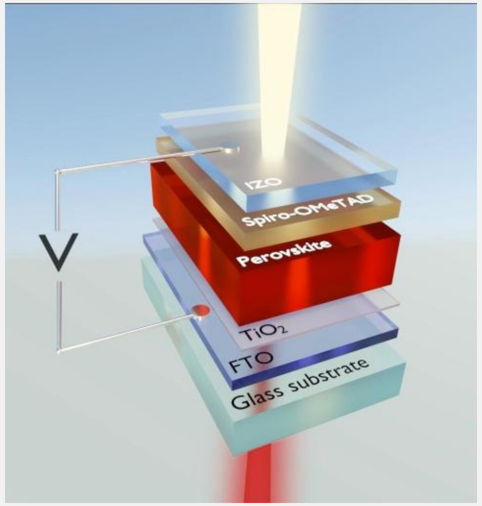
Adjustment of efficiency for temperature effects

- Cell temperature: 30 + (45-20) × 1050/800 = 62.8 °C
- Adjusted efficiency: 17.2 × [1 – 0.004 × (62.8 – 25)] = 14.6%
- Power production: 14.6/17.2 × 280 = 237.7 W

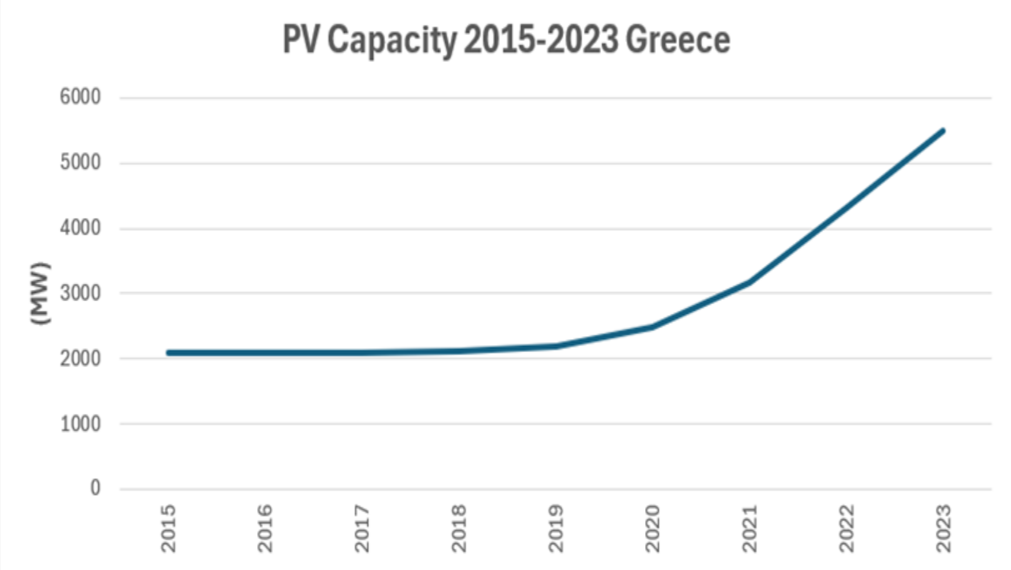
Types of PV technologies

- Conventional Panels
  - Monocrystaline silicon (typical efficiency ~ 20%)
  - Polycrystaline silicon (recycled materials, cheaper, lower efficiency)
- Bifacial PVs
  - Antireflective coatings to absorb radiation from both sides
  - High efficiency (~24%)
- Concentrator PVs
  - Use lenses or mirrors to transmit sunlight in specific spectral range for plant growth, while concentrating the rest for power generation
  - Require **direct sunlight** or **solar tracking**
  - Very high efficiency (>40% in multi-junction cells)
  - High manufacturing cost
- Semi-transparent PVs
  - Absorb specific bands of light (e.g., blue and green light, allowing for red to be absorbed by crops)
  - Lower efficiency
- Perovskite PVs
  - High efficiency (>25%)
  - Low cost
  - Unstable (highly affected by temperature, moisture and UV radiation)

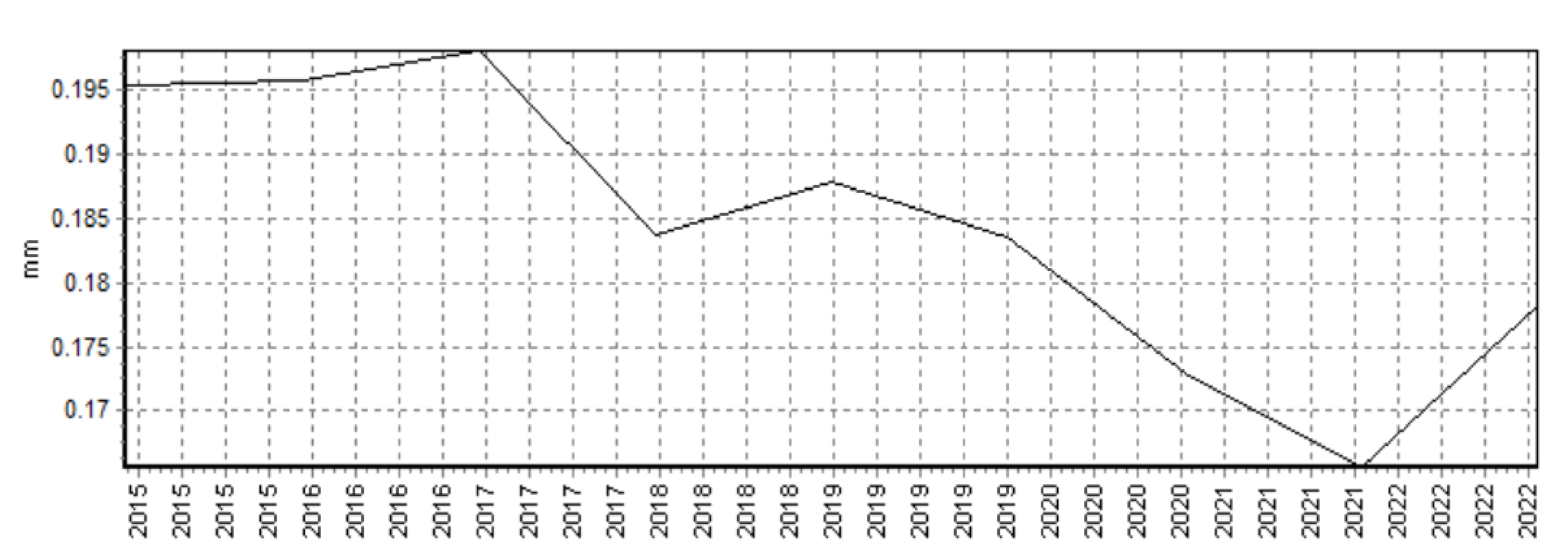




More installed capacity = more power (?)



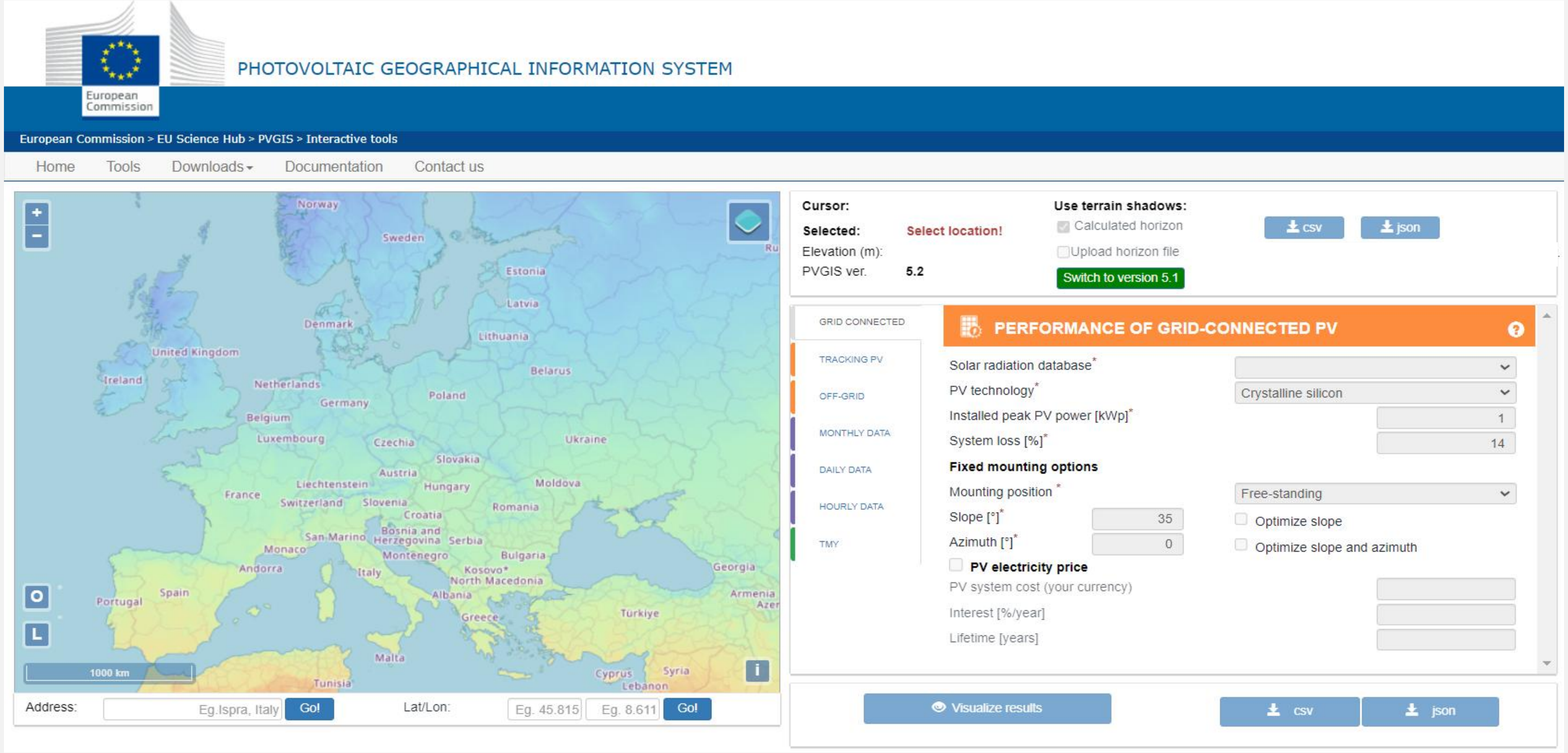
- Greece's National Energy and Climate Plan expects PV capacity to reach **22.4 GW by 2030** (6.77 GW in 2024, **230% increase**)
- However, the annual capacity factor of PVs across **Greece peaked in 2017** and has only been **decreasing** ever since (with the exception of 2022-2023), meaning that PV installations have been **underperforming**.
- Is it beneficial (both in technical and economic terms) to **uncontrollably increase renewable energy penetration** without appropriate **regulation and storage**?



Source: Tsoloudi, 2025. https://www.itia.ntua.gr/en/docinfo/2535/

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/

Newer release: https://pvgis.com/

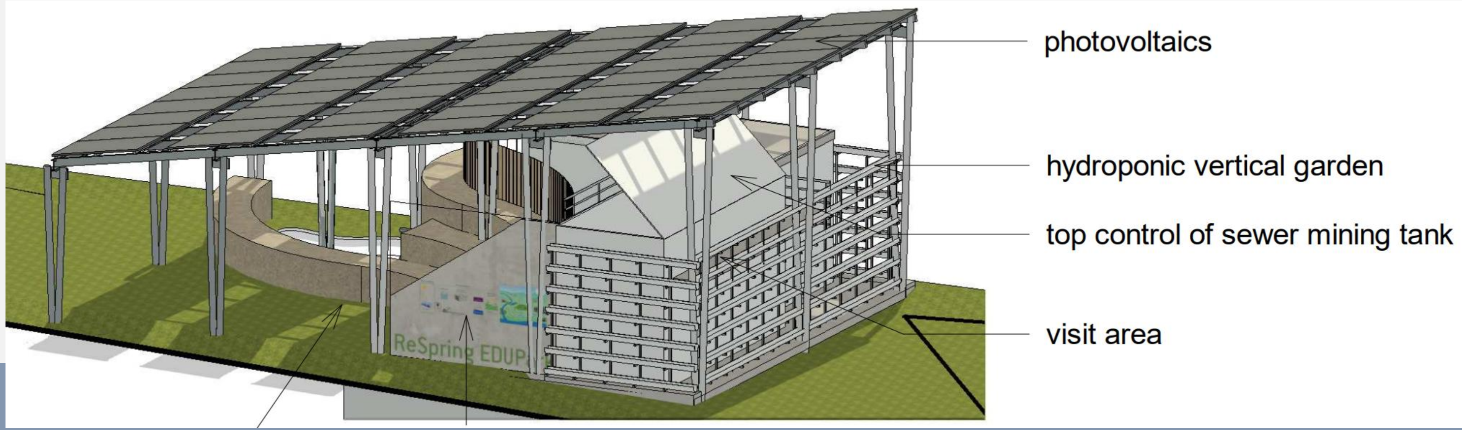
Information about the database and the processing of the satellite data can be found here:

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

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)



Agrovoltaics

- Agrovoltaics (AVs) offer a **synergistic approach** of land use that combines **agricultural production** with the **generation of renewable energy** through photovoltaic (PV) systems.

- Solar panels are installed above cropland or grazing areas, allowing dual land use, finding great applicability in countries with limited open space. The installation height and array distances vary based on crop type, irrigation techniques and machineries used.

- The contribution of PVs to the Water-Energy-Food-Land Nexus is pivotal, offering the following benefits:
  - Reduced irrigation needs (due to reduced evapotranspiration offered by PV shading)
  - Energy production that can be utilized in local scale
  - Enhanced PV performance due lower temperature (stemming from the microclimate created by the crops underneath)
  - Increased crop yield (increased crop exposure to direct sunlight can damage the plants' DNA)
  - Reduced soil erosion

Sewer Mining Units coupled with Photovoltaics

- Sewer mining (SM) technology is a **mobile wastewater treatment system** in containers, which extracts wastewater from local sewers, treat it directly and reuse at the point of demand in dense urban environments. The unit consists of a membrane bioreactor unit (MBR) and a UV disinfection unit and produces high quality reclaimed water for irrigation of green areas, aquifer recharge and other urban uses.

- The SM unit is very **efficient** and **stable** in terms of treatment, **requires limited space** (small footprint), **reduces waste** and increases availability of resources, **saves energy as water is extracted, treated & reused at the same location**

- The installation of PVs above the SM unit contributes to its **reduced grid dependence**, while also accounting for **aesthetics**, which are inextricably linked with **social acceptance**

- The Sewer Mining technology fully aligns with the principles of Circular Economy, allowing for water reuse, as well as the utilization of the treatment byproducts (i.e., sludge) as fertilizer and/or for energy recovery (through rapid composting)

Floatovoltaics: PVs over reservoirs & open channels