

# SOLAR RESOURCE



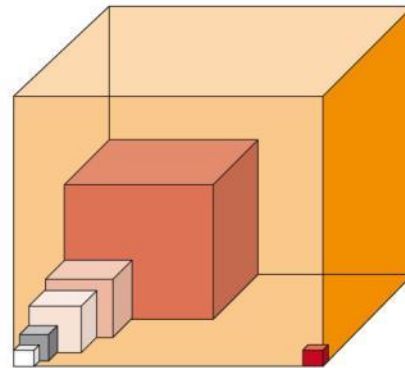
# Solar resource

- Radiation from the Sun
- Atmospheric effects
- Insolation maps
- Tracking the Sun
- PV in urban environment

# Solar resource

- Solar resource is immense
  - Human energy use:  $4.0 \times 10^{14}$  kWh/year
  - Solar resource on Earth's surface:  $5.5 \times 10^{17}$  kWh/year

## The physical potential of renewable energies



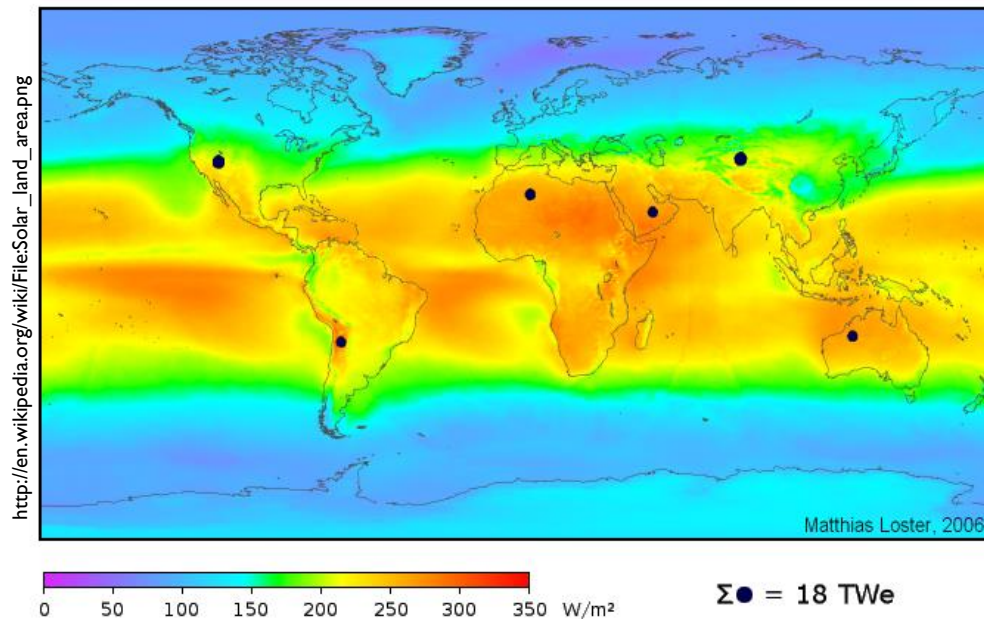
- Current annual Global Primary Energy Consumption (GPEC)
- Solar power (continents, 1,800 x GPEC)
- Wind energy (200 x GPEC)
- Biomass (20 x GPEC)
- Geothermal energy (10 x GPEC)
- Ocean and wave energy (2 x GPEC)
- Hydro energy (1 x GPEC)

Source: Nitsch F. "Technologische und energiewirtschaftliche Perspektiven erneuerbarer Energien, Deutsches Zentrum für Luft- und Raumfahrt (DLR)", 2007.

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# Solar resource

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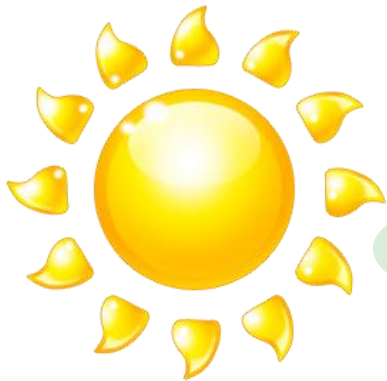
Local solar irradiance averaged over three years from 1991 to 1993 (24 hours a day) taking into account the cloud coverage available from weather satellites

Solar power systems covering the areas defined by the dark disks could provide more than the world's total primary energy demand (assuming a conversion efficiency of 8%).

# Solar resource

- Solar resource is **immense**
  - Human energy use:  $4.0 \times 10^{14}$  kWh/year
  - Solar resource on Earth's surface:  $5.5 \times 10^{17}$  kWh/year
- Solar resource is **global** and **democratic**
- Solar resource is relatively **constant** but depends on
  - atmospheric effects, including absorption and scattering
  - local variations in the atmosphere, such as water vapour, clouds, and pollution
  - latitude of the location
  - the season of the year and the time of day

# Solar resource

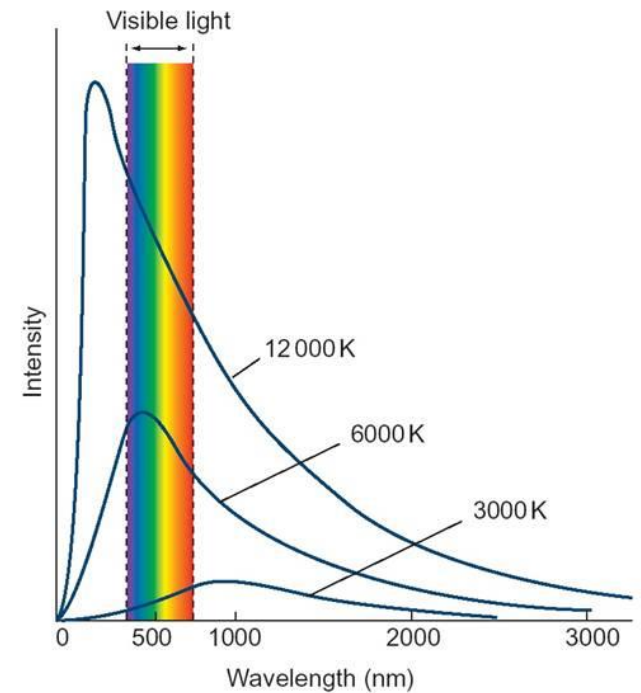


$$P_0 = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

Total radiative power (Stefan Boltzman)  $T=5762K$

Surface area of sun

Power radiated per unit area  
 $5.96 \times 10^7 \text{ W/m}^2$



# Solar resource



$$P_0 = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

Ratio of surface areas of the 2 spheres

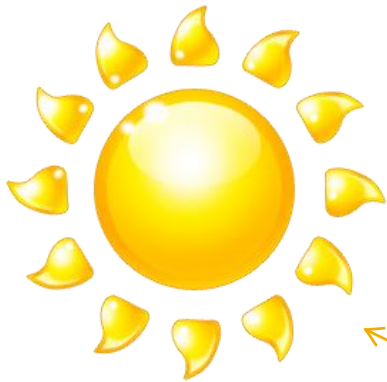
**Solar constant** average energy flux incident at the Earth's orbit:  
**1366 W/m<sup>2</sup>**

$$S = \frac{4\pi R_{sun}^2}{4\pi D^2} P_0$$

Distance Sun-Earth

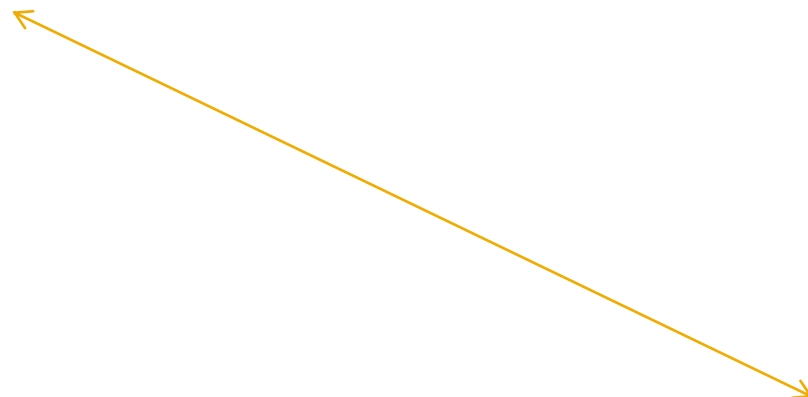


# Solar resource



$$P_0 = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

$R_{sun}$      $6.96 \times 10^5$  km  
 $D_{avg}$      $1.5 \times 10^8$  km  
 $R_{Earth}$     $6.35 \times 10^3$  km



$$S = \frac{4\pi R_{sun}^2}{4\pi D^2} P_0$$

Energy incident on Earth

Total area of Earth

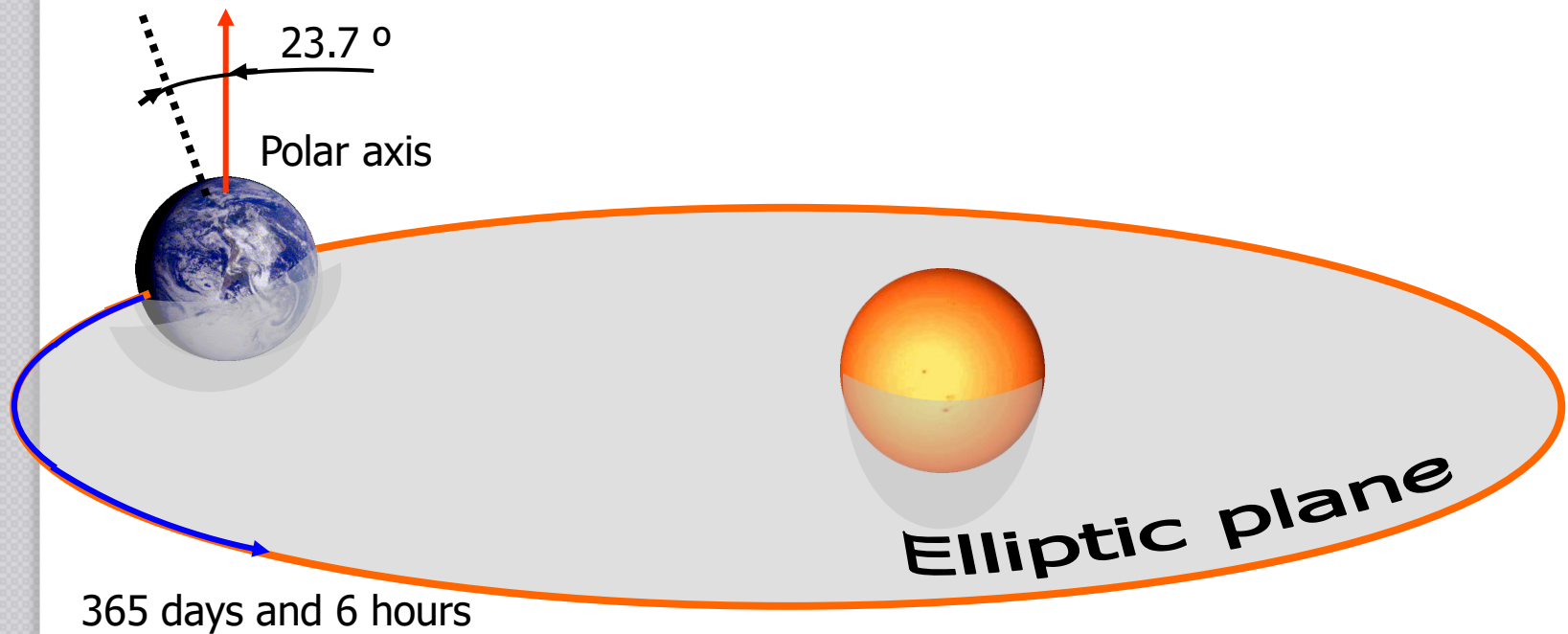
$$\frac{S \times \pi R_{Earth}^2}{4\pi R_{Earth}^2} = \frac{S}{4}$$

Average energy incident per unit area of surface of Earth:  
**342 W/m<sup>2</sup>**



# Solar resource

- Earth-Sun motion

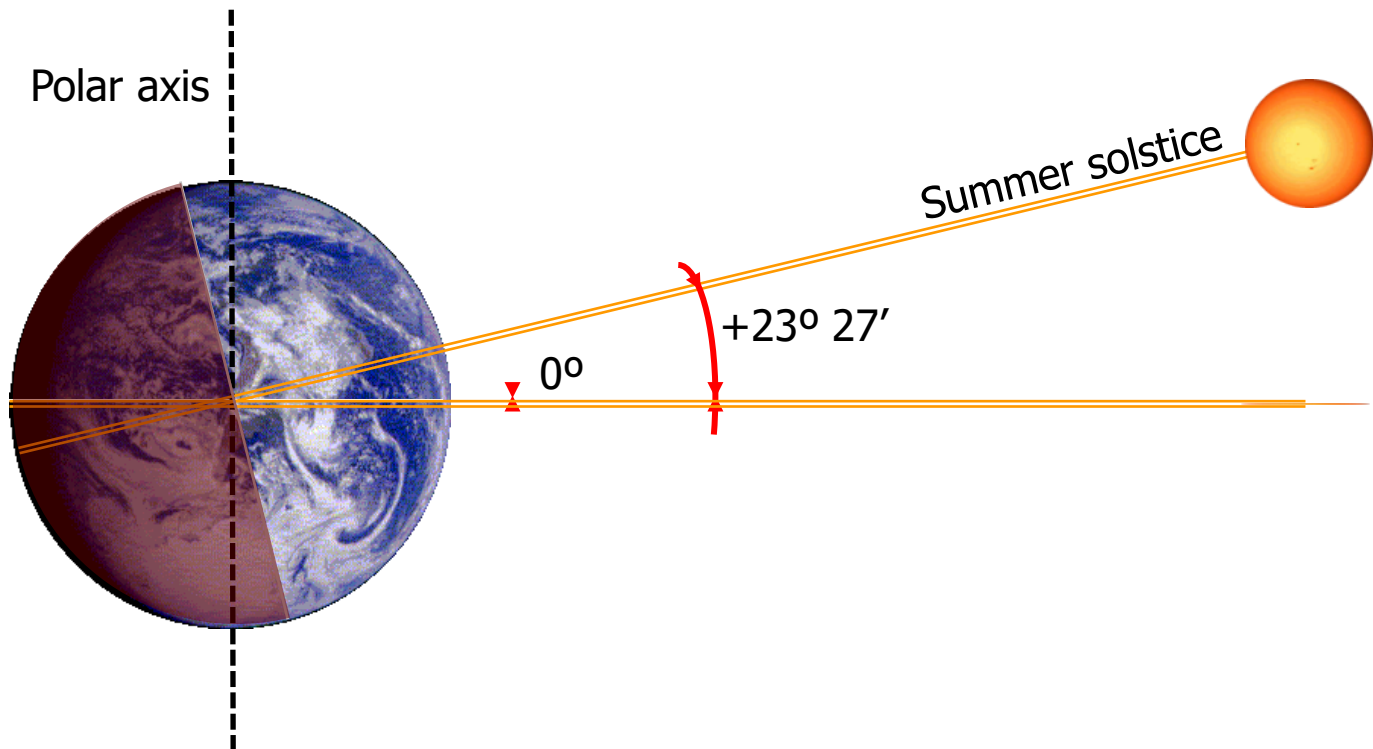


$$\frac{H}{S} = 1 + 0.033 \cos\left(\frac{360(n-2)}{365}\right)$$

$H$ (W/m<sup>2</sup>) is radiant power density outside the atmosphere;  $S$  is solar constant;  $n$  is day of the year

# Solar resource

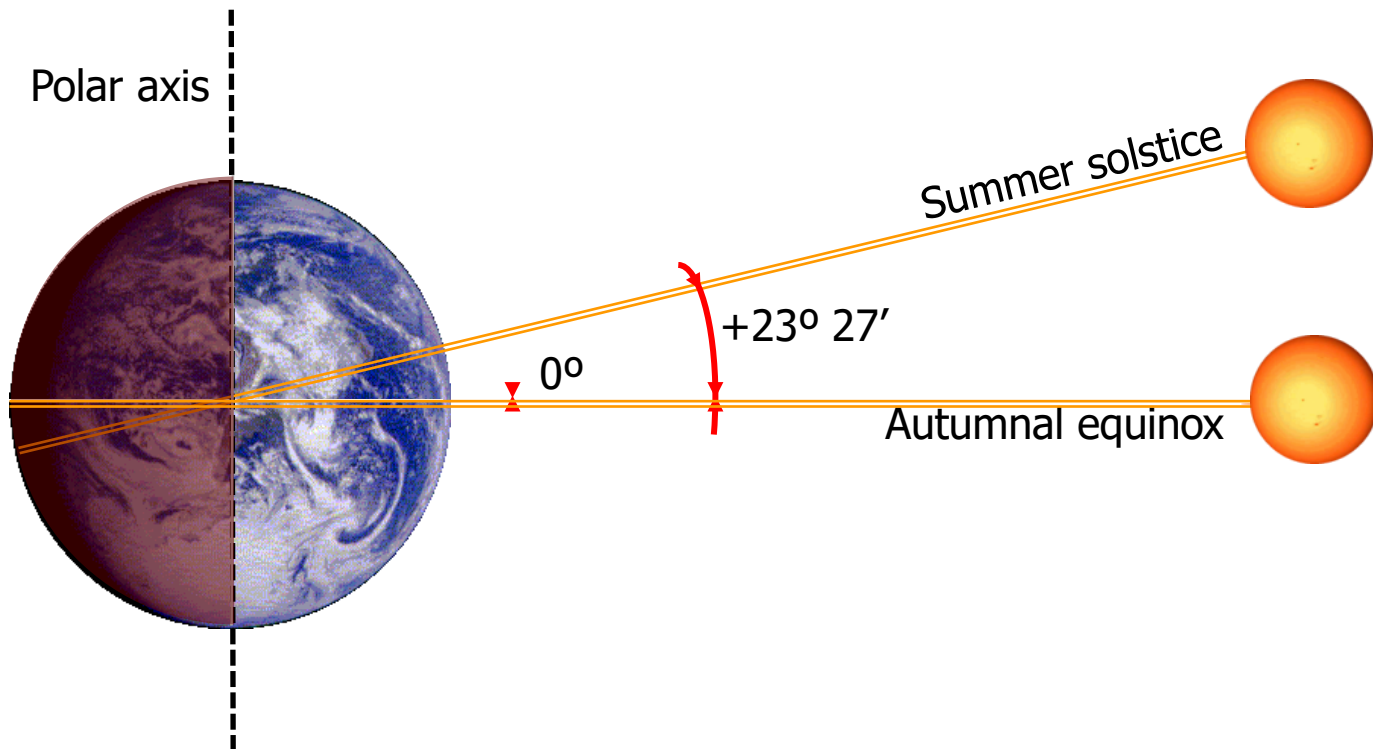
- Earth-Sun motion
  - **Solar declination:** angle between line joining centres of Earth and Sun and the equatorial plane



# Solar resource

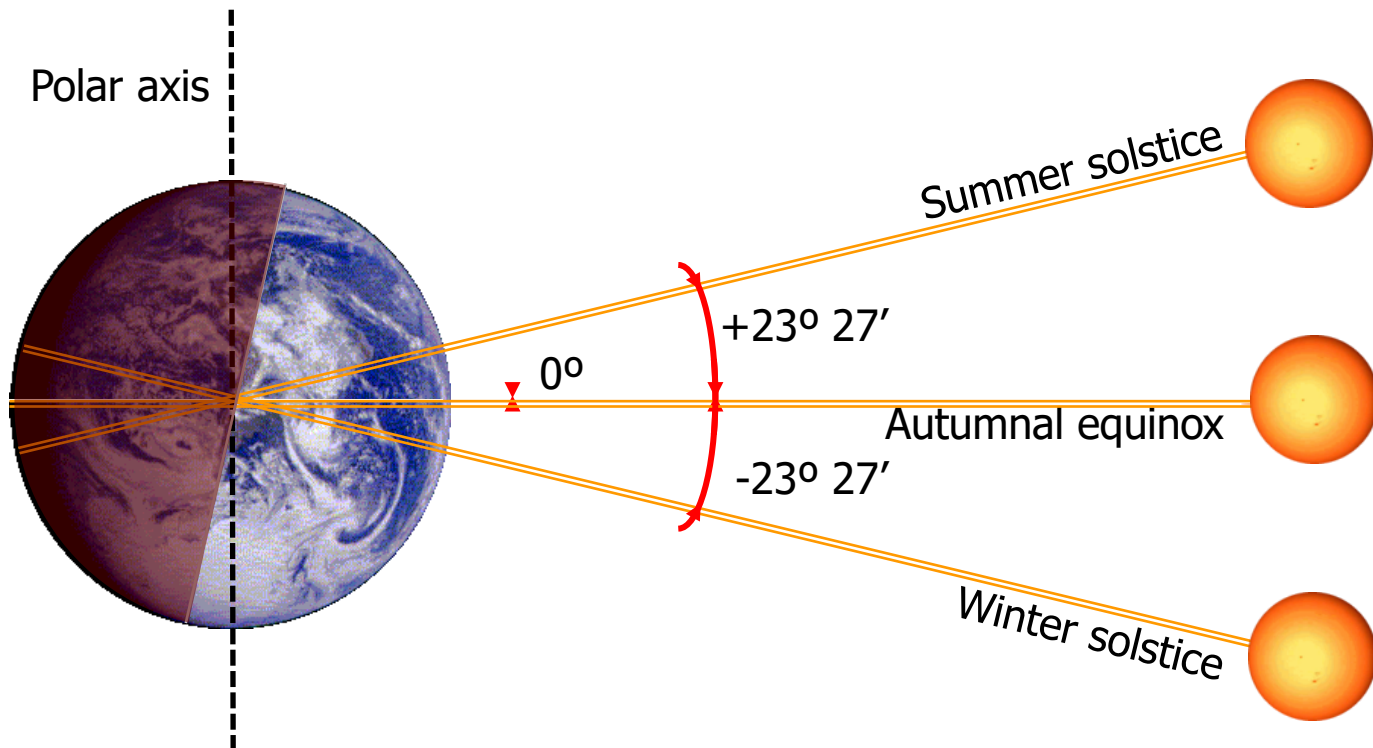
- Earth-Sun motion

- **Solar declination:** angle between line joining centres of Earth and Sun and the equatorial plane



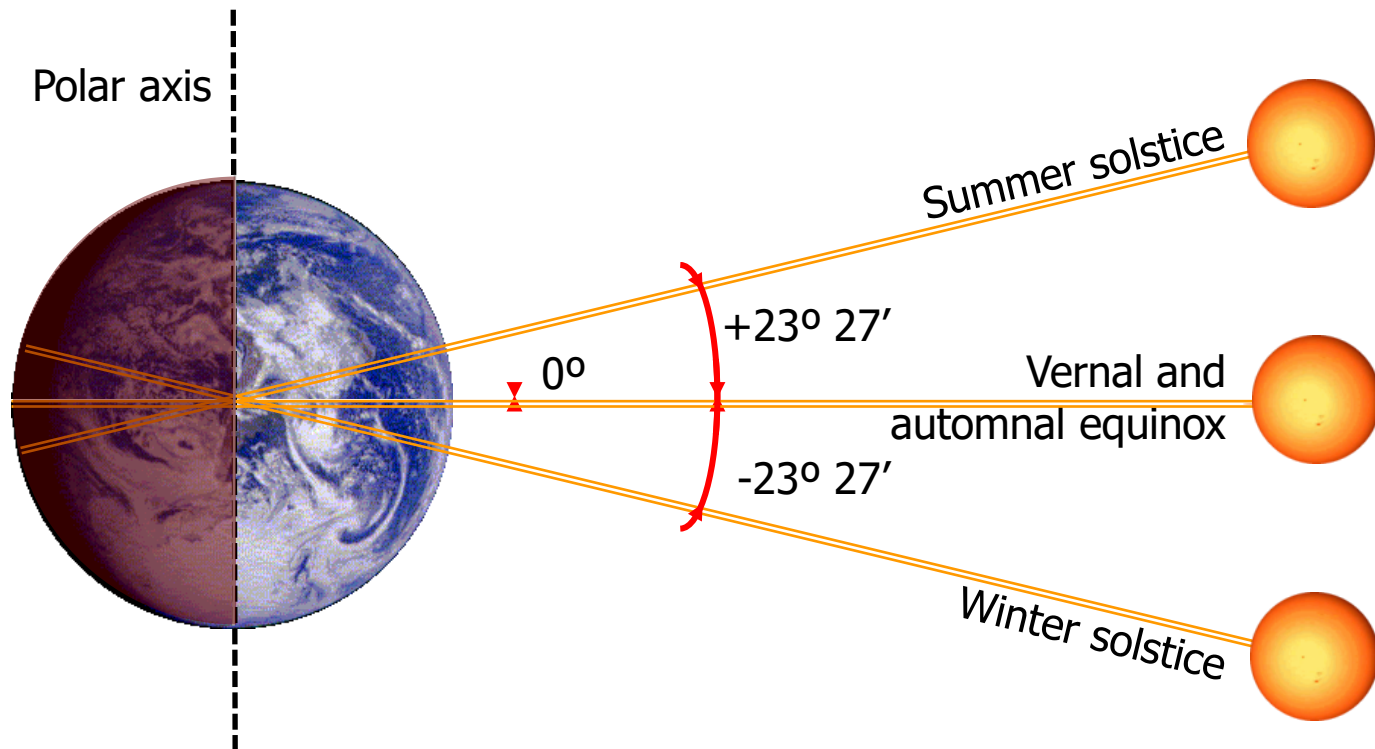
# Solar resource

- Earth-Sun motion
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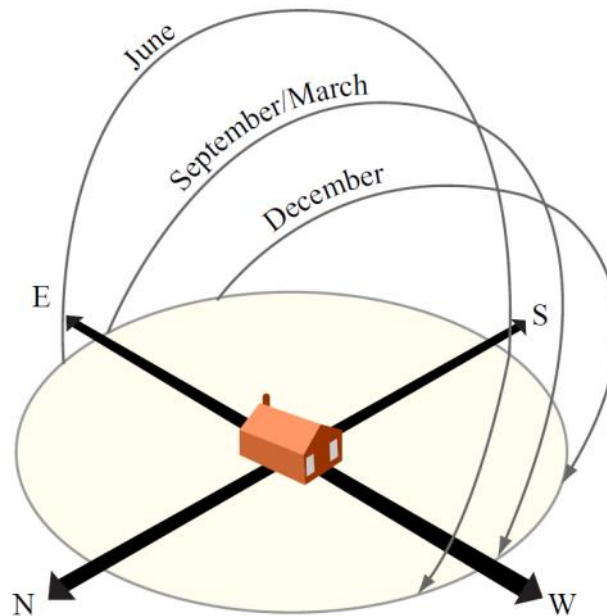
# Solar resource

- Earth-Sun motion
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# Solar resource

- Earth-Sun motion
  - **Solar declination:** angle between line joining centres of Earth and Sun and the equatorial plane



*Building orientation with the long axis facing south*

$$\delta = \pi \frac{23.45}{180} \sin\left(2\pi \frac{284 + n}{365}\right)$$

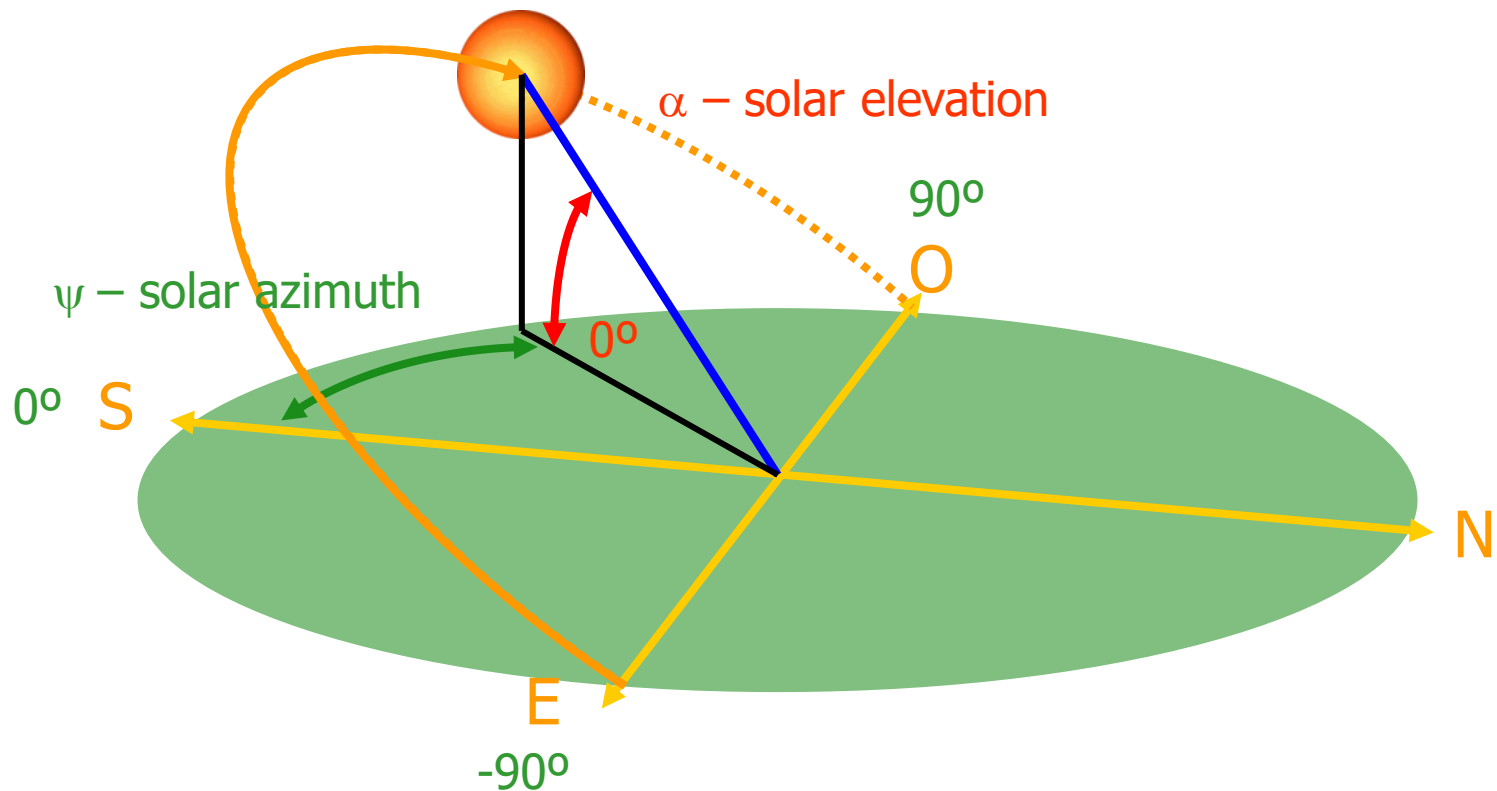
Declination in radians; n is the number of the day (Jan 1st = 1)

# Solar resource

- Earth-Sun motion

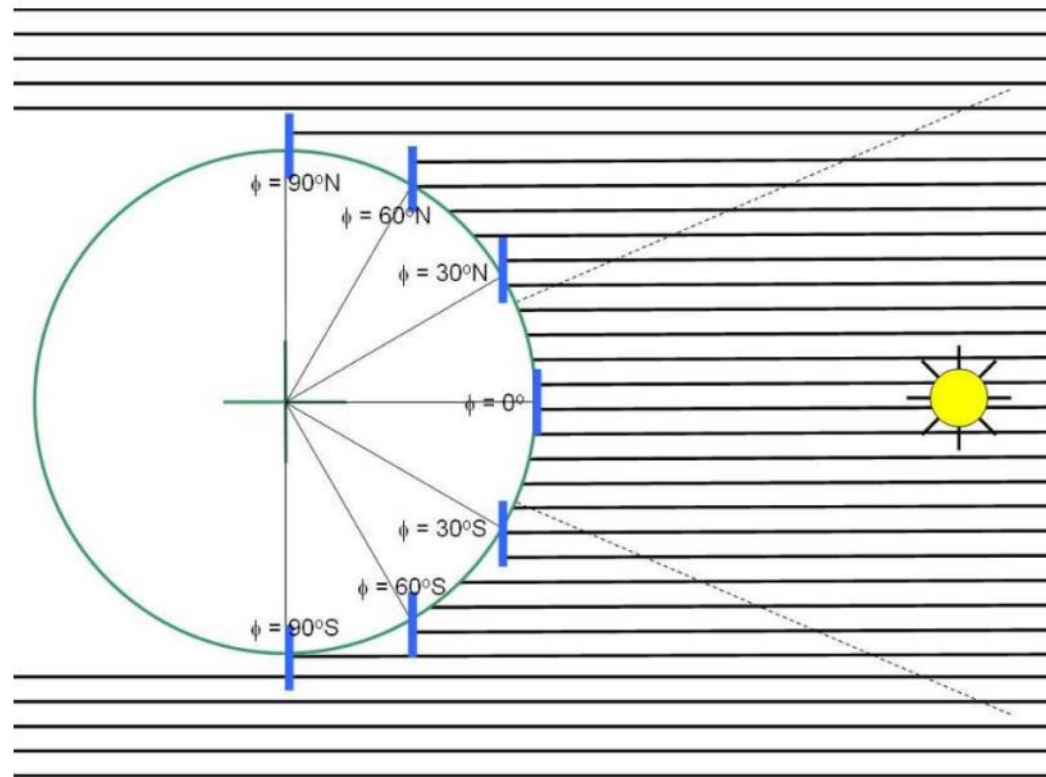
$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi$$

$$\cos \psi = \frac{\sin \alpha \sin \phi - \sin \delta}{\cos \alpha \cos \phi}$$



# Solar resource

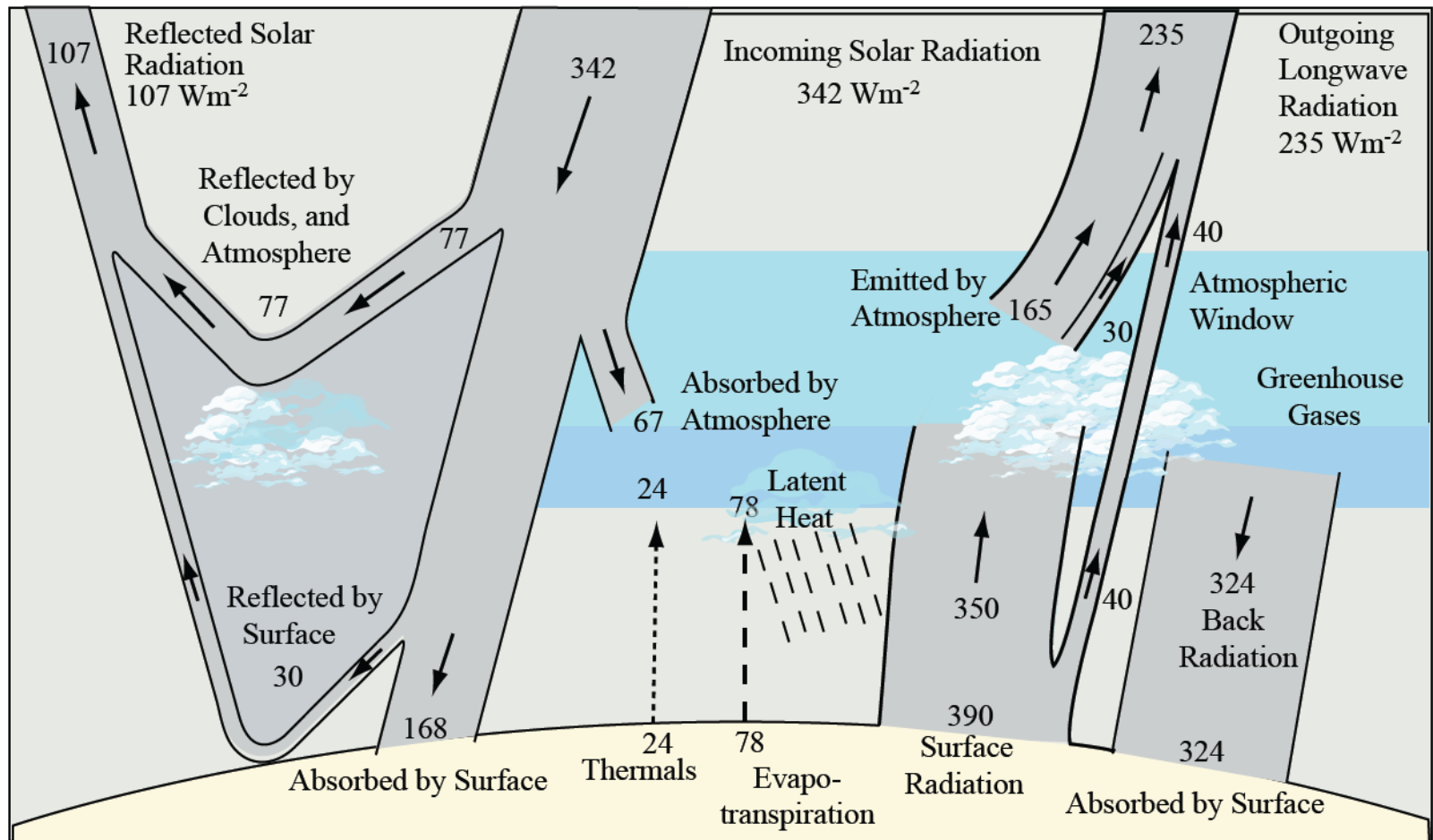
- Optimum orientation: facing south (north in the southern hemisphere)
- Optimum inclination: local latitude – but not quite





# Solar resource

## Atmospheric effects



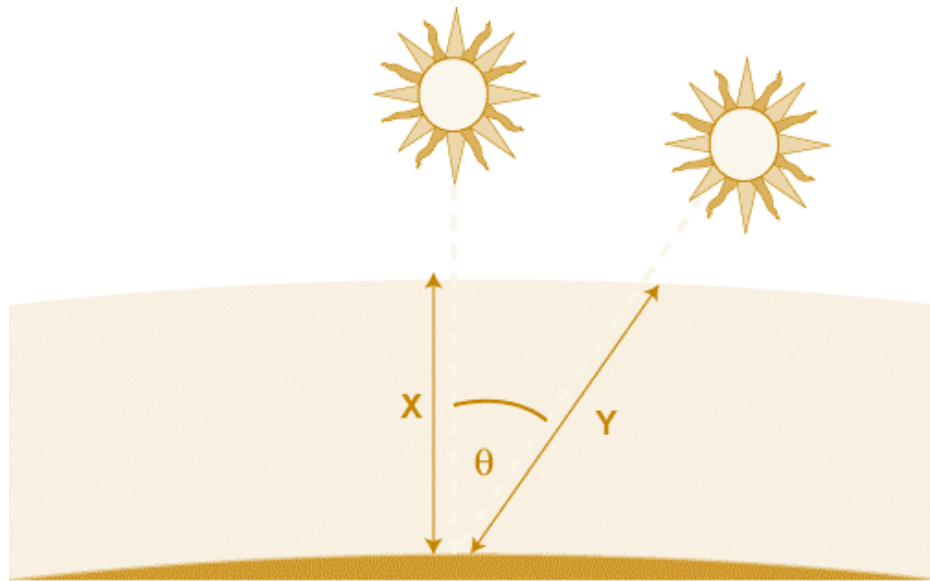
# Solar resource

## **Atmospheric effects** on solar radiation at the Earth's surface:

- a **reduction in the power** of the solar radiation due to absorption, scattering and reflection in the atmosphere;
- a **change in the spectral content** of the solar radiation due to greater absorption or scattering of some wavelengths;
- the **introduction of a diffuse** or indirect component into the solar radiation; and
- local variations in the atmosphere (such as water vapour, clouds and pollution) which have additional effects on the incident power, spectrum and directionality.

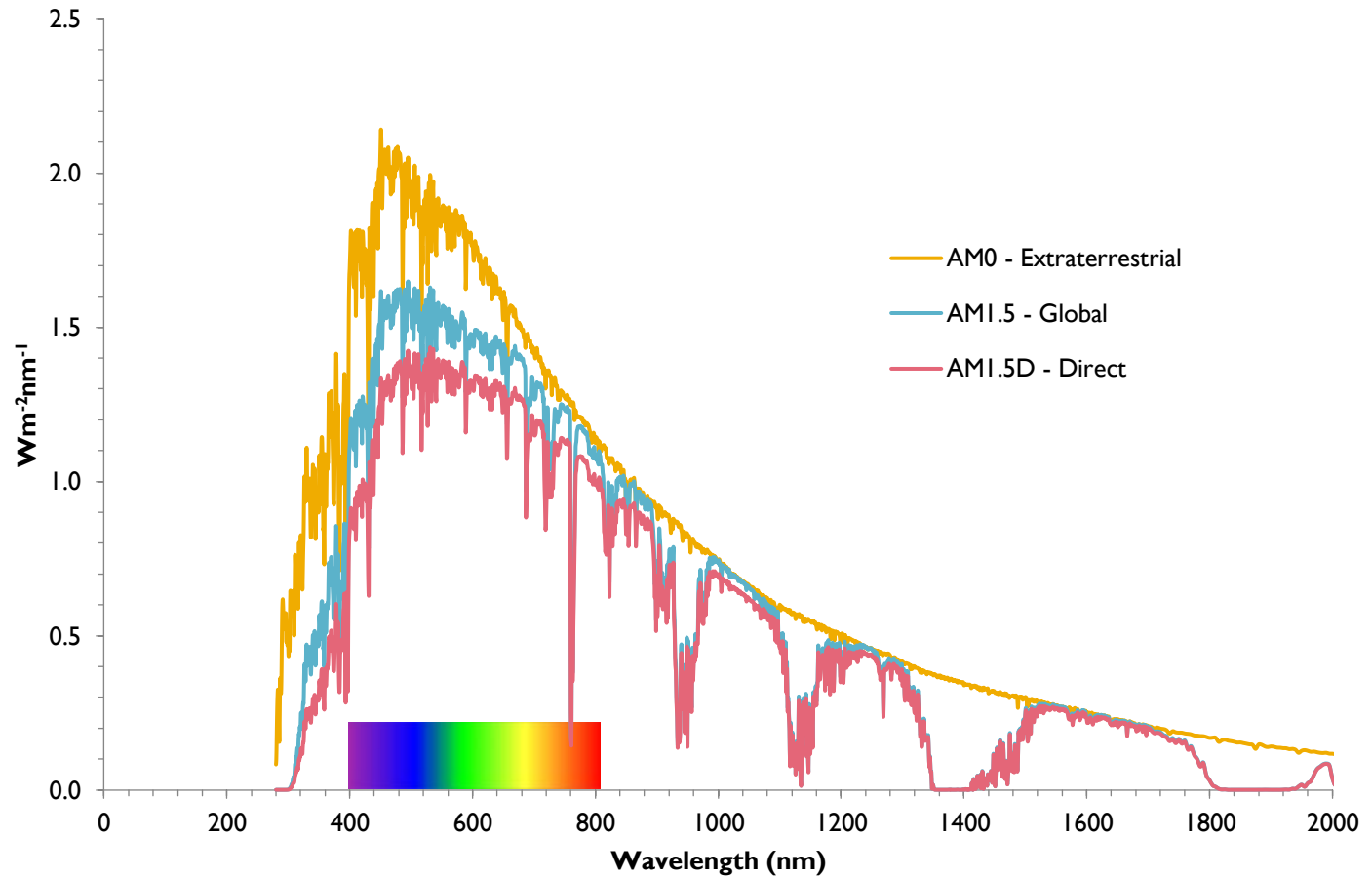
# Solar resource

- **Air Mass** is a measure of the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust



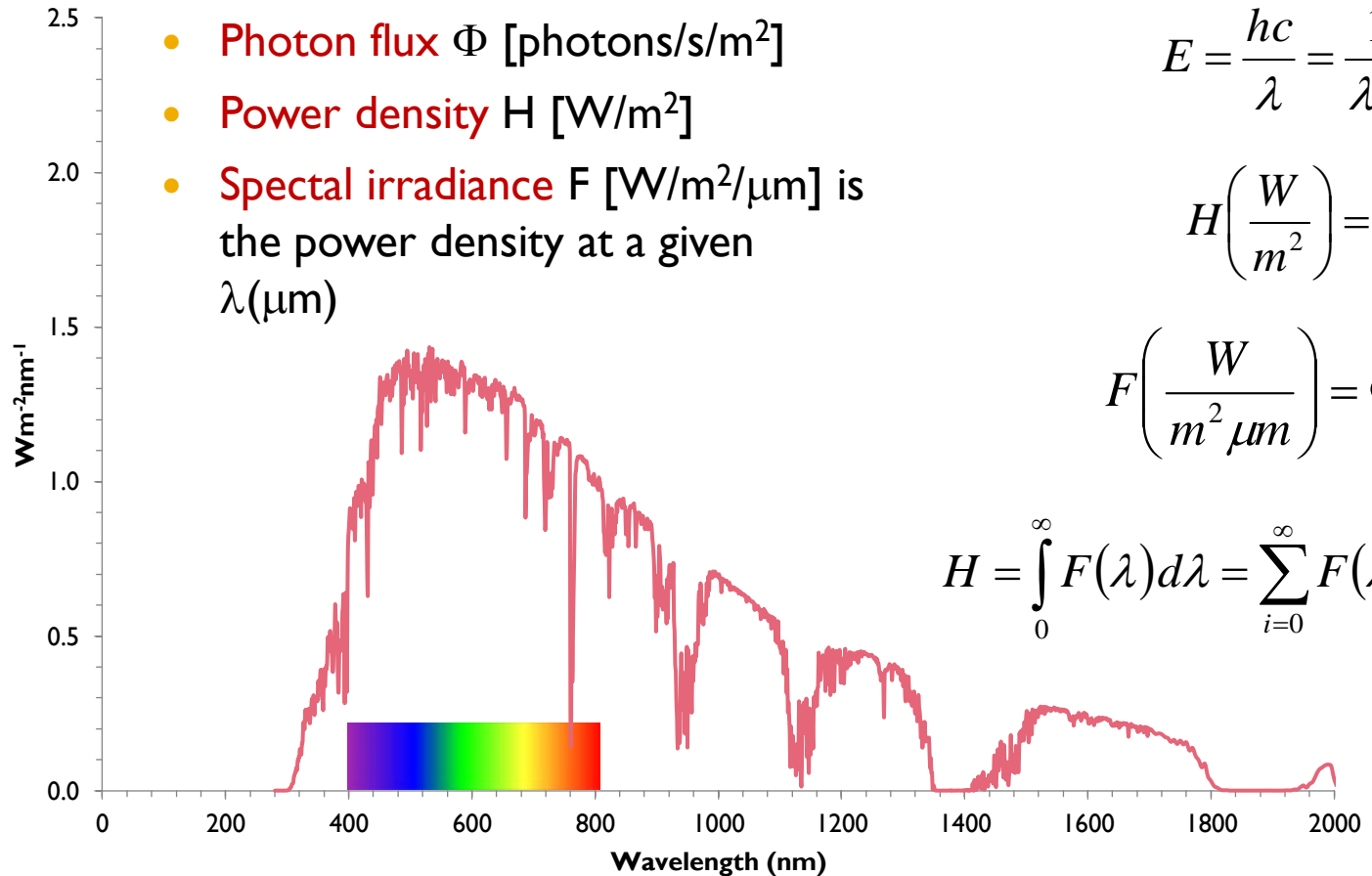
$$AM = \frac{1}{\cos \theta}$$

# Solar resource



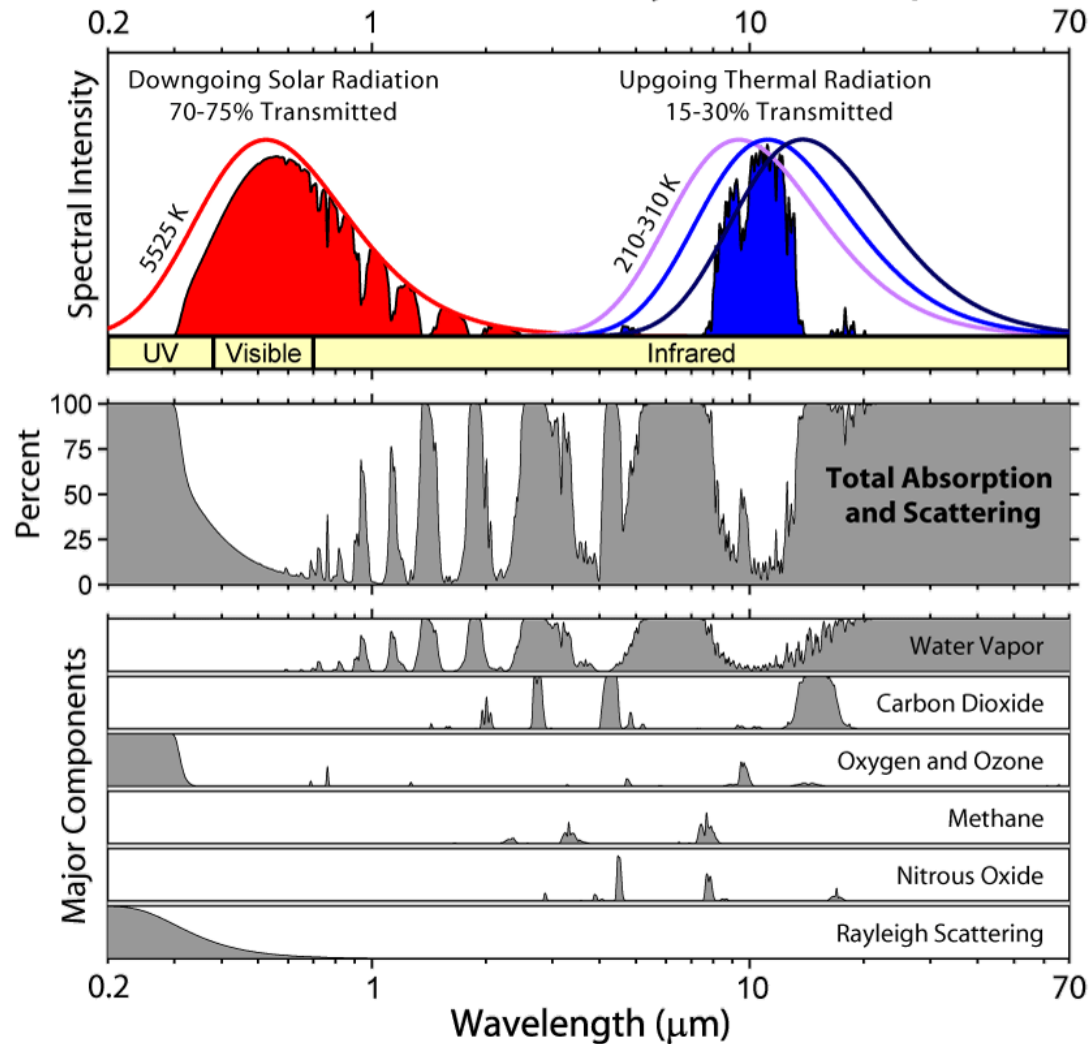
# Solar resource

- **Photon flux**  $\Phi$  [photons/s/m<sup>2</sup>]
- **Power density**  $H$  [W/m<sup>2</sup>]
- **Spectral irradiance**  $F$  [W/m<sup>2</sup>/μm] is the power density at a given  $\lambda$ (μm)

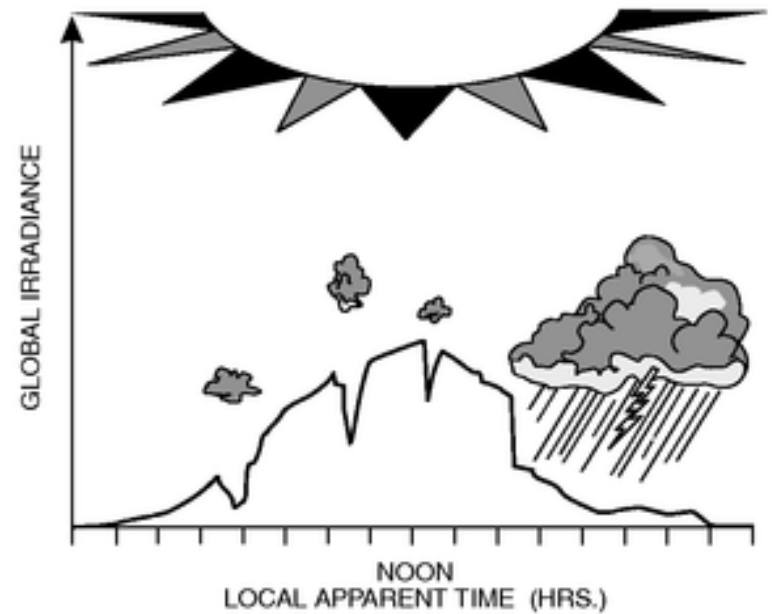
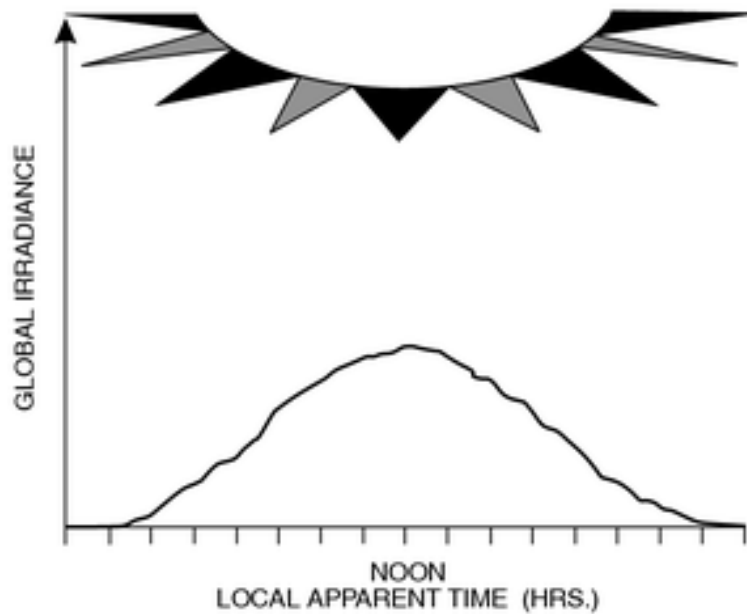


# Solar resource

## Radiation Transmitted by the Atmosphere



# Solar resource

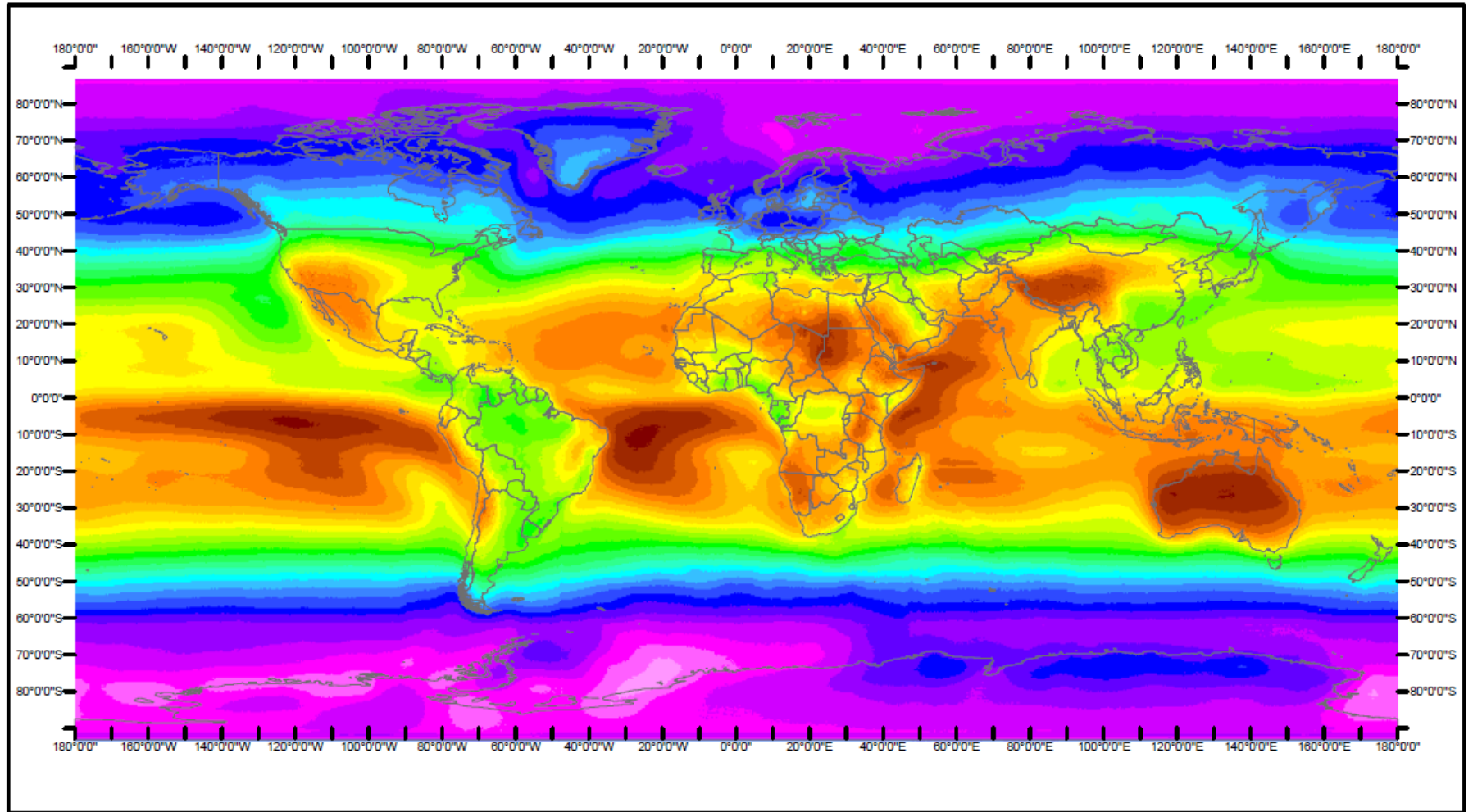


# Solar resource

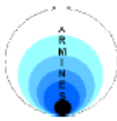
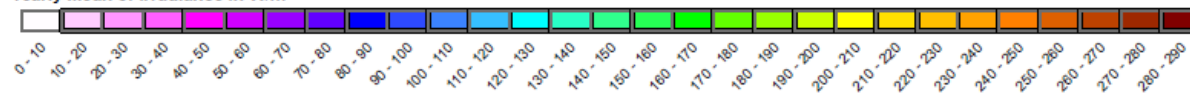
- Insolation: **Incoming Solar Radiation**
- Typical units: **kWh/m<sup>2</sup>/day**
- Affected by latitude, local weather patterns,...
- Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. *Potential of solar electricity generation in the European Union member states and candidate countries*. Solar Energy, 81, 1295–1305, <http://re.jrc.ec.europa.eu/pvgis/>.



# Averaged Solar Radiation 1990-2004

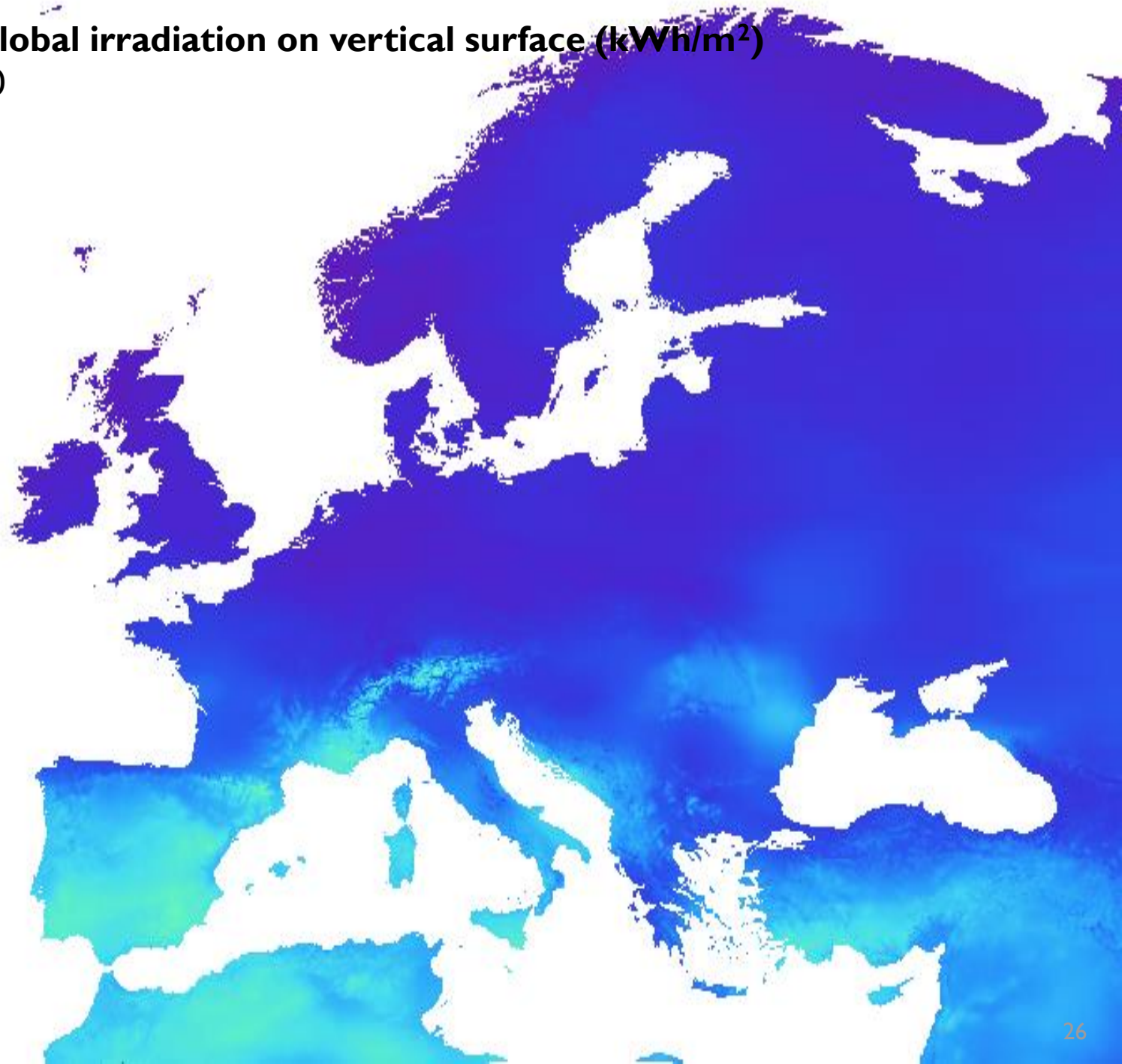


Yearly Mean of Irradiance in  $W/m^2$

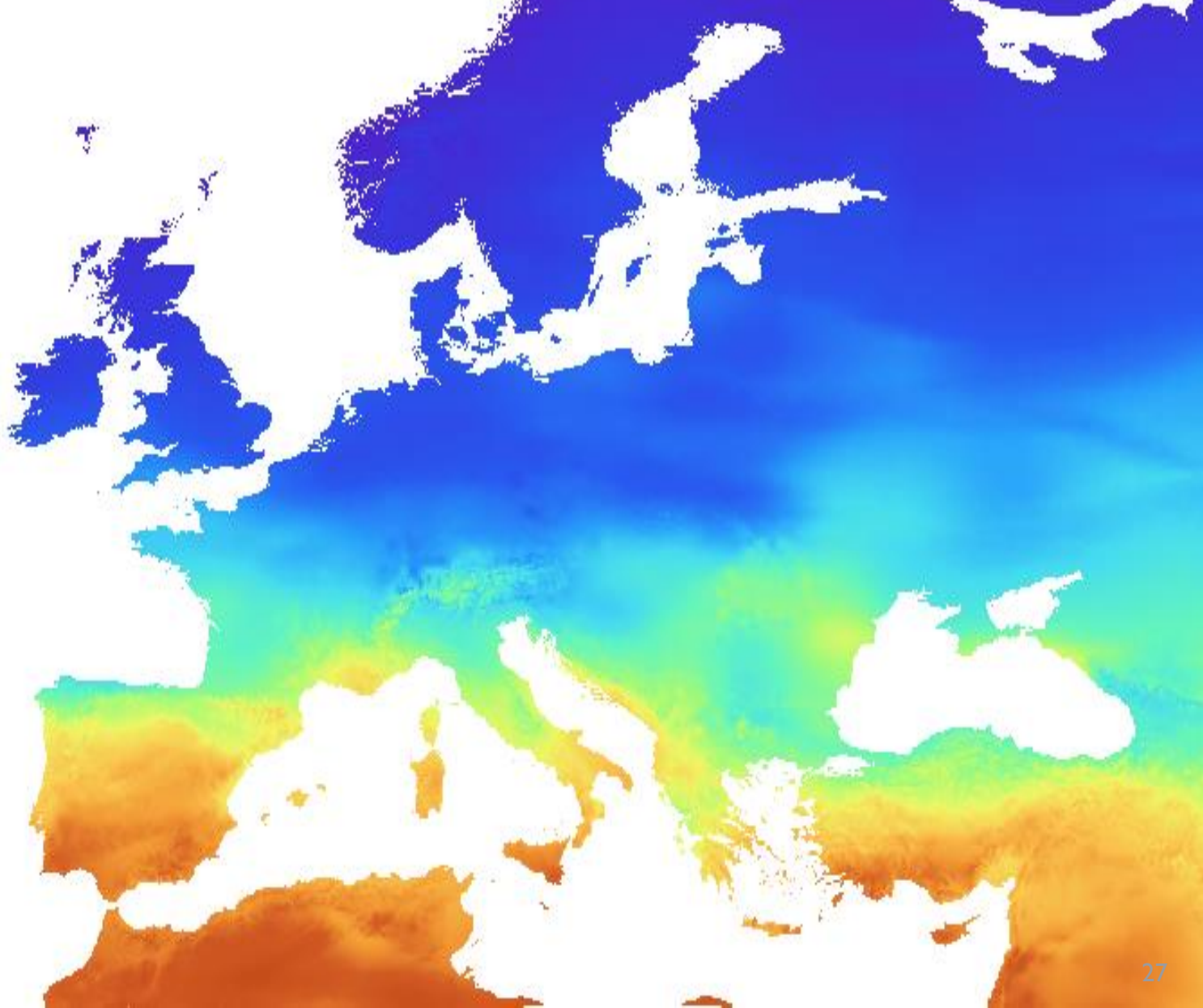


Realized by Michel Albuissou, Mireille Lefèvre, Lucien Wald.  
Edited and produced by Thierry Ranchin. Date of production: 23 November 2006.  
Centre for Energy and Processes, Ecole des Mines de Paris / Ammines / CNRS.  
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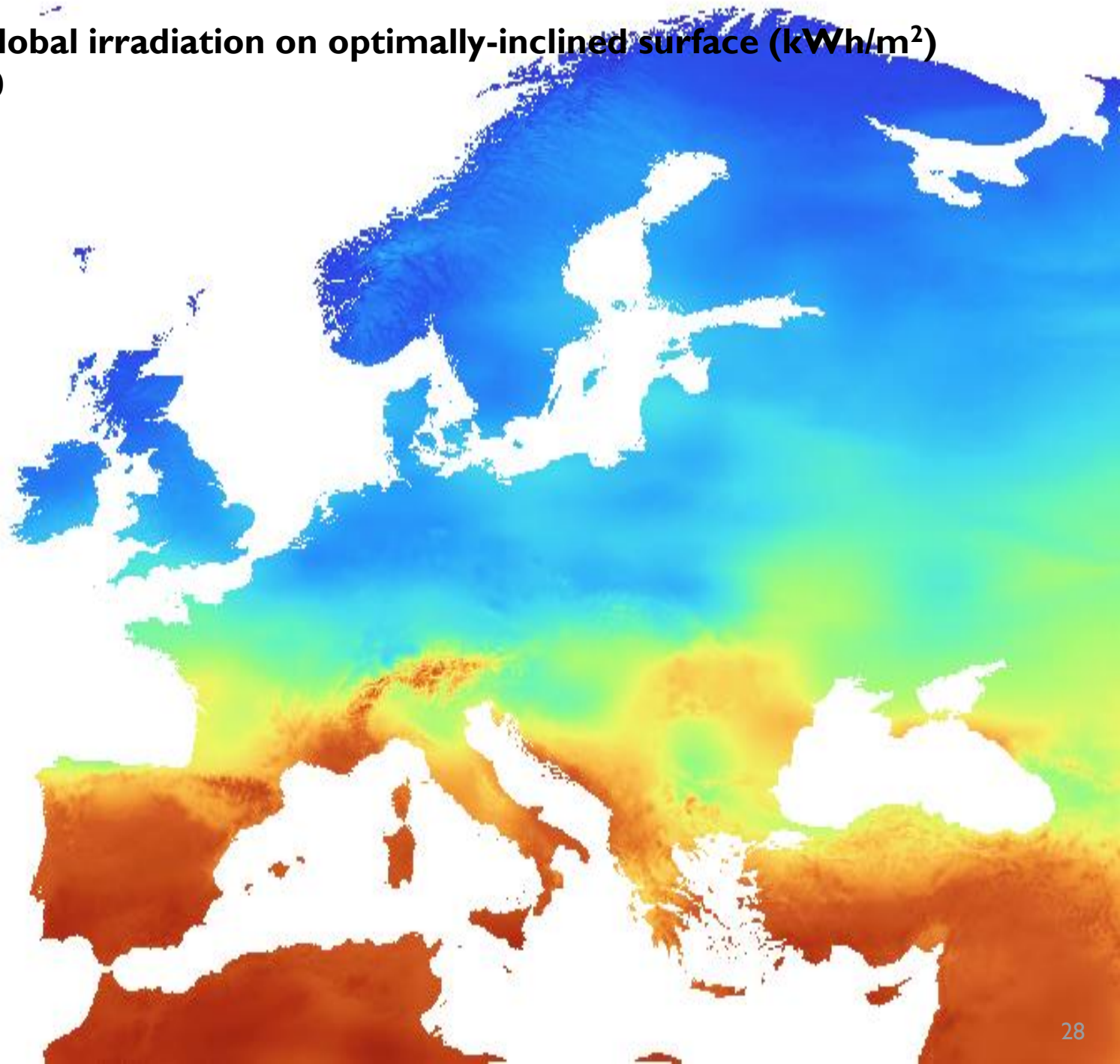
# Yearly sum of global irradiation on vertical surface (kWh/m<sup>2</sup>) period 1981-1990



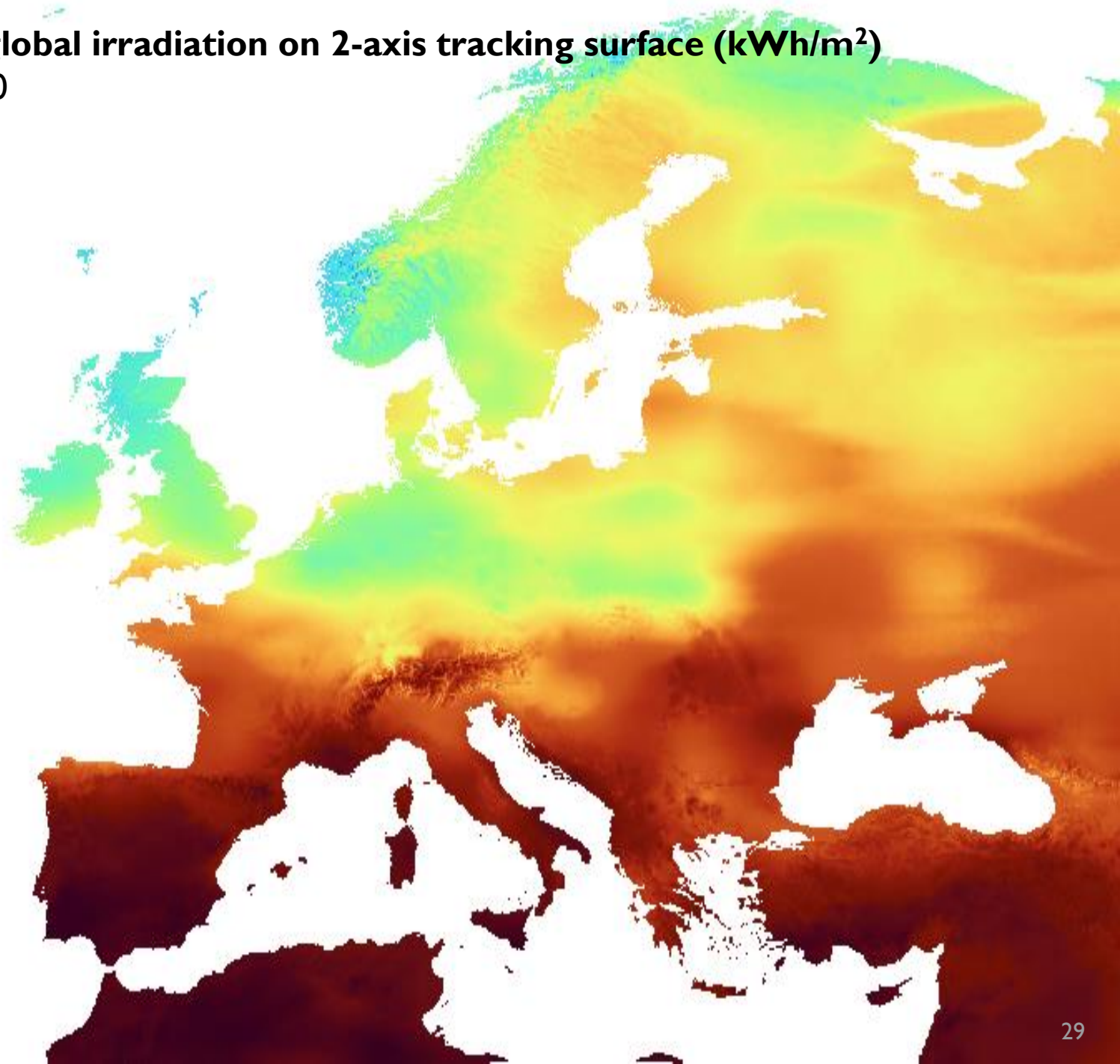
# Yearly sum of global irradiation on horizontal surface (kWh/m<sup>2</sup>) period 1981-1990



**Yearly sum of global irradiation on optimally-inclined surface (kWh/m<sup>2</sup>)  
period 1981-1990**

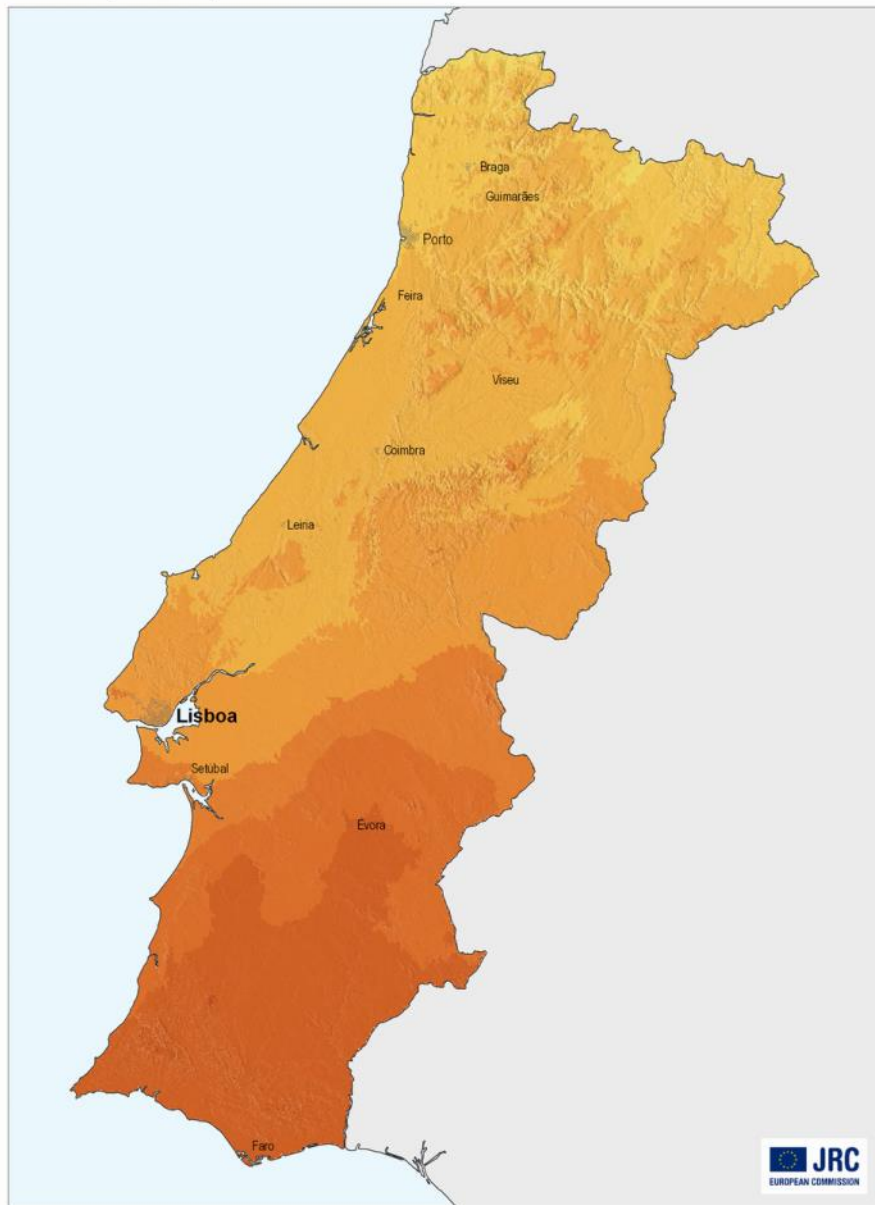


**Yearly sum of global irradiation on 2-axis tracking surface (kWh/m<sup>2</sup>)  
period 1981-1990**



**Global irradiation and solar electricity potential**  
Horizontally mounted photovoltaic modules

**Portugal**



Yearly sum of global irradiation [ $\text{kWh}/\text{m}^2$ ]

<1500 1600 1700 1800



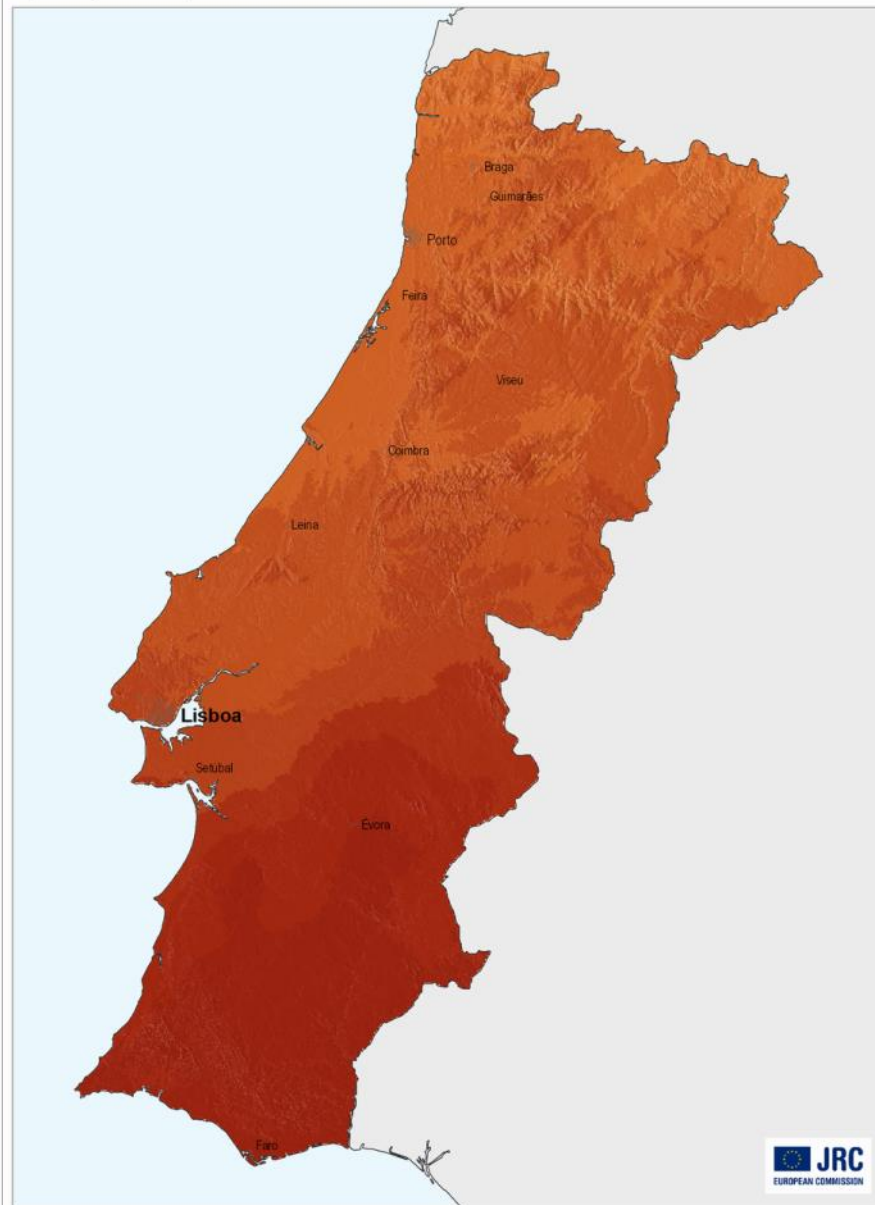
Yearly electricity generated by  $1\text{kW}_{\text{peak}}$  system with performance ratio 0.75 [ $\text{kWh}/\text{kW}_{\text{peak}}$ ]

Authors: M. Šúri, T. Cebecauer, T. Huld, E. D. Dunlop  
PVGIS © European Communities, 2001-2008  
<http://re.jrc.ec.europa.eu/pvgis/>

0 25 50 km

**Global irradiation and solar electricity potential**  
Optimally-inclined photovoltaic modules

**Portugal**



Yearly sum of global irradiation [ $\text{kWh}/\text{m}^2$ ]

1700 1800 1900 2000>

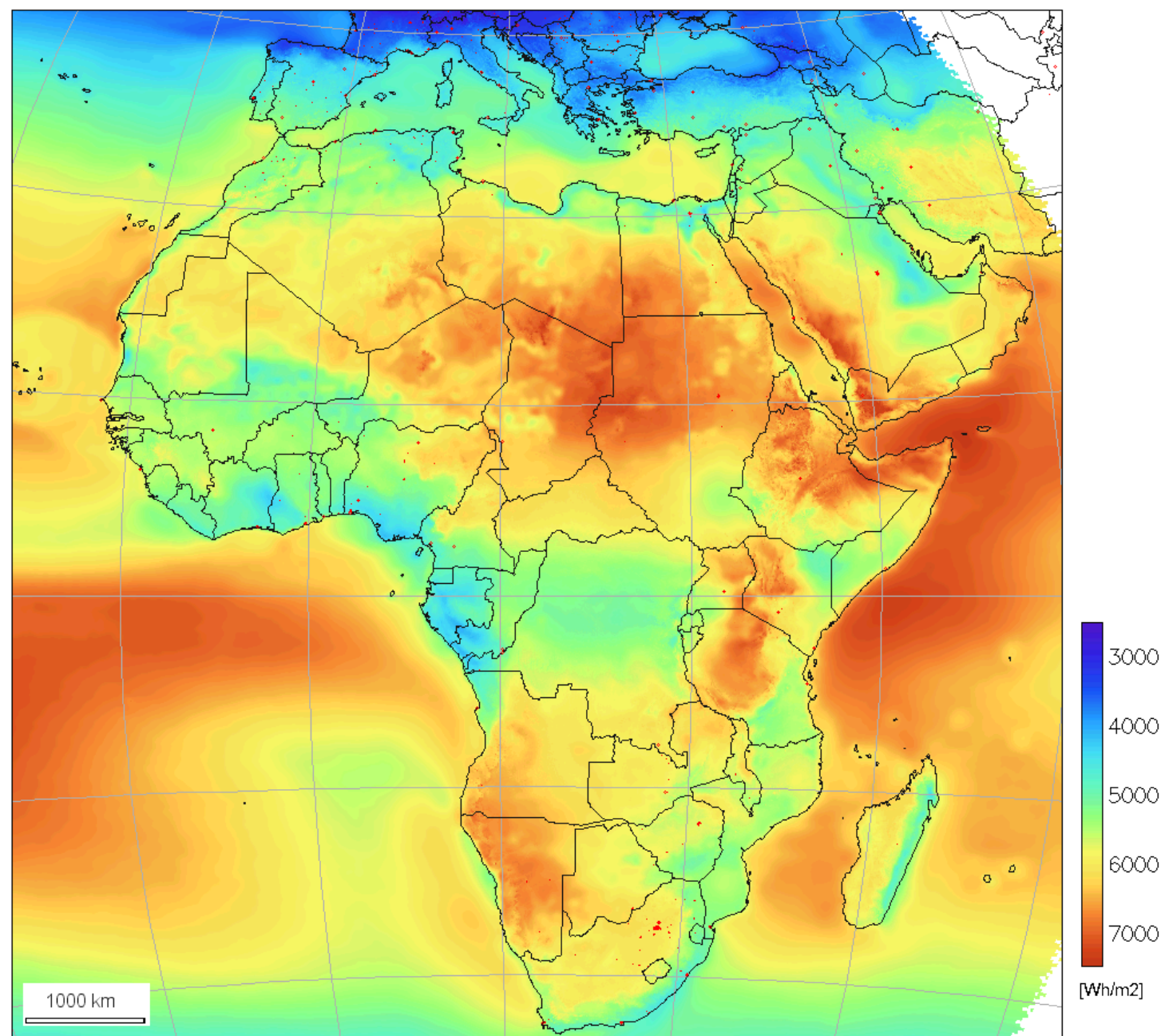


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PVGIS © European Communities, 2001-2008  
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0 25 50 km

# Global horizontal irradiation (1985-2004) (annual average of daily sums, Gh)



# Solar resource

- Coastal areas and higher mountains face wider variations (up to 10%)
- Winter is much more variable (up to x6) than summer months

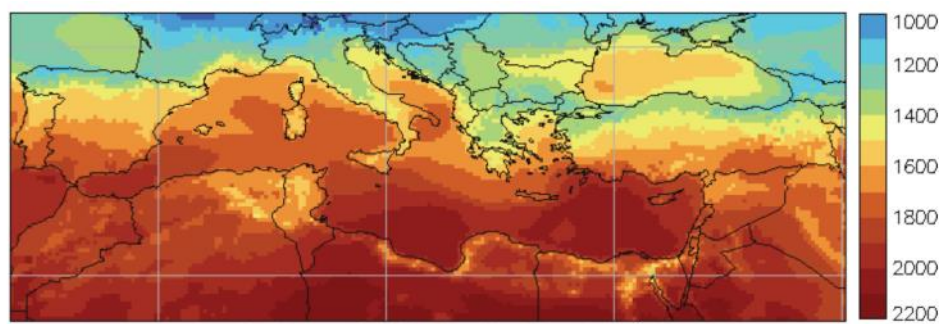


Figure 1: Long-term average of yearly sums of global horizontal irradiation (kWh/m<sup>2</sup>, time series representing years 1985, 1987, and 1989-2004)

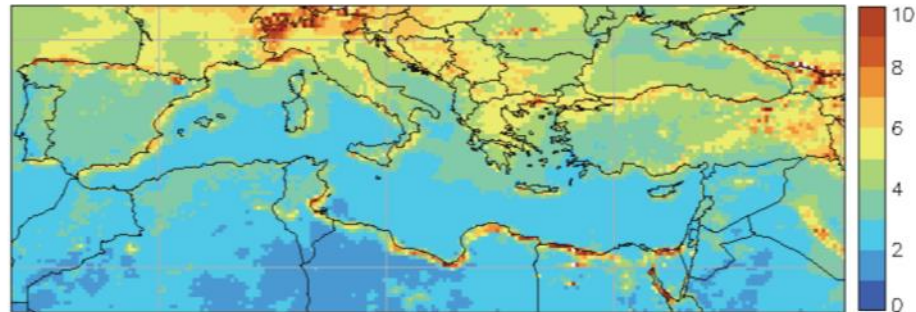


Figure 2: Standard deviation (in %) of yearly sums of global horizontal irradiation (years 1985, 1987, and 1989-2004)

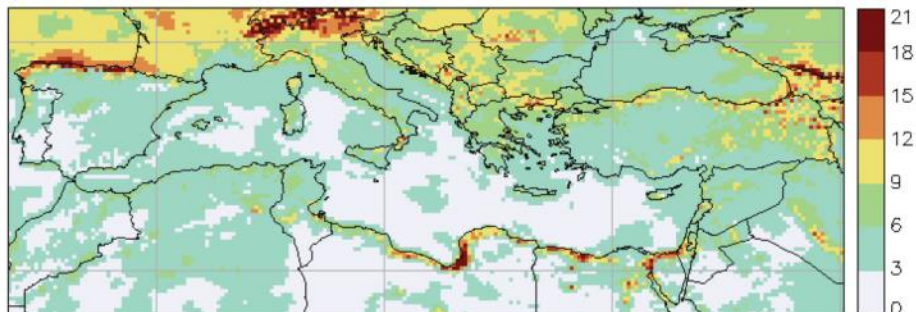


Figure 6: Relative difference of the highest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

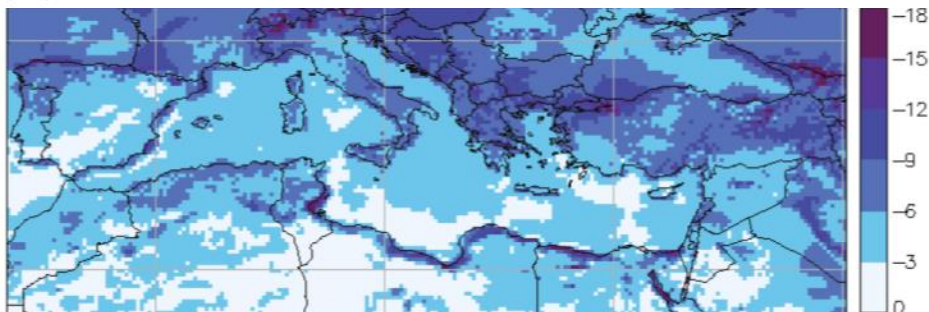


Figure 5: Relative difference of the lowest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

Šúri M., Huld T., Dunlop E.D., Albuissou M., Lefèvre M., Wald L., 2007. *Uncertainties in photovoltaic electricity yield prediction from fluctuation of solar radiation*. Proceedings of the 22nd European Photovoltaic Solar Energy Conference, Milano, Italy 3-7.9.2007

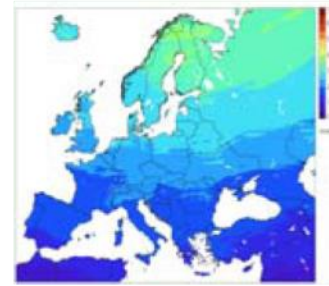


# Solar tracking

Compared to PV with modules fixed at optimum angle:

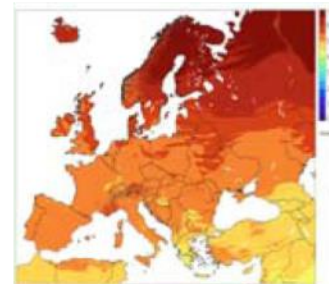
- Changing inclination twice a year contributes only marginally

## Fixed mounting - two (seasonal) optimum angles



*Optimum angle  
of modules  
in summer [°]*

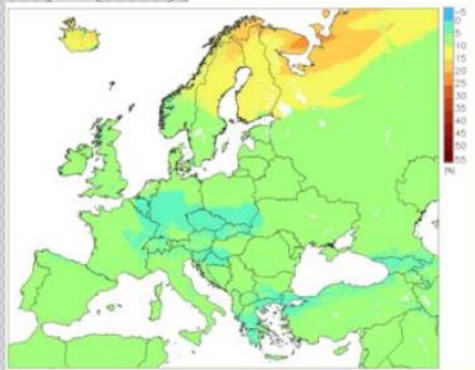
**+ 1.5 to 4.5 %**



*Optimum angle  
of modules  
in winter [°]*

# Solar tracking

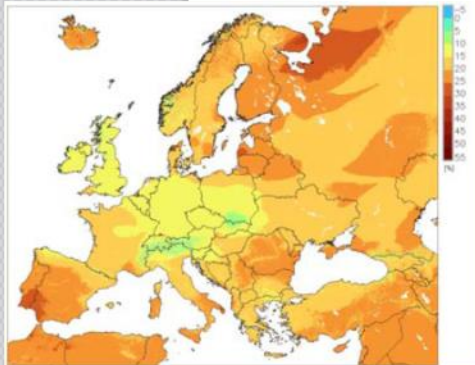
## One-axis tracking



Horizontal axis pointing East-West



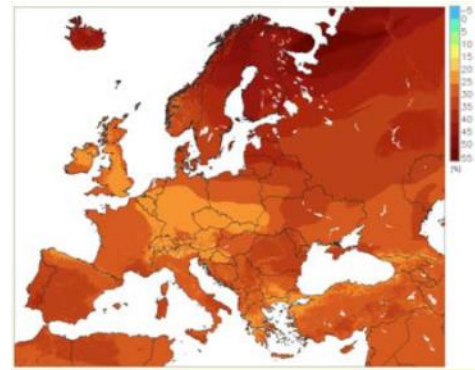
+ 0 to 21 %



Horizontal axis pointing North-South



+ 0 to 31 %



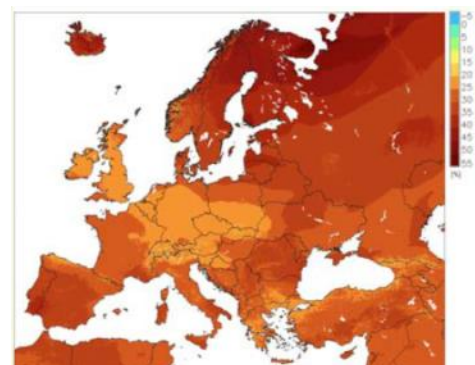
Vertical axis + modules mounted at optimum angle



+ 11 to 55 %



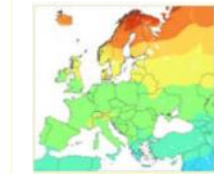
Optimum angle of modules [°]



Axis inclined at an optimum angle towards South



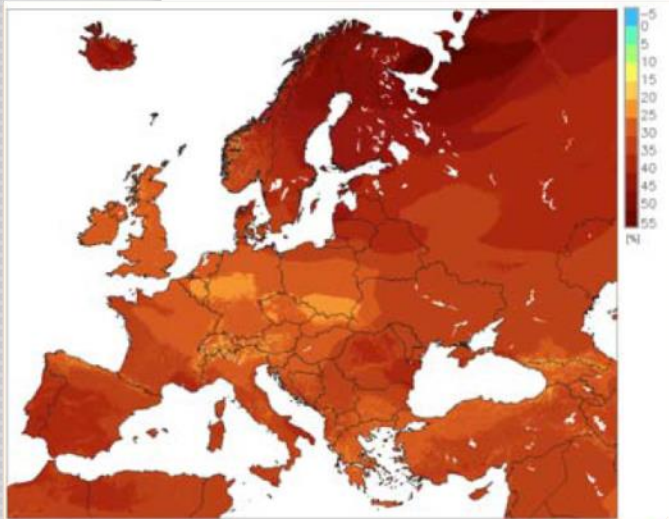
+ 12 to 50 %



Optimum angle of the axis [°]

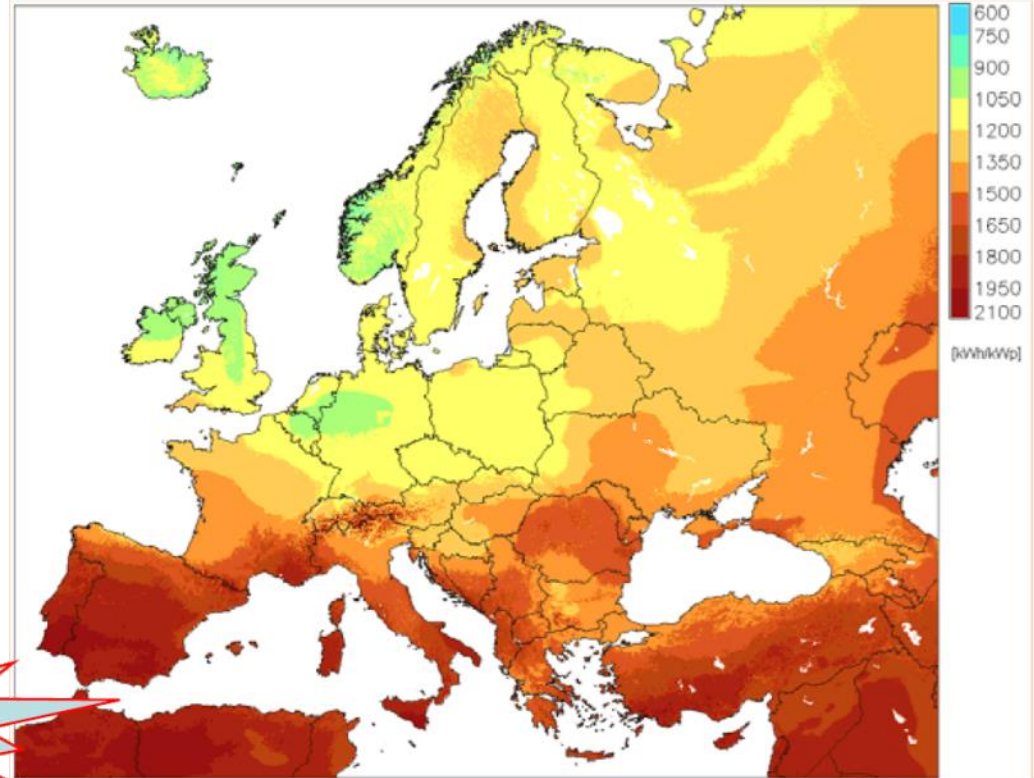
# Solar tracking

Two-axis tracking



+13 to 55 %

Highest achievable



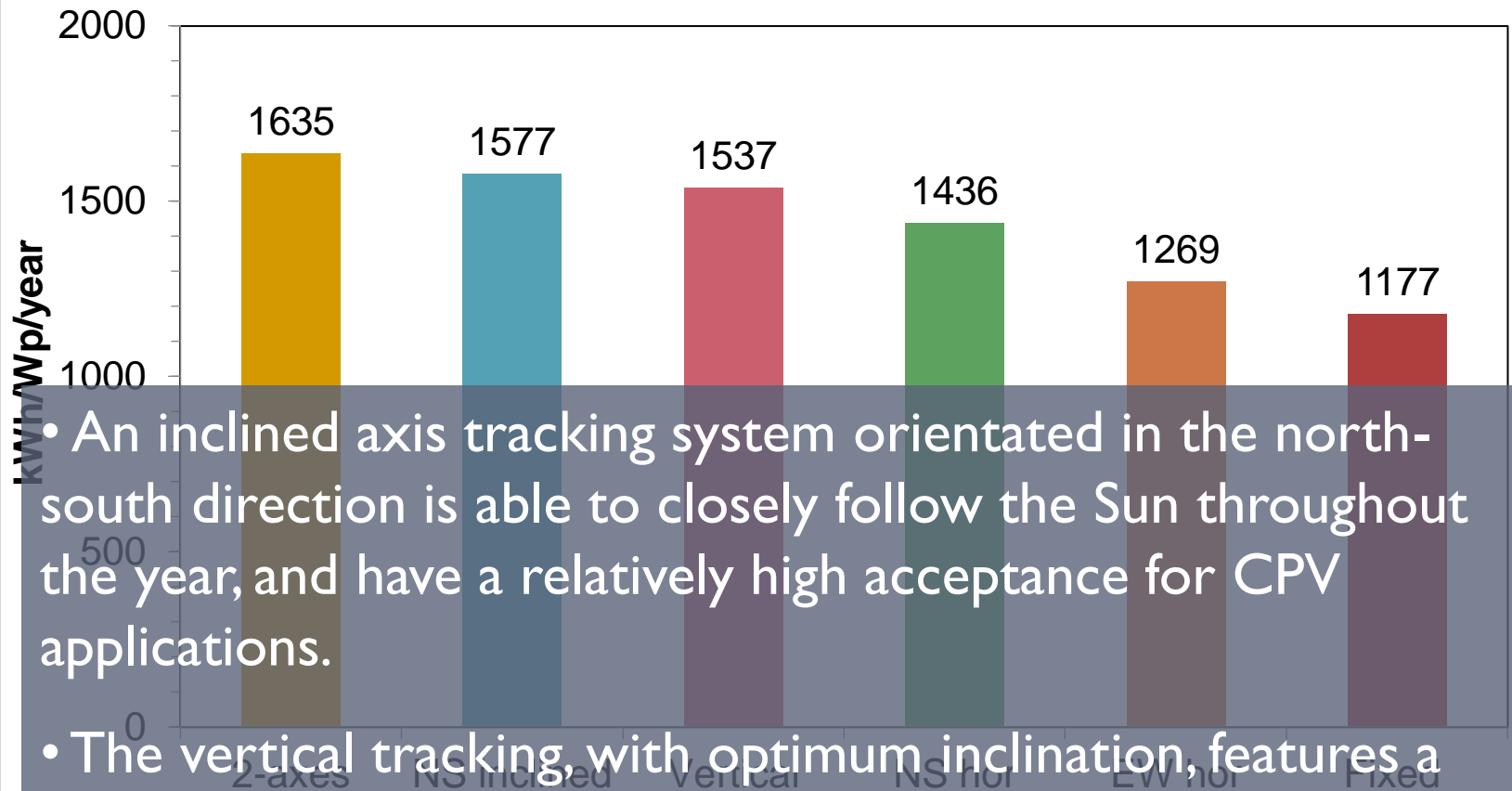
Yearly sum of solar electricity generated from 1kWp PV system [kWh]

# Solar tracking

Compared to PV with modules fixed at optimum angle:

- Changing inclination twice a year contributes only marginally (2-4%)
- 1-axis tracking PV with vertical or South-inclined axis generates only 1-4% less than 2-axis tracking system
- 1-axis tracking PV with horizontal axis-oriented E-W typically performs only slightly better than fixed mounting systems

# Solar tracking



- An inclined axis tracking system orientated in the north-south direction is able to closely follow the Sun throughout the year, and have a relatively high acceptance for CPV applications.

- The vertical tracking, with optimum inclination, features a similar performance that an inclined axis tracking system orientated in the north-south direction.

# Solar tracking



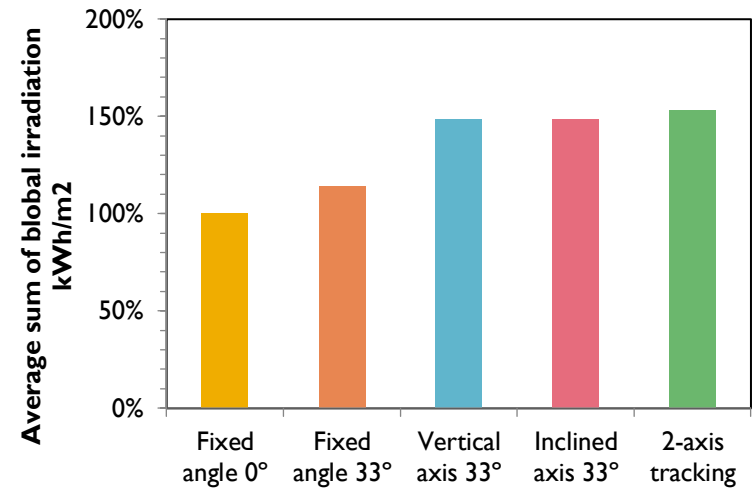
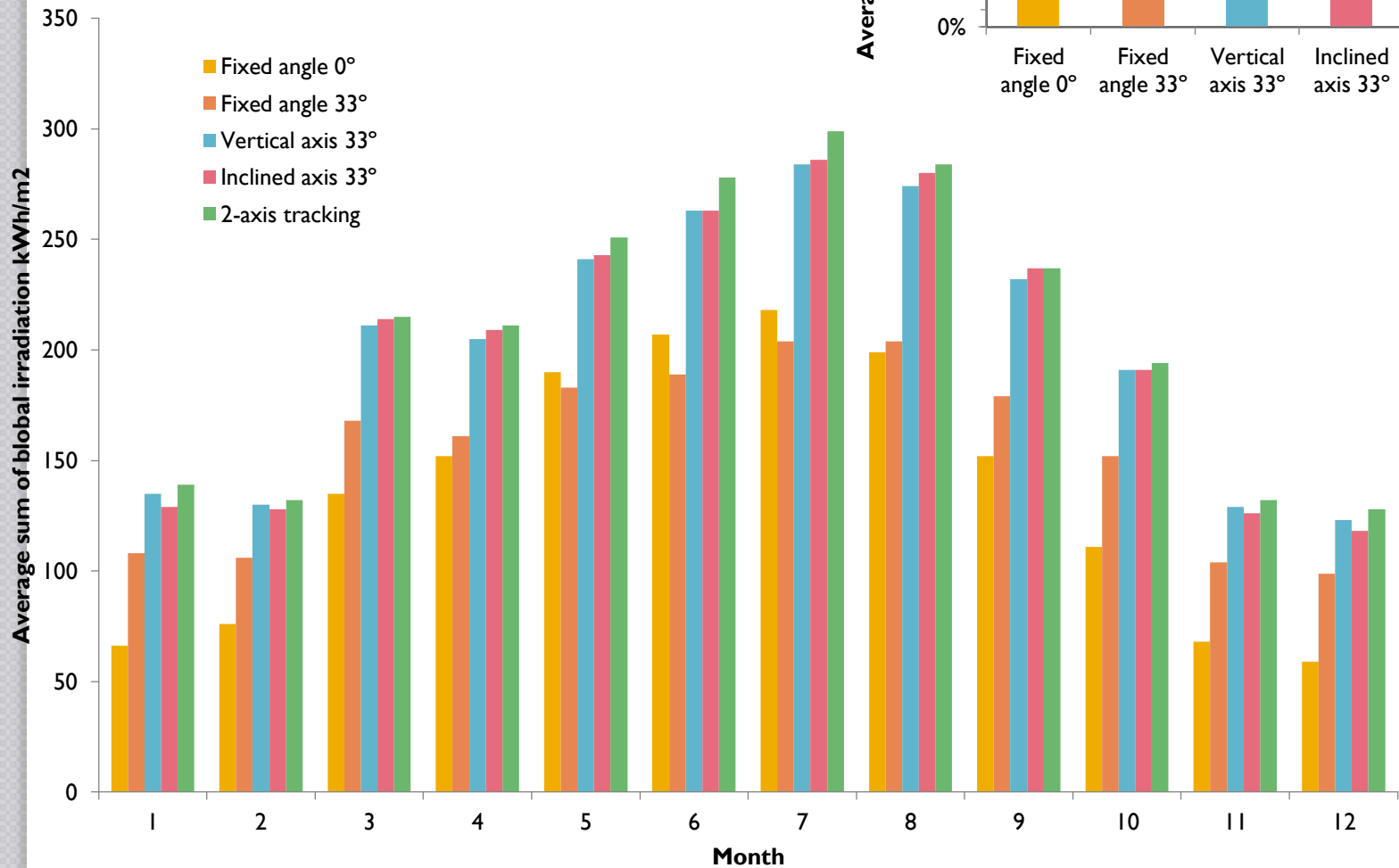
▲ Installing a screw foundation for a dual-axis tracking system (Deger-Traker) at Am Peterswald PV park in Germany: Bftec GmbH pre-drills the ground at the site and then the foundation is installed. The foundation's unusual form, which consists of a smooth side wall with a coil at the bottom (if necessary, two coils), guarantees a firm grip. The foundation can rotate in the ground without displacing or loosening the surrounding earth.

# Solar tracking



# Solar tracking

## PVGIS exercise: Lisbon





# Solar tracking

## Shadowing effect

- Ground cover ratio = PV area / total area

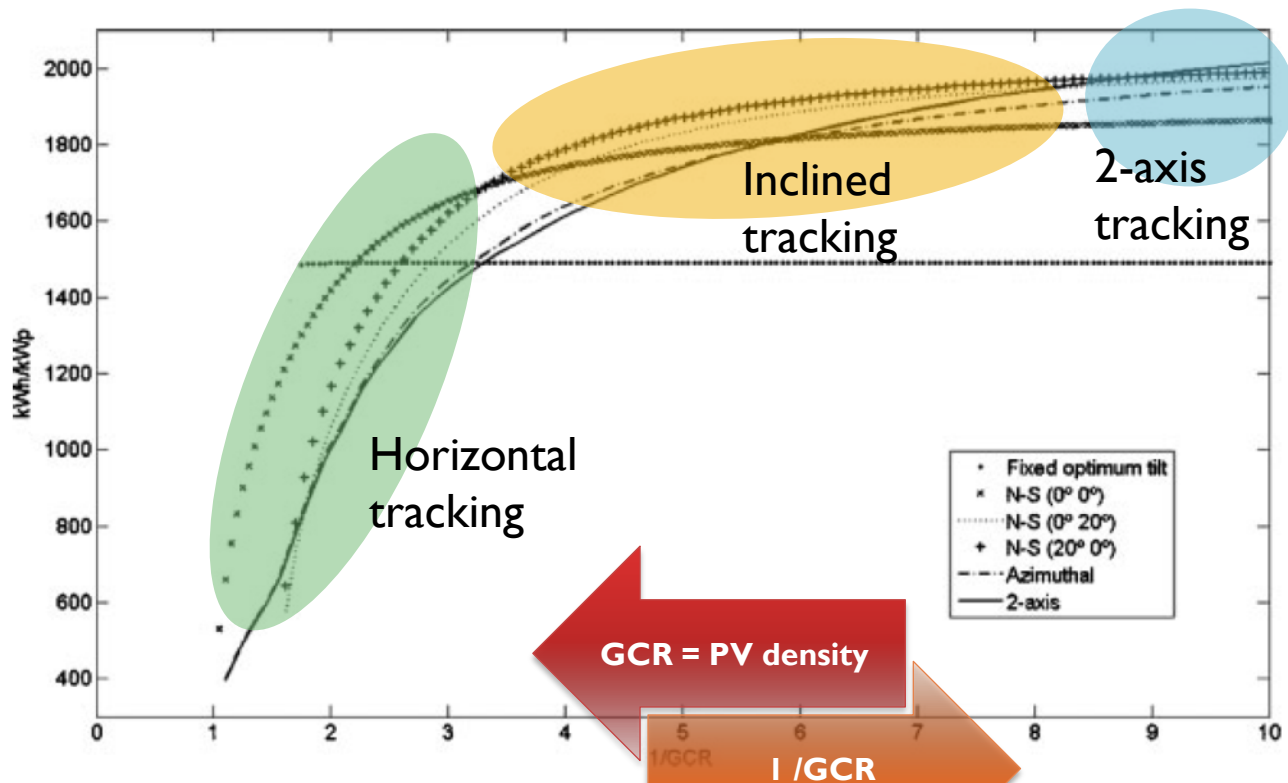


Figure 13. Evolution of yearly energy yield in Almería for the tracking strategies considered here, for the pessimistic shading case and assuming a constant dirtiness degree of 3%

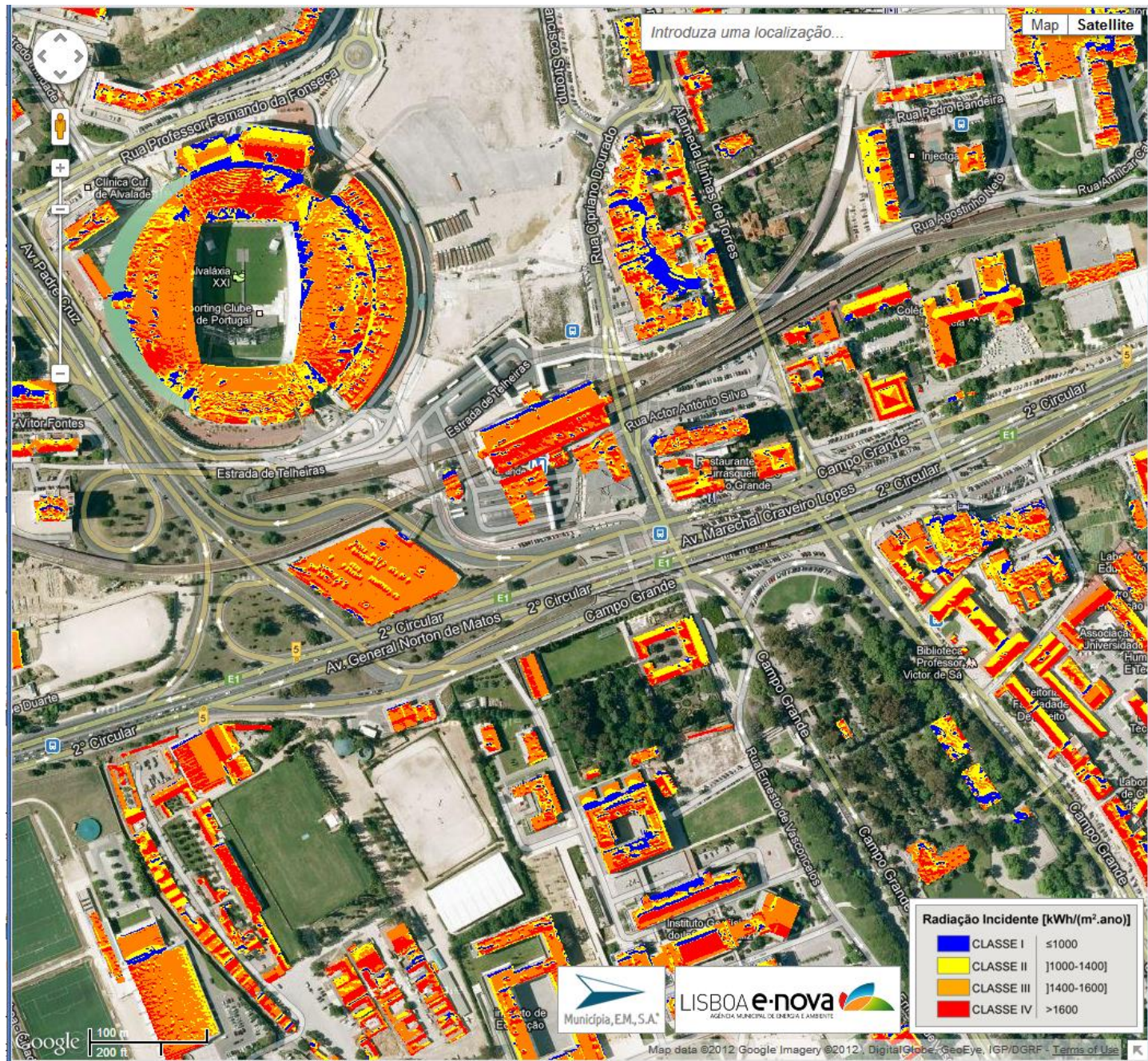
# Solar in the city

PV potential in the urban landscape is harder to estimate

- ❑ **Geographical** solar potential  
*locations where this energy can be captured*
- ❑ **Technical** solar potential  
*technical characteristics of the rooftop/equipment used*
- ❑ **Economic** solar potential  
*only viable systems*



Needs to take into consideration mutual shading between buildings, rooftop structures, etc.



# Solar in the city

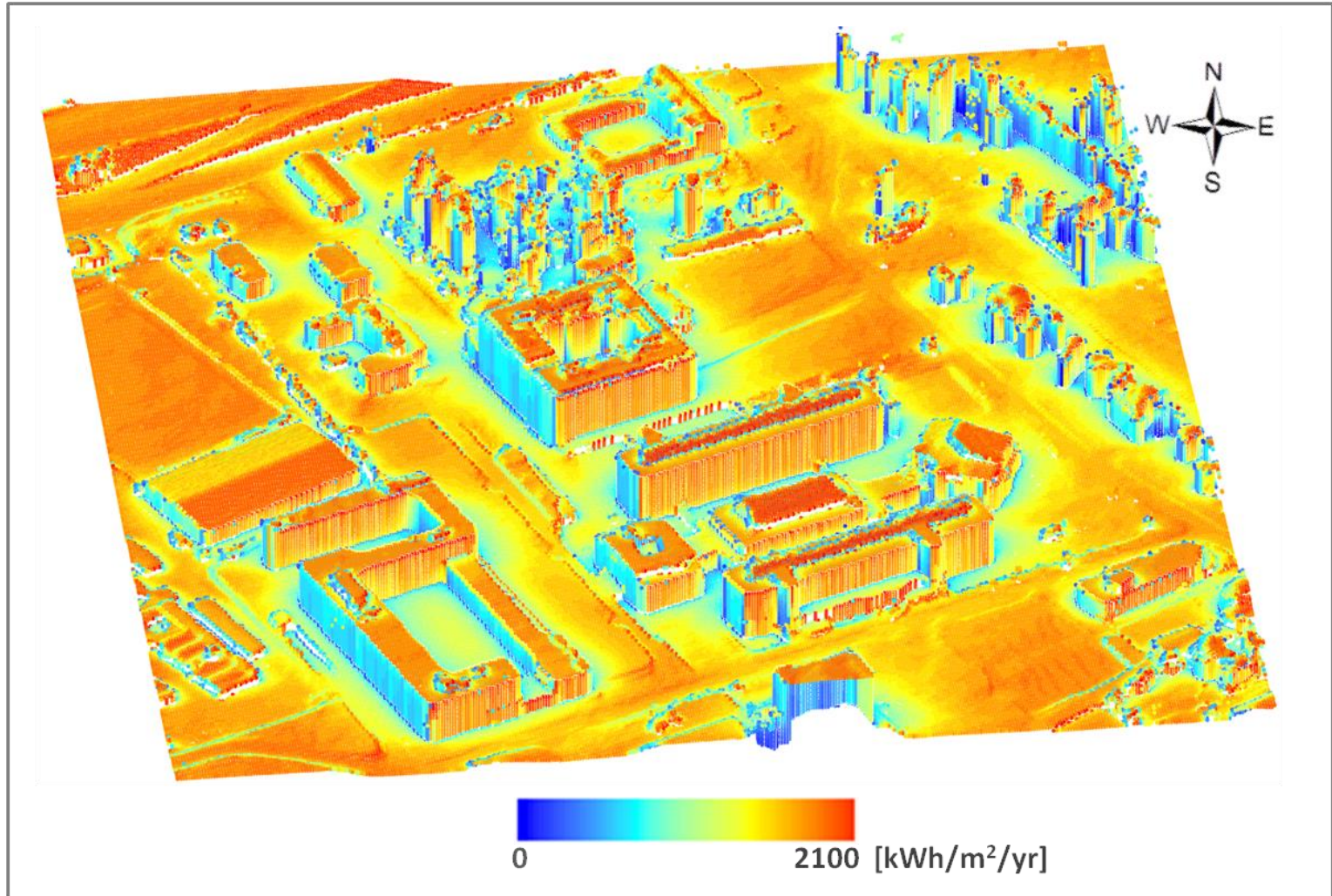


# Solar in the city

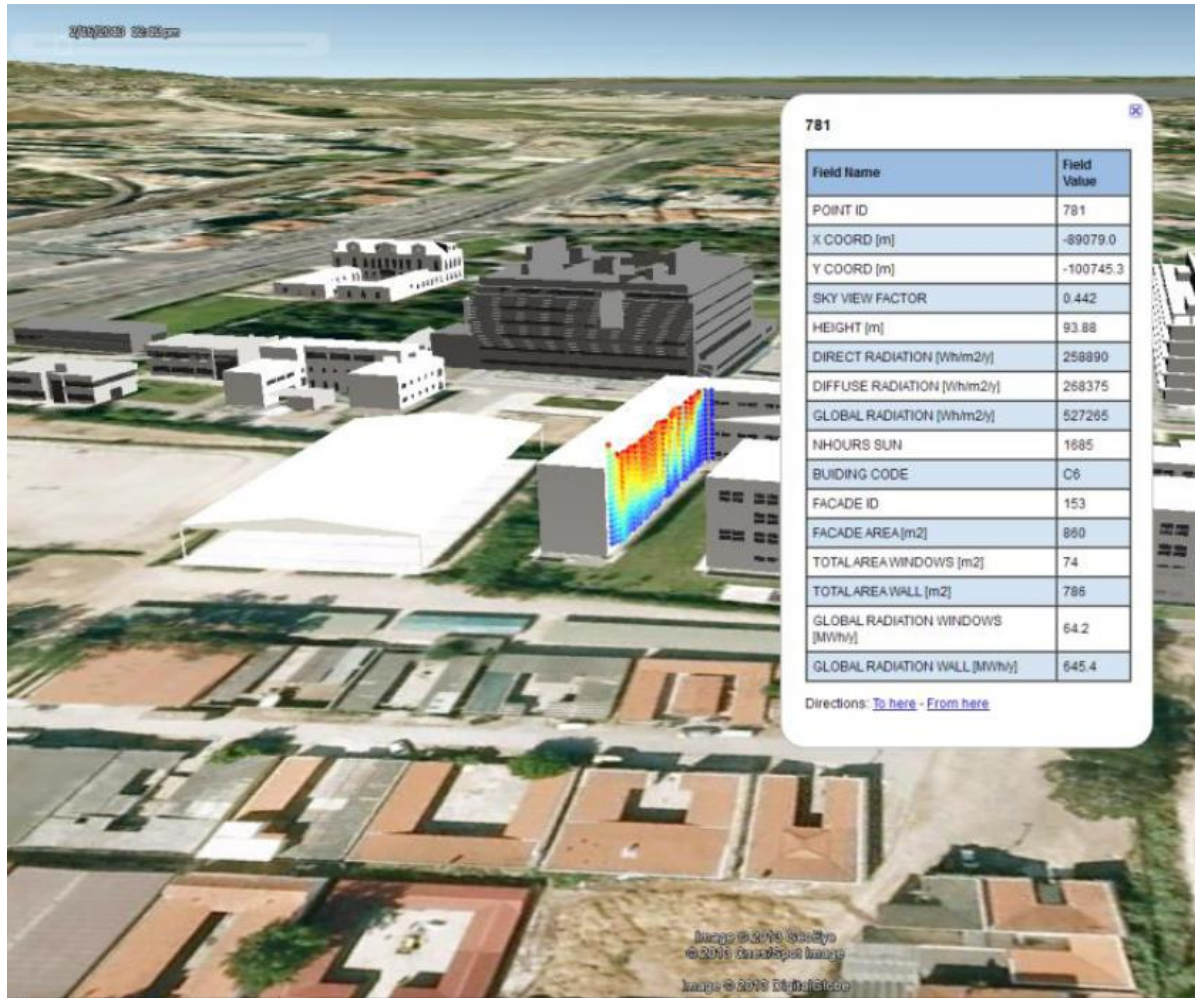


0  2 100  
[kWh/m<sup>2</sup>/y]

# Solar in the city



# Solar in the city





Lat: 38.755402 | Lon: -9.157754 | Alt: 65.0 | Acc: 1.0m.

