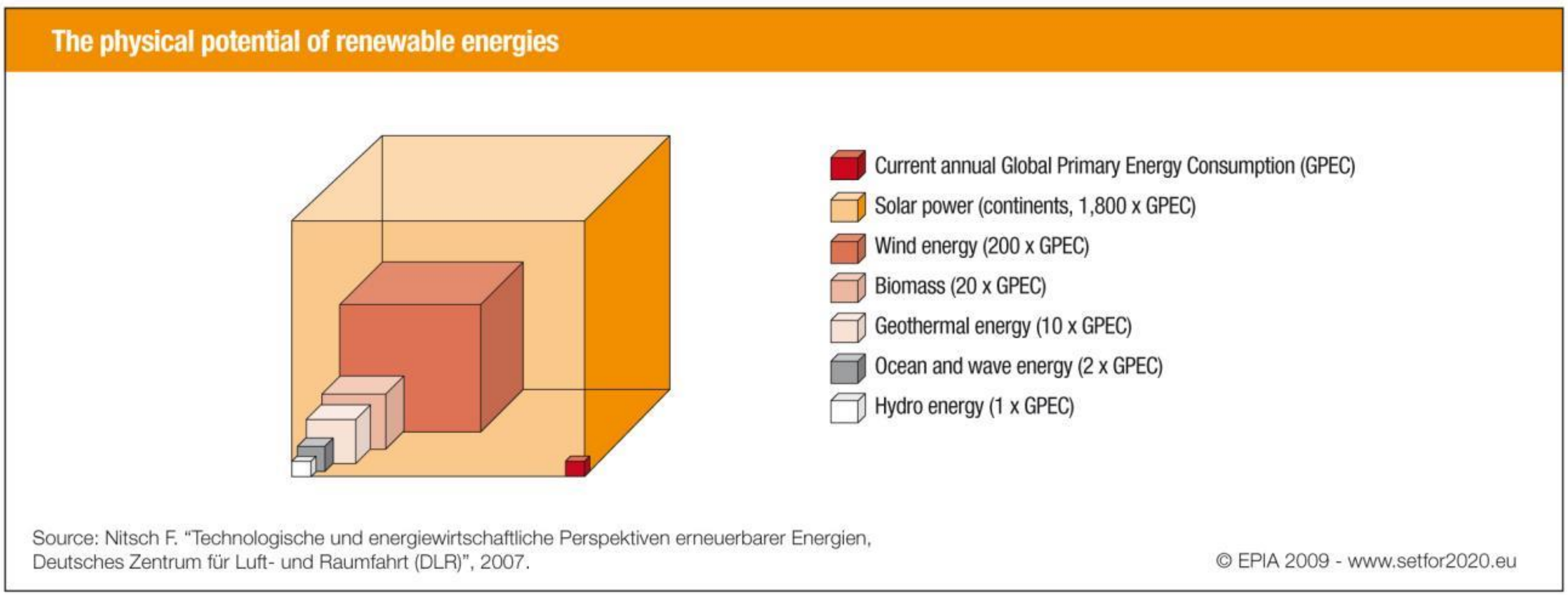
SOLAR RESOURCE

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: 4.0×10^{14} kWh/year
  - Solar resource on Earth's surface: 5.5×10^{17} kWh/year



Solar resource

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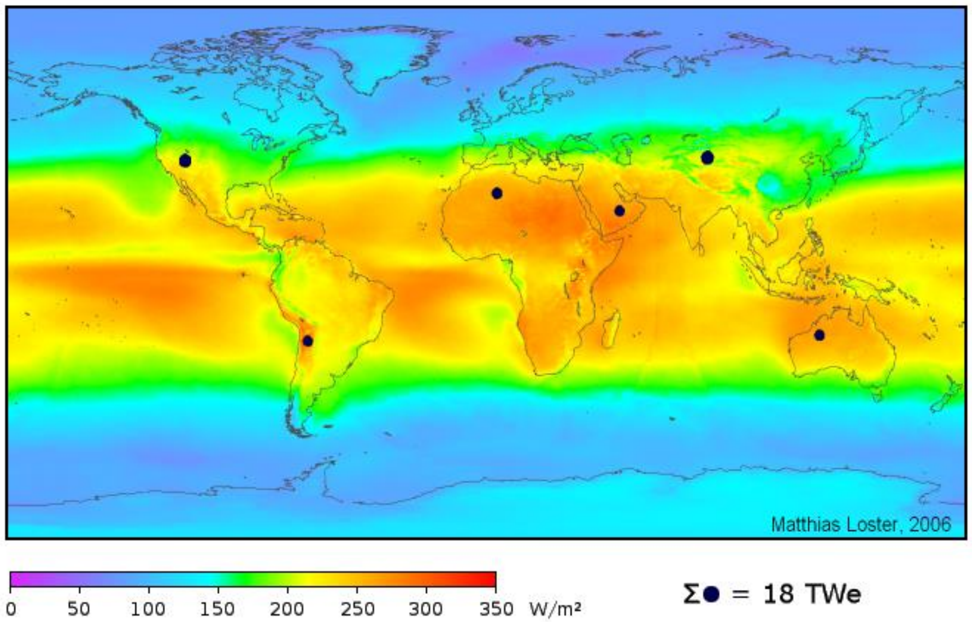
  - Human energy use: 4.0×10^{14} kWh/year
  - Solar resource on Earth's surface: 5.5×10^{17} kWh/year

http://en.wikipedia.org/wiki/File:Solar_land_area.png



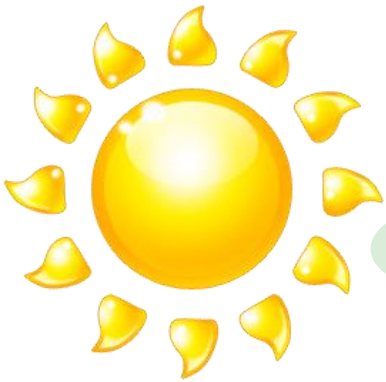
Local solar irradiance averaged over three years from 1991 to 1993 (24 hours a day) taking into account the cloud coverage available from weather satellites

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: 4.0×10^{14} kWh/year
  - Solar resource on Earth's surface: 5.5×10^{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

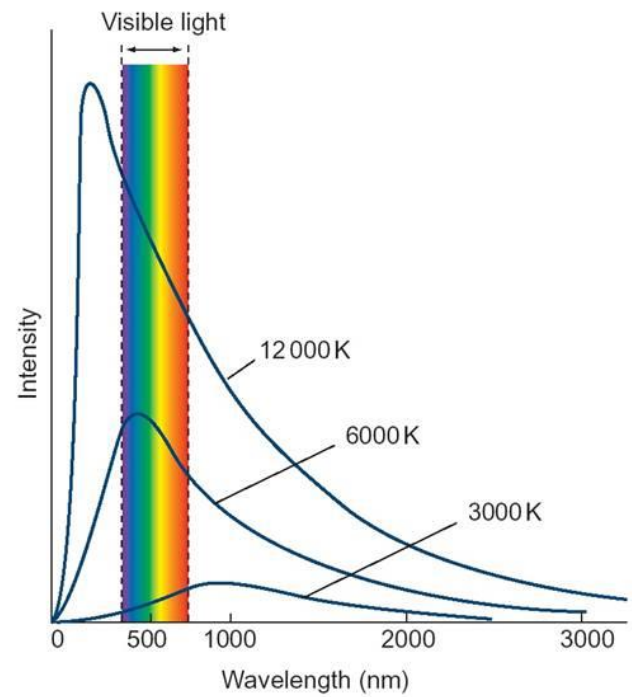


$$P_0 = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

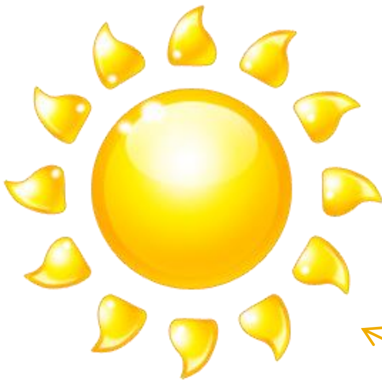
Total radiative power (Stefan Boltzman) T=5762K

Surface area of sun

Power radiated per unit area
5.96×10^7 W/m^2



Solar resource



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

Ratio of surface areas of the 2 spheres

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

Solar constant average energy flux incident at the Earth's orbit: **1366 W/m²**

Distance Sun-Earth

Solar resource

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

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

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

Energy incident on Earth

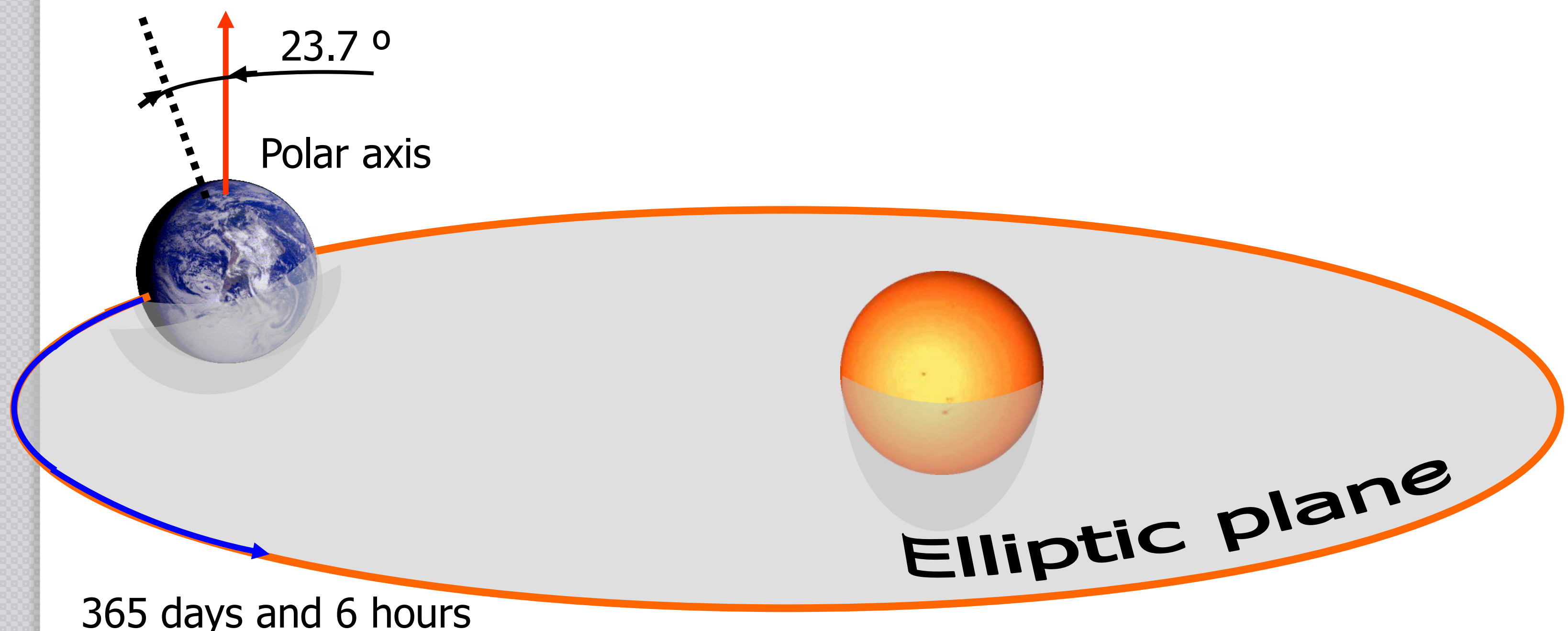
Total area of Earth

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

Average energy incident per unit area of surface of Earth: **342 W/m²**

Solar resource

- Earth-Sun motion

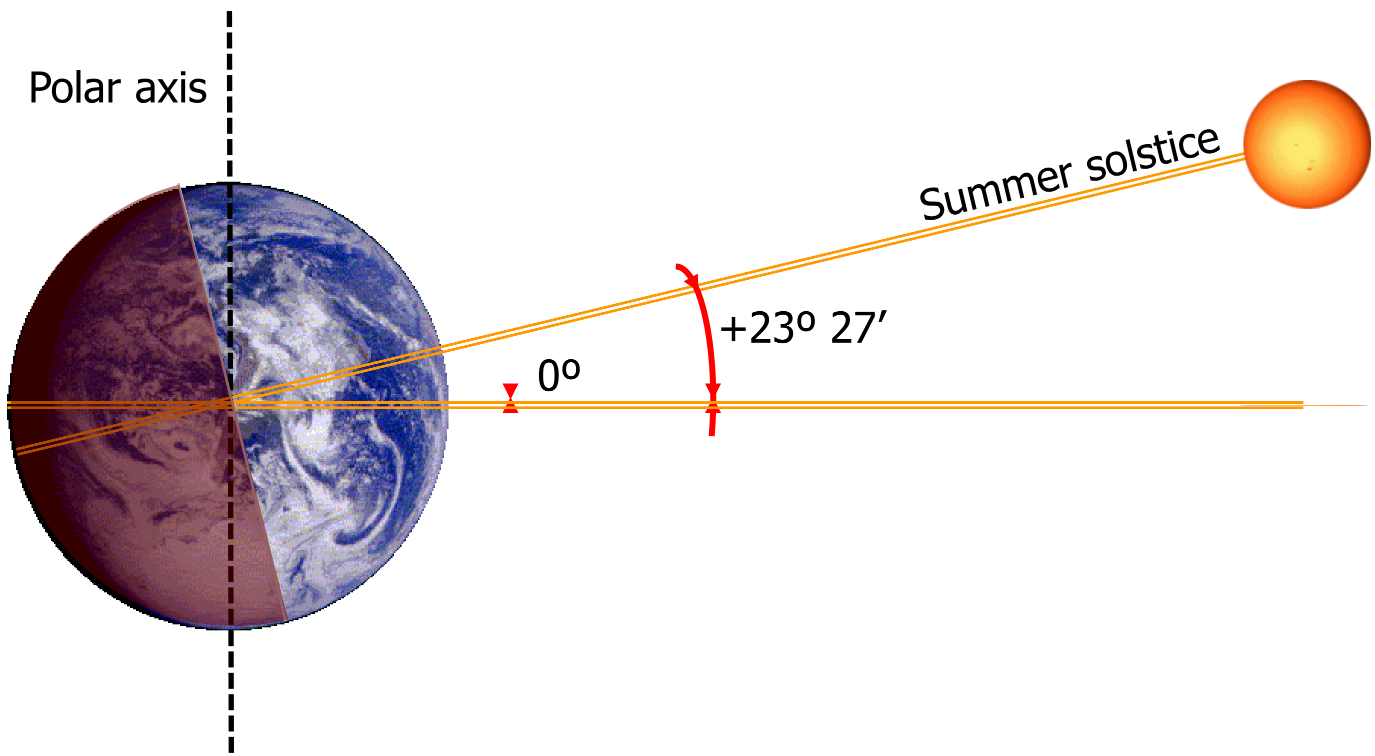


$$\frac{H}{S} = 1 + 0.033\cos\left(\frac{360(n-2)}{365}\right)$$

H(W/m2) 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

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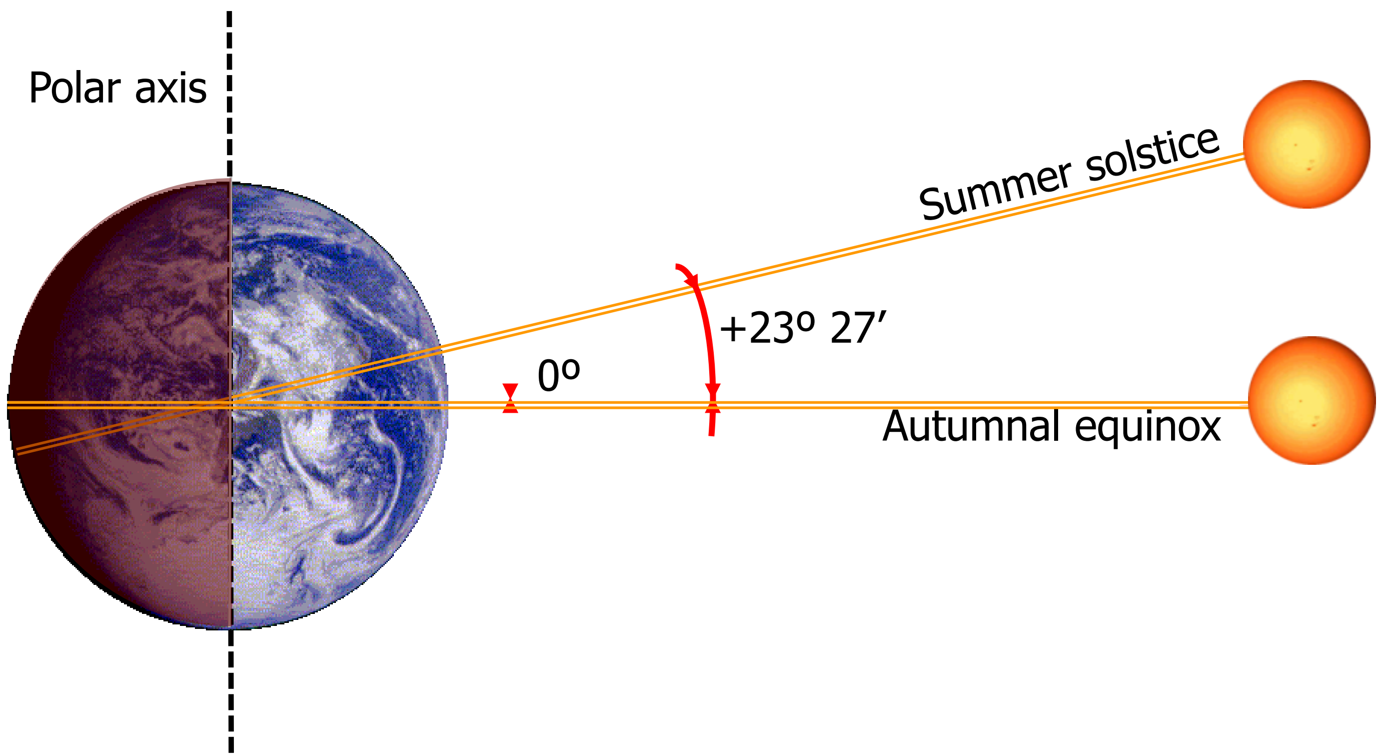
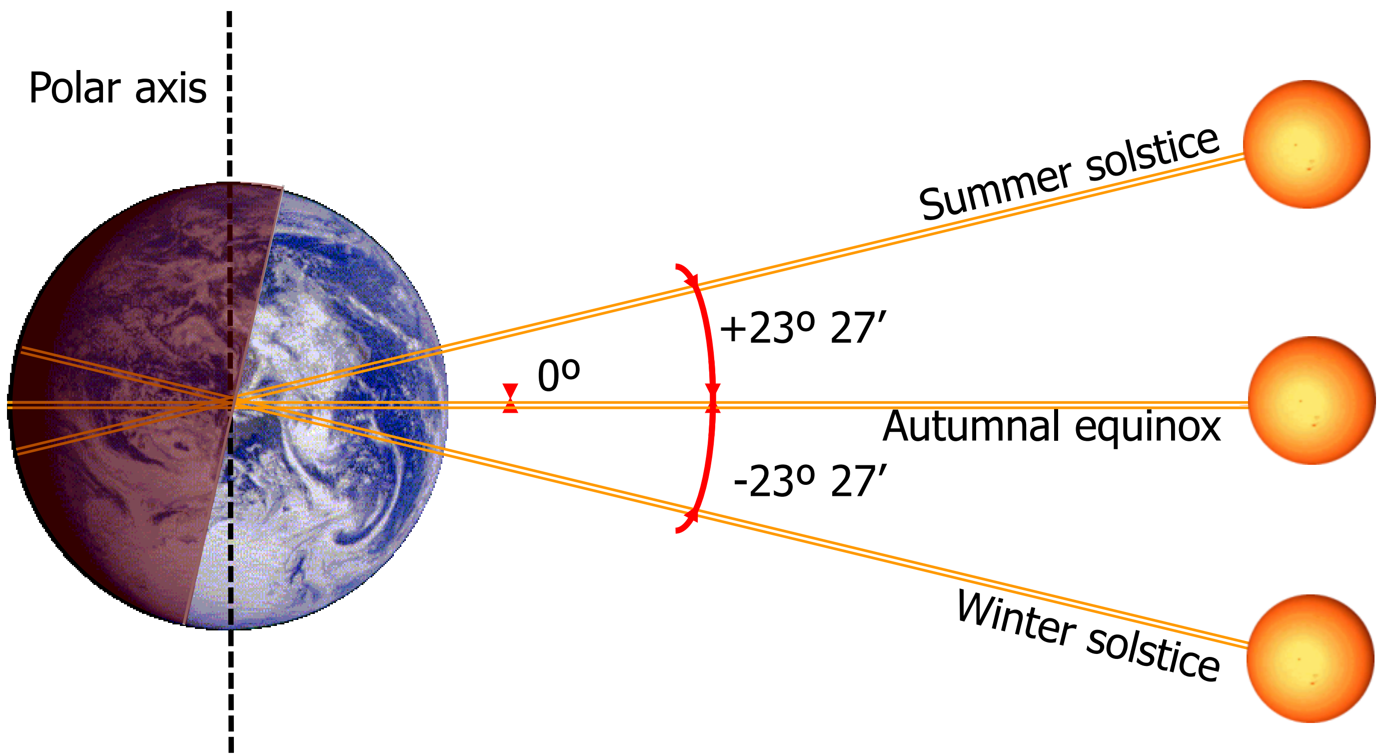


Solar resource

- 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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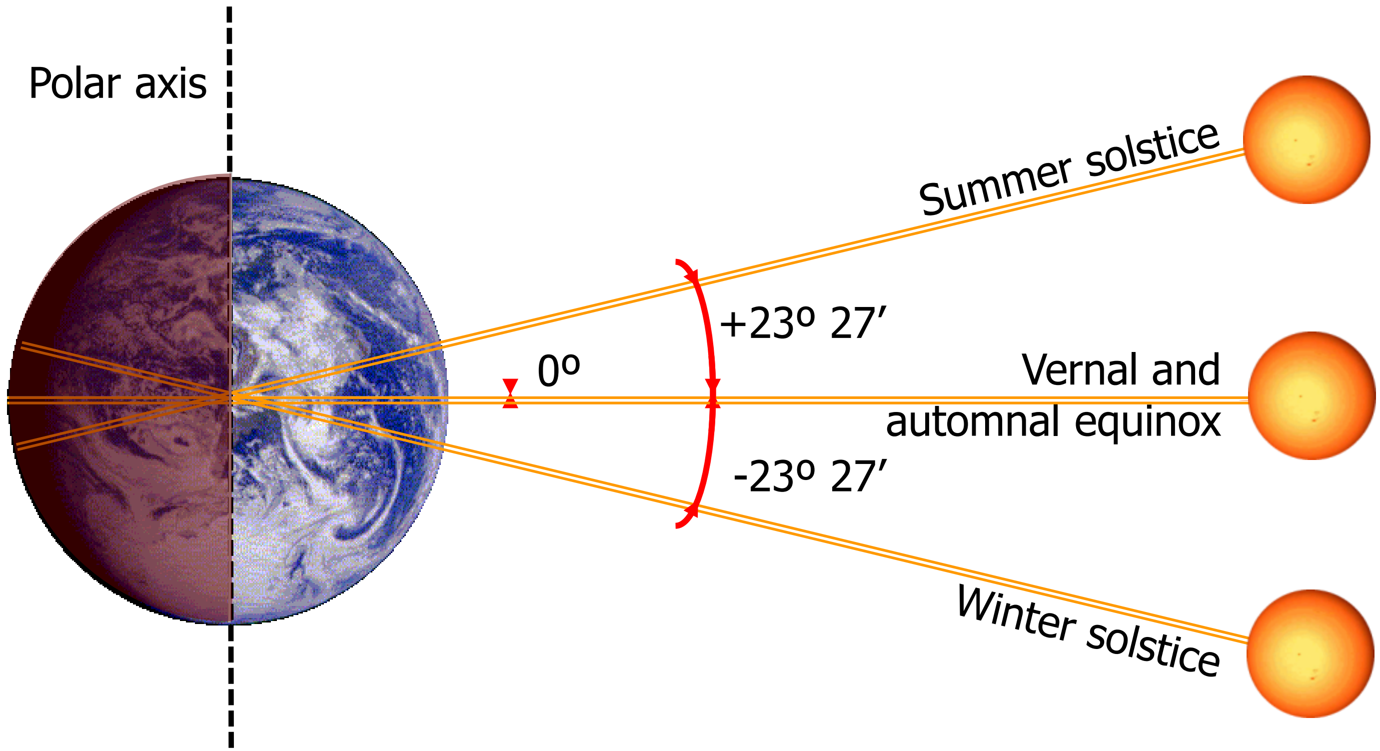

Solar resource

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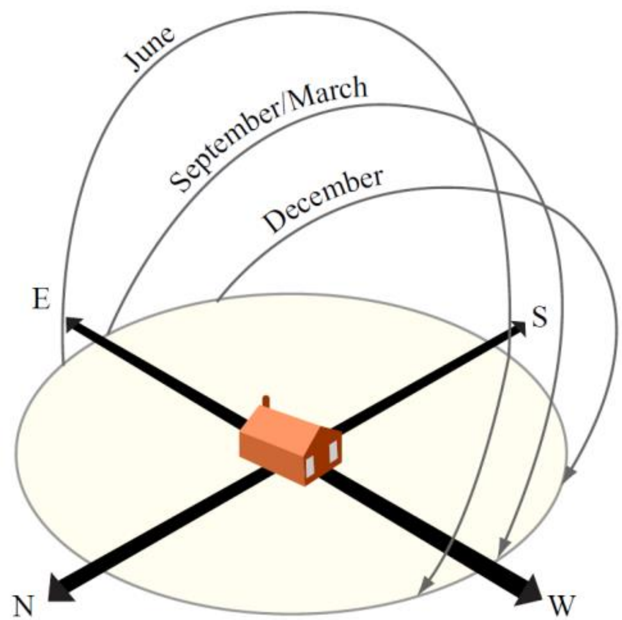


Building orientation with the long axis facing south

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

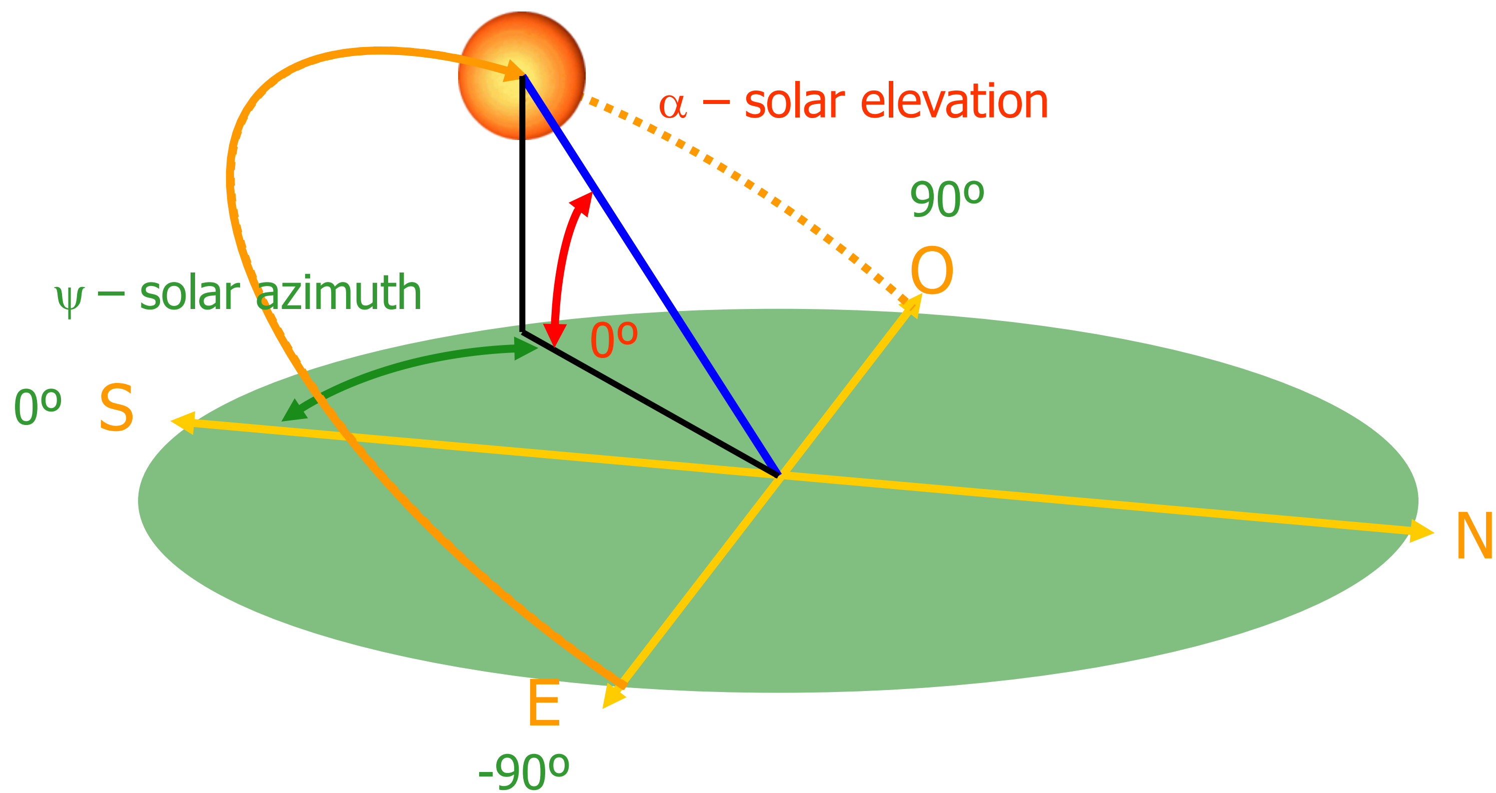
Declination in radians; n is the number of the day (Jan 1st = 1)

Solar resource

- Earth-Sun motion

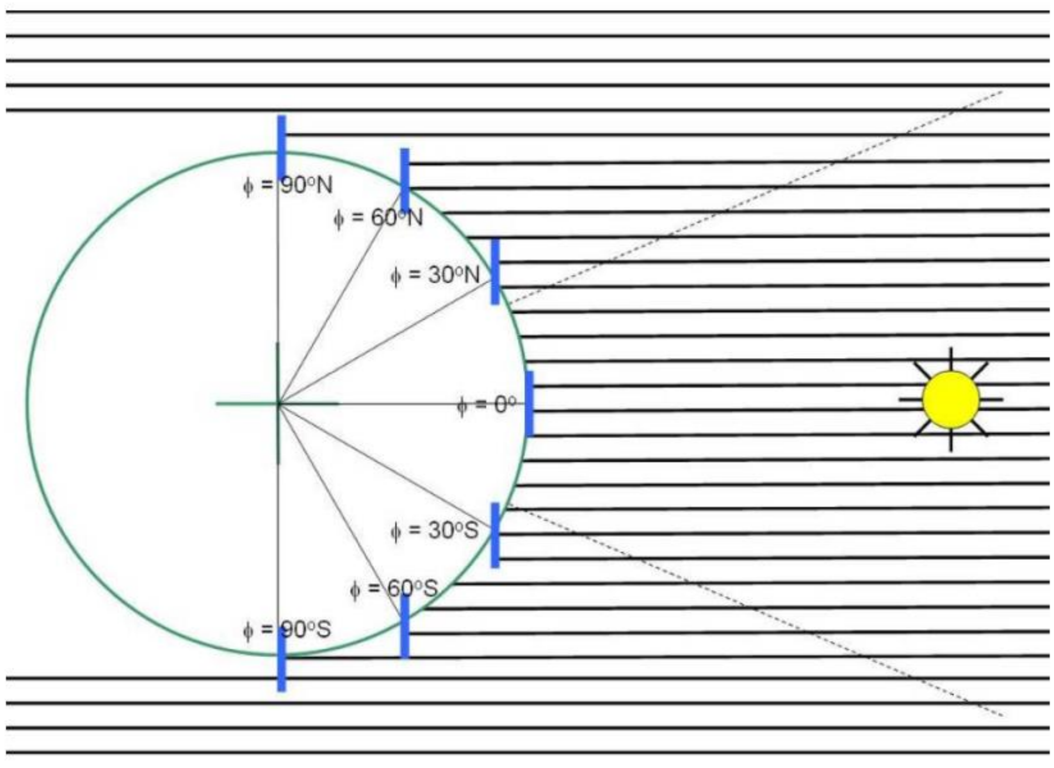
$$\sin\alpha = \sin\delta\sin\phi + \cos\delta\cos\phi$$

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



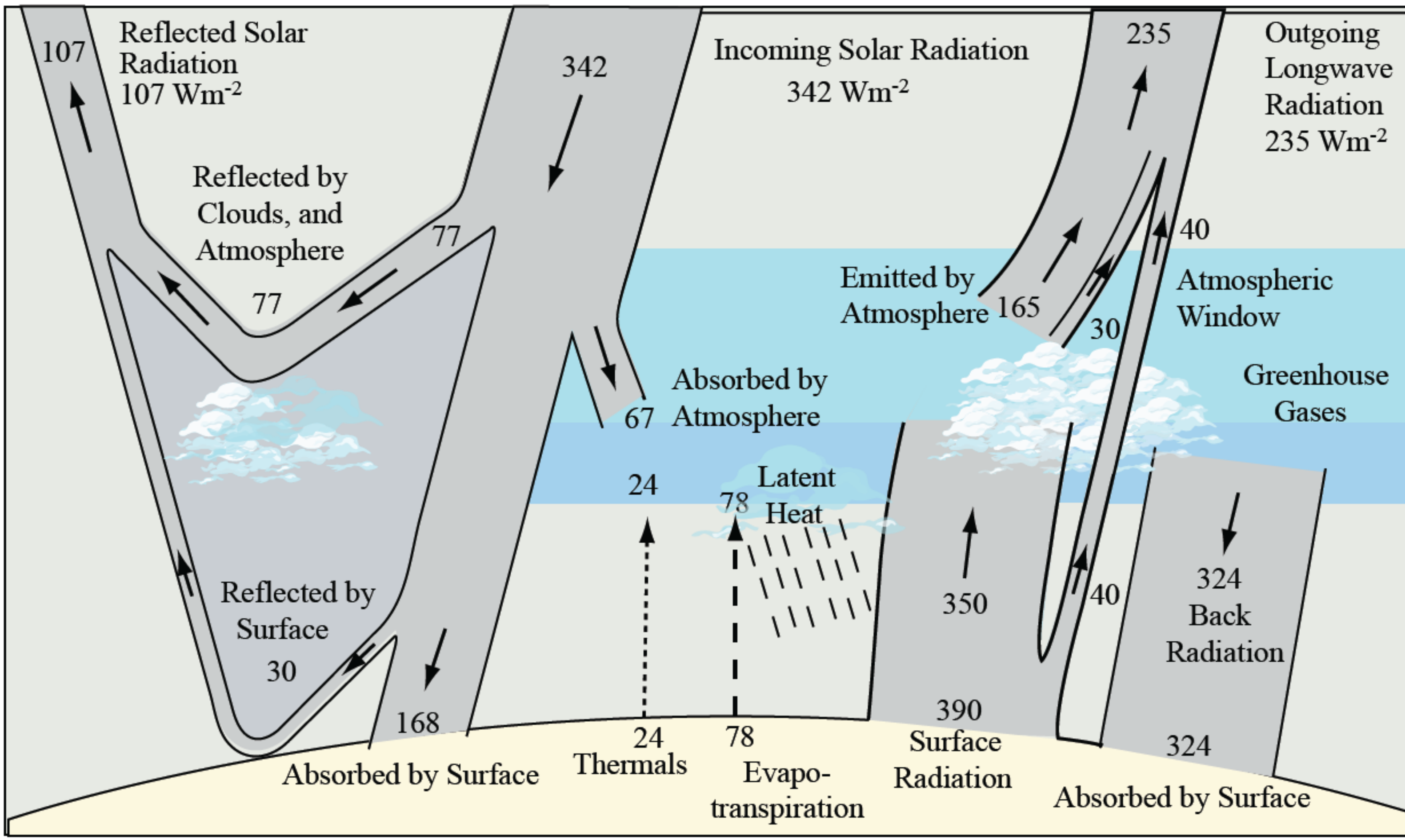
Solar resource

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



Solar resource

Atmospheric effects



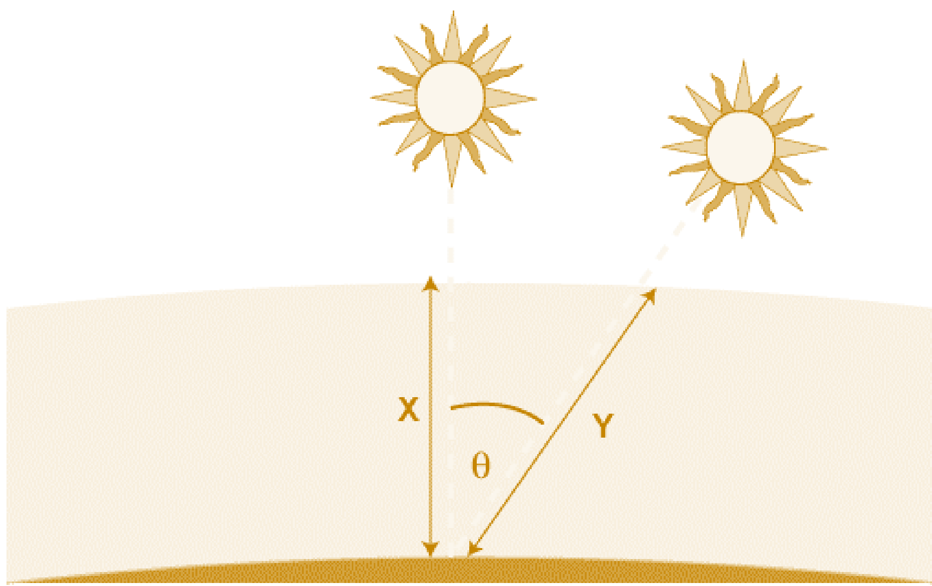
Solar resource

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.

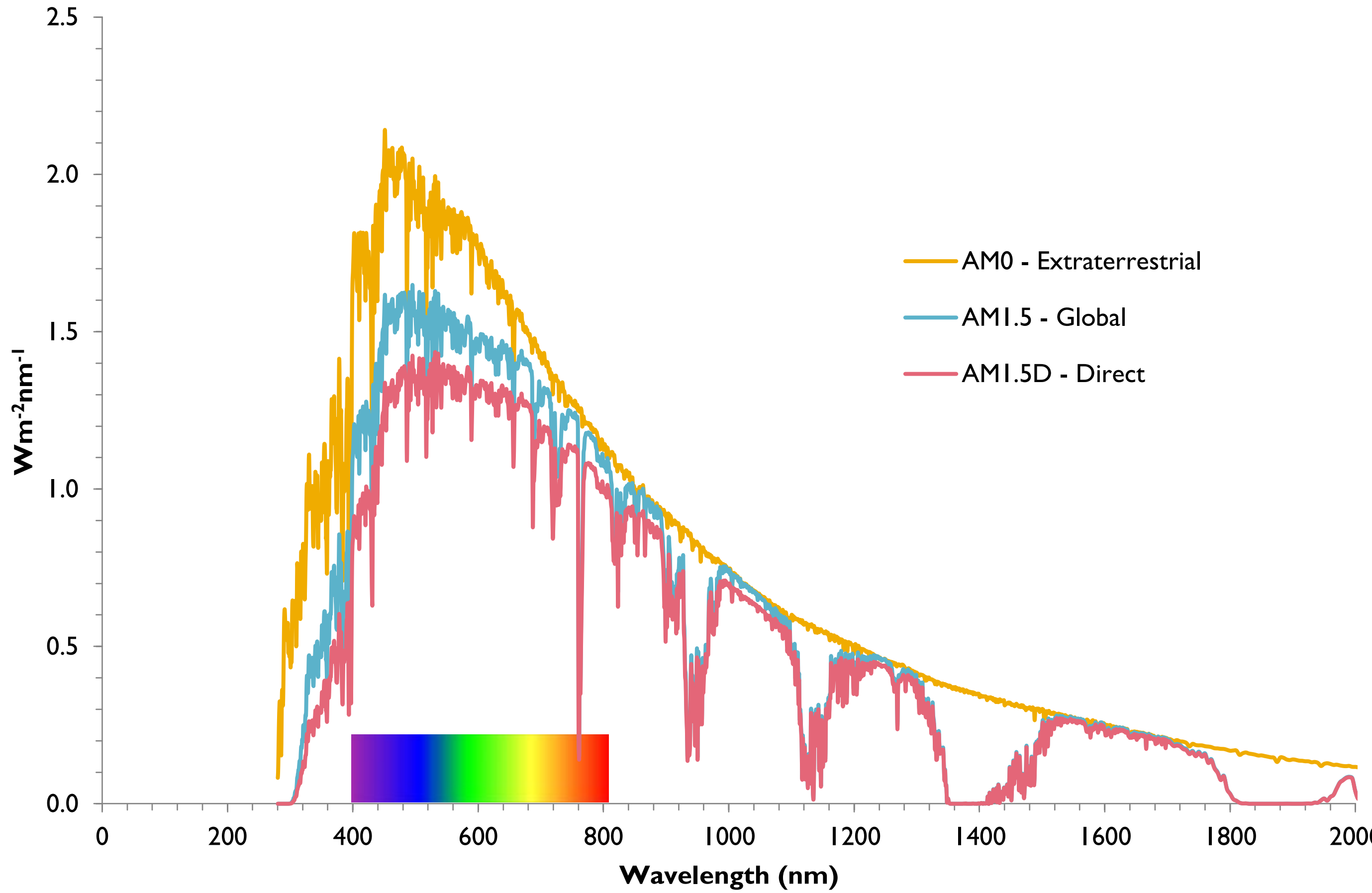
Solar resource

- 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 Φ [photons/s/m^2]
- Power density H [W/m^2]
- Spectal irradiance F [W/m^2/μm] is the power density at a given λ(μm)

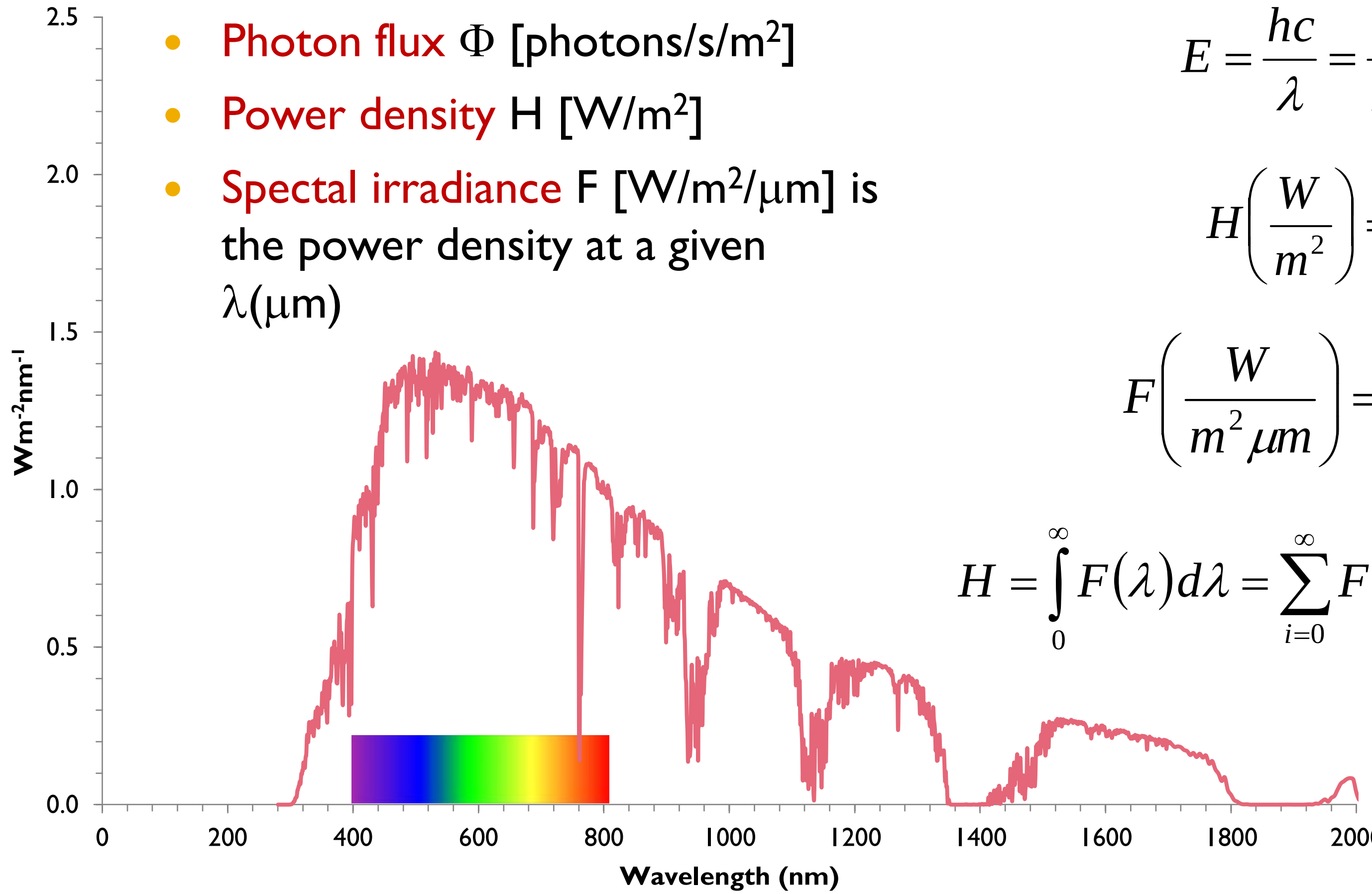
$$\Phi = \frac{photons}{m^2 s}$$

$$E = \frac{hc}{\lambda} = \frac{1.24}{\lambda(\mu m)}$$

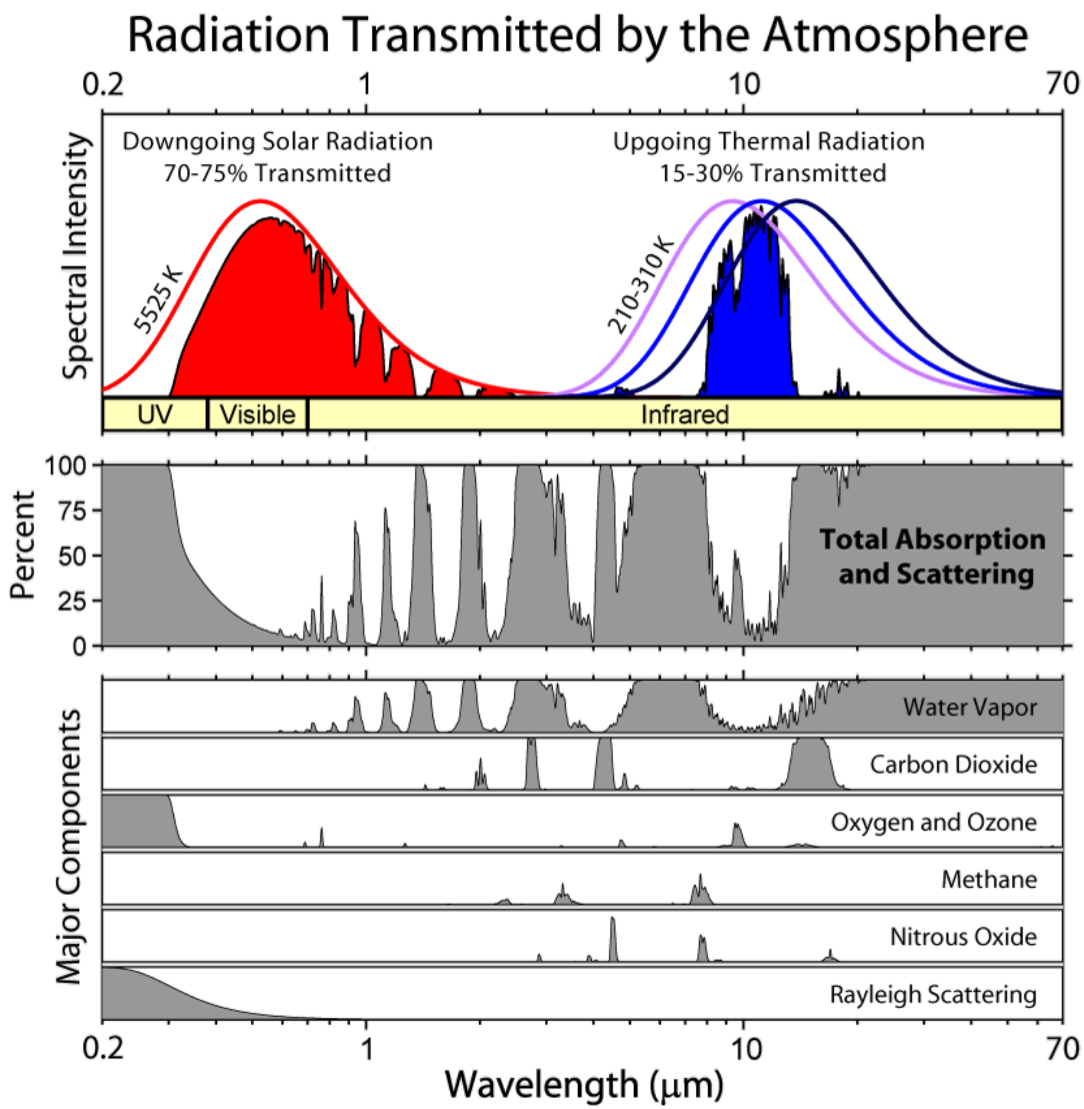
$$H\left(\frac{W}{m^2}\right) = \Phi \frac{hc}{\lambda}$$

$$F\left(\frac{W}{m^2 \mu m}\right) = \Phi \frac{hc}{\lambda^2}$$

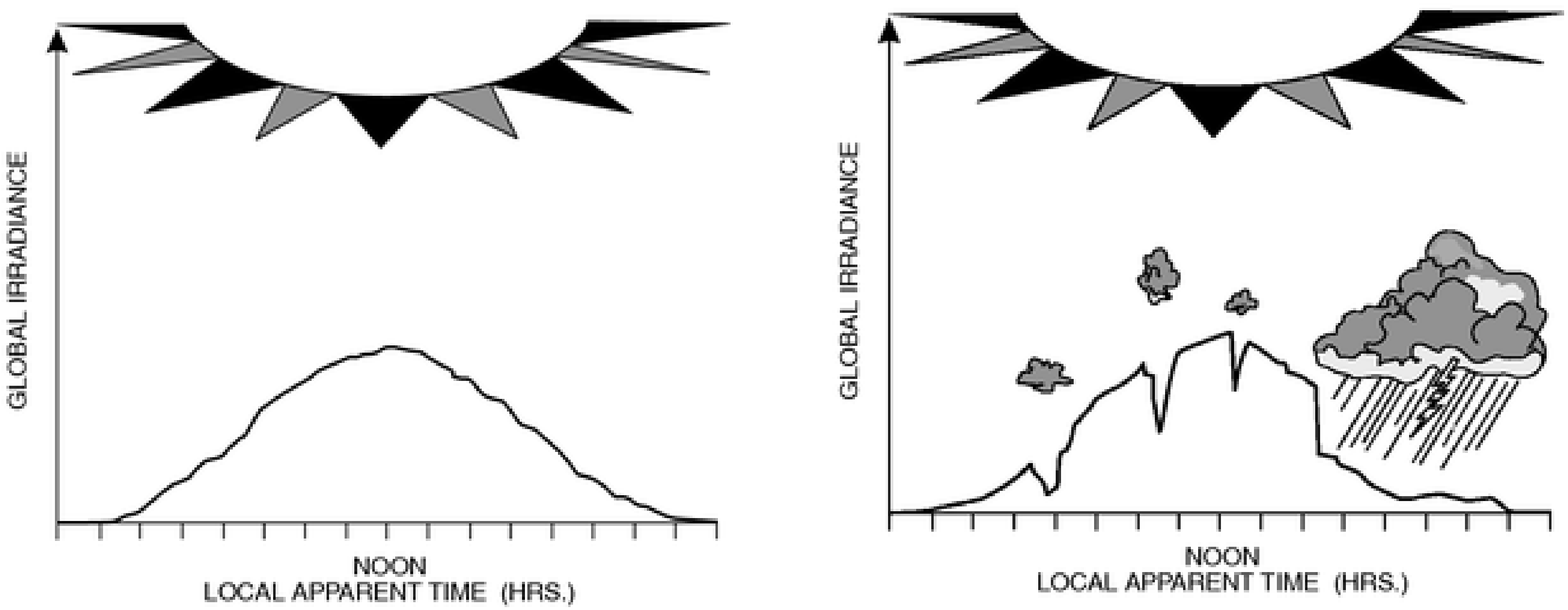
$$H = \int_0^\infty F(\lambda)d\lambda = \sum_{i=0}^{\infty} F(\lambda)\Delta\lambda$$



Solar resource



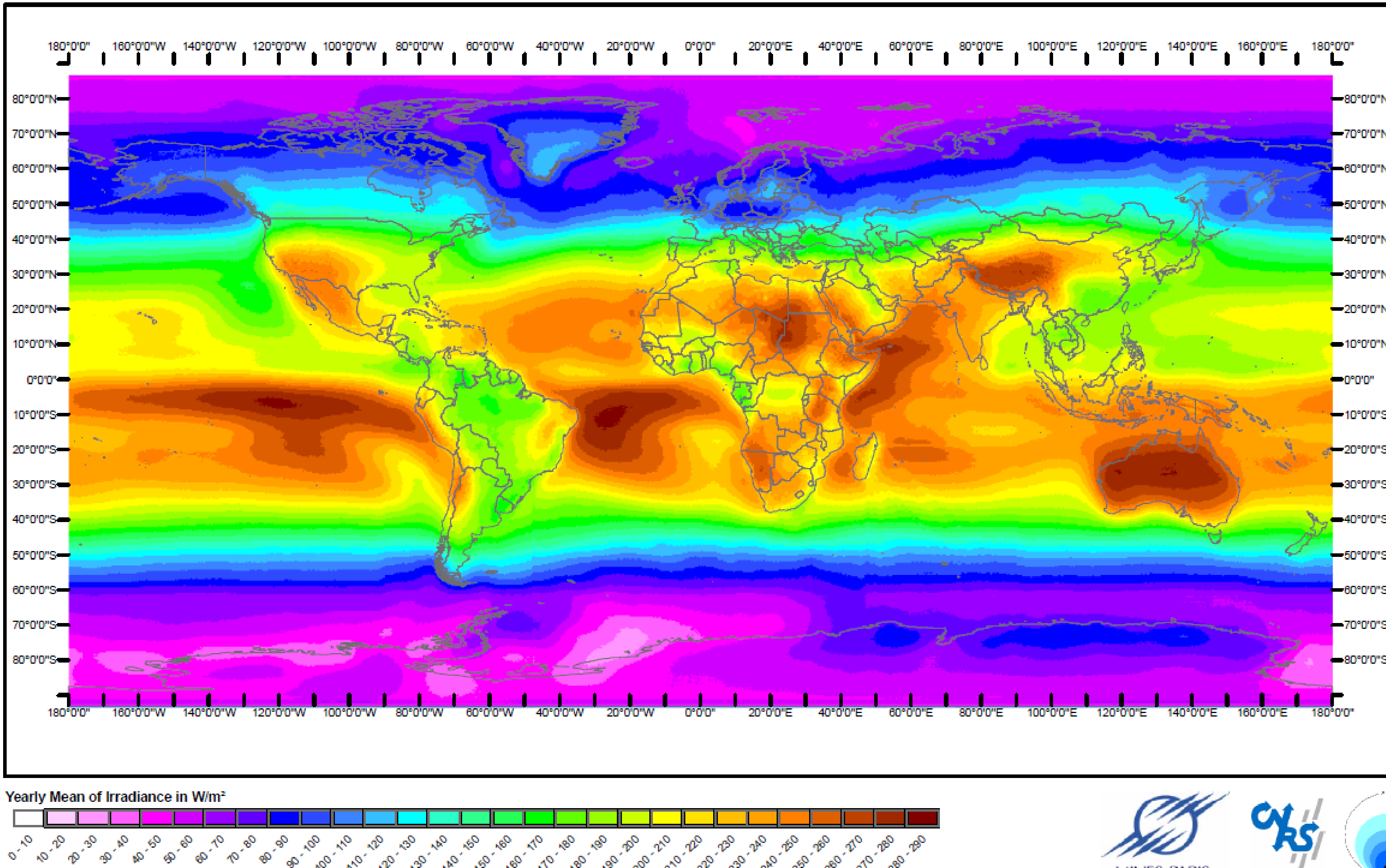
Solar resource



Solar resource

- Insolation: **In**coming **Sol**ar Radia**tion**
- Typical units: kWh/m^2/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

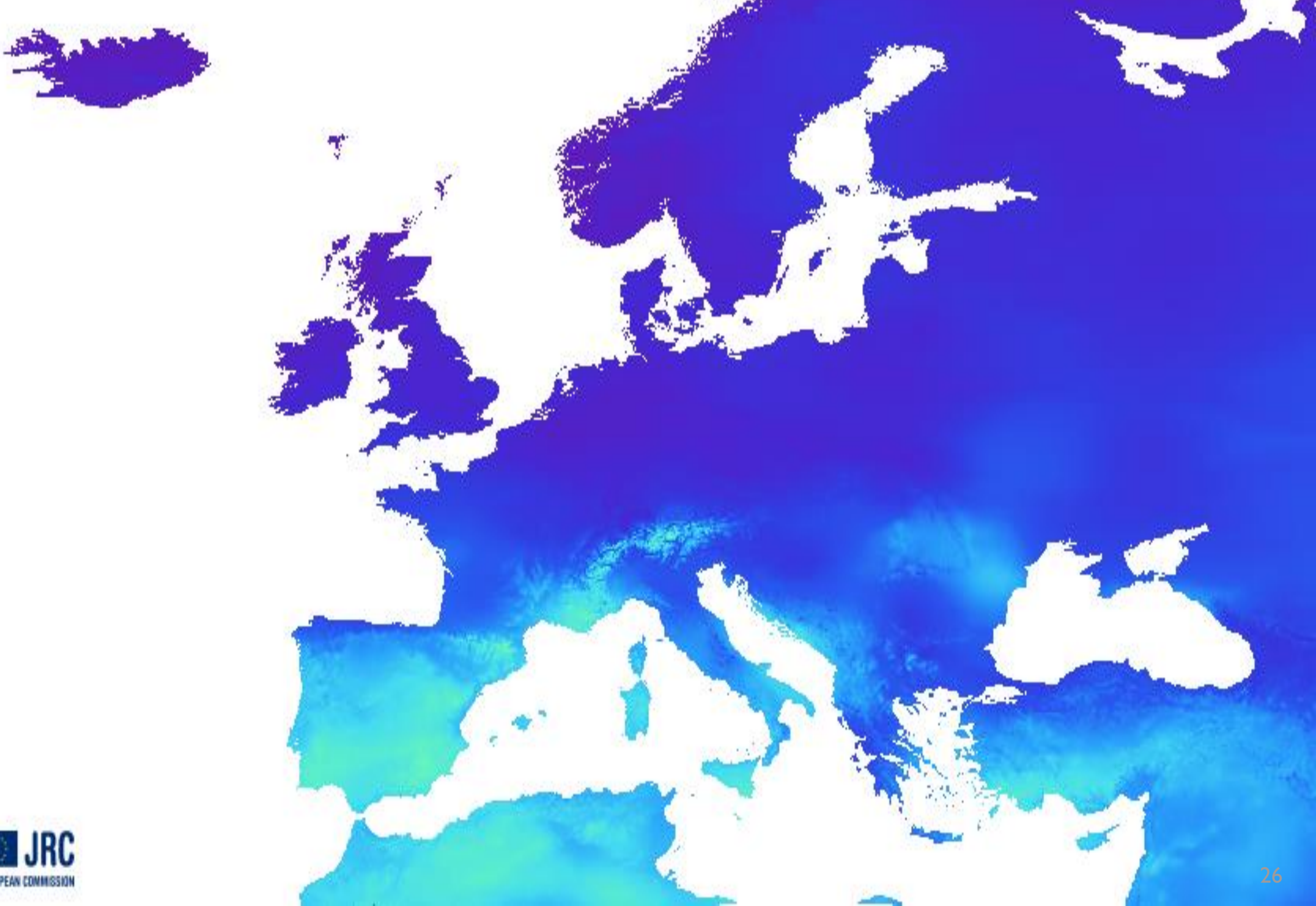


MINES PARIS

Realized by Michel Albuisson, 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 / Armines / CNRS.

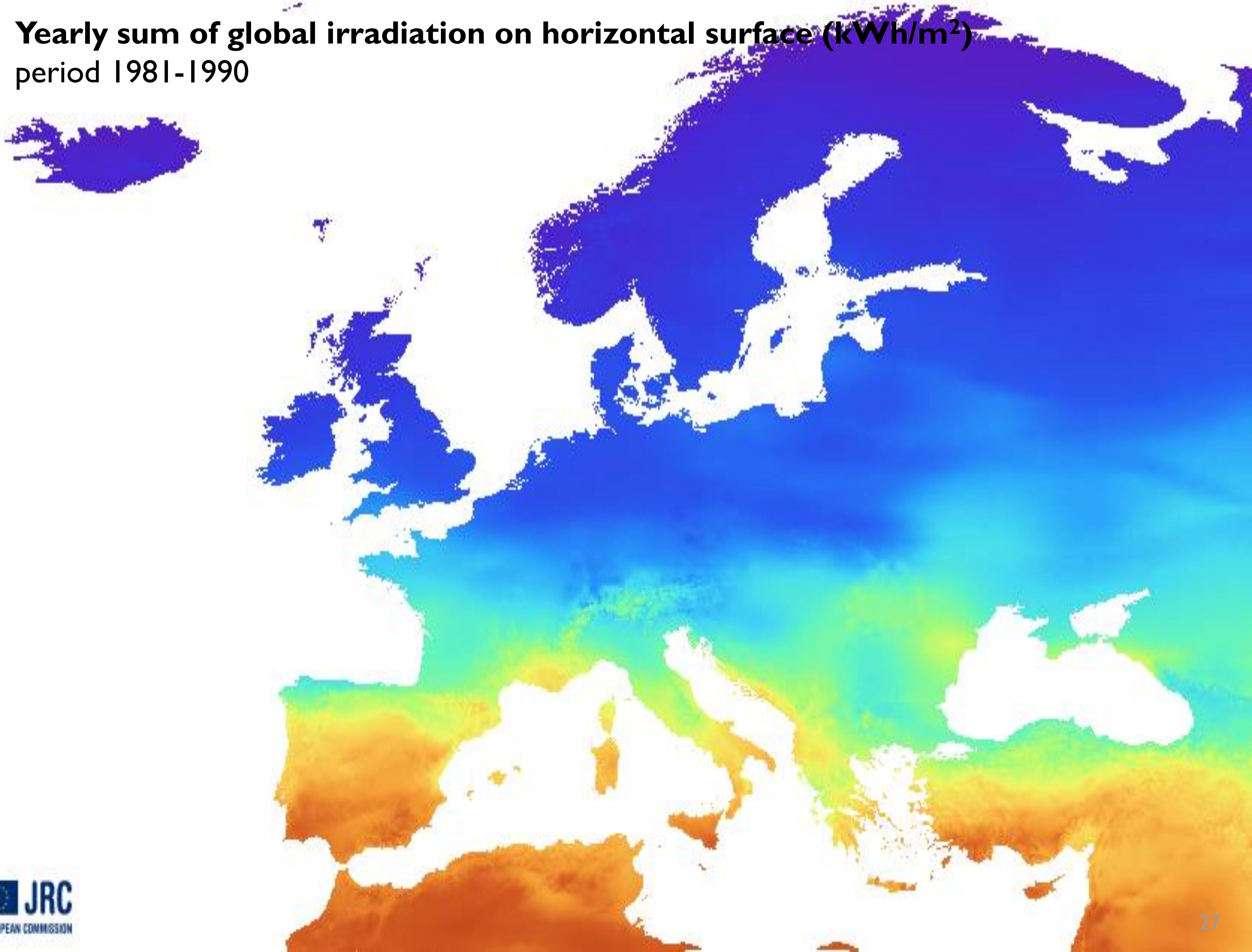
Yearly sum of global irradiation on vertical surface (kWh/m²)

period 1981-1990

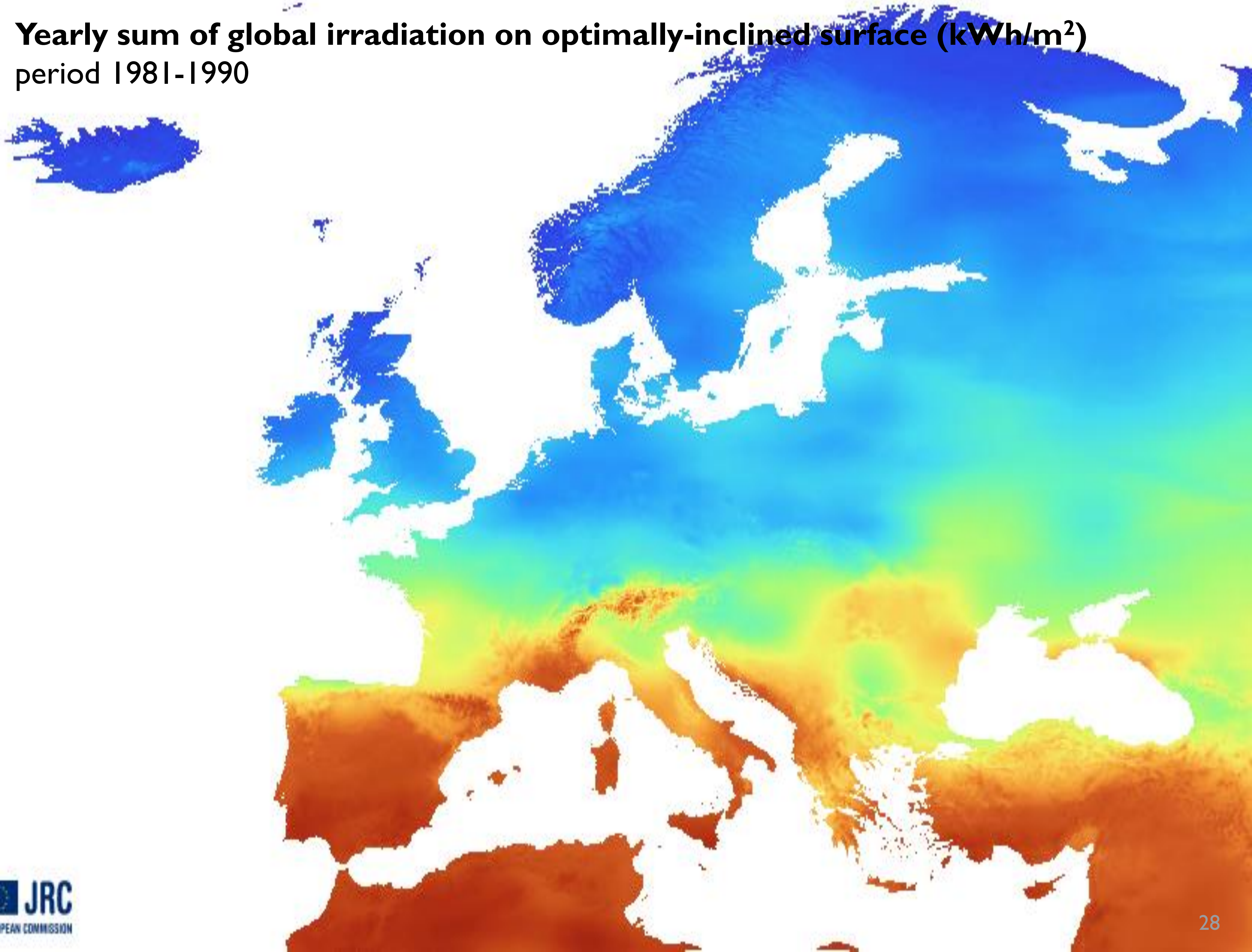


JRC
EUROPEAN COMMISSION

Yearly sum of global irradiation on horizontal surface (kWh/m²)
period 1981-1990

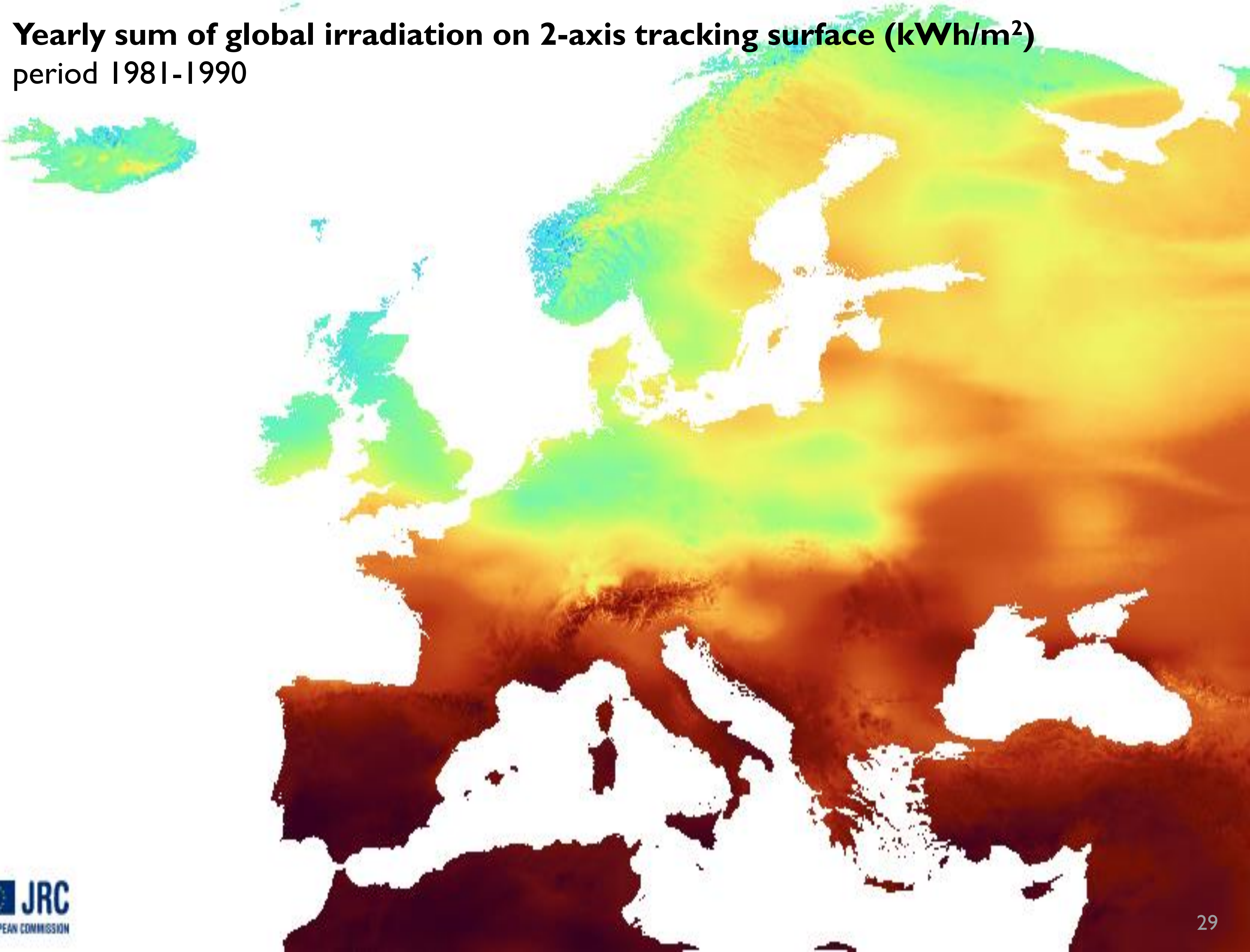


Yearly sum of global irradiation on optimally-inclined surface (kWh/m²)
period 1981-1990



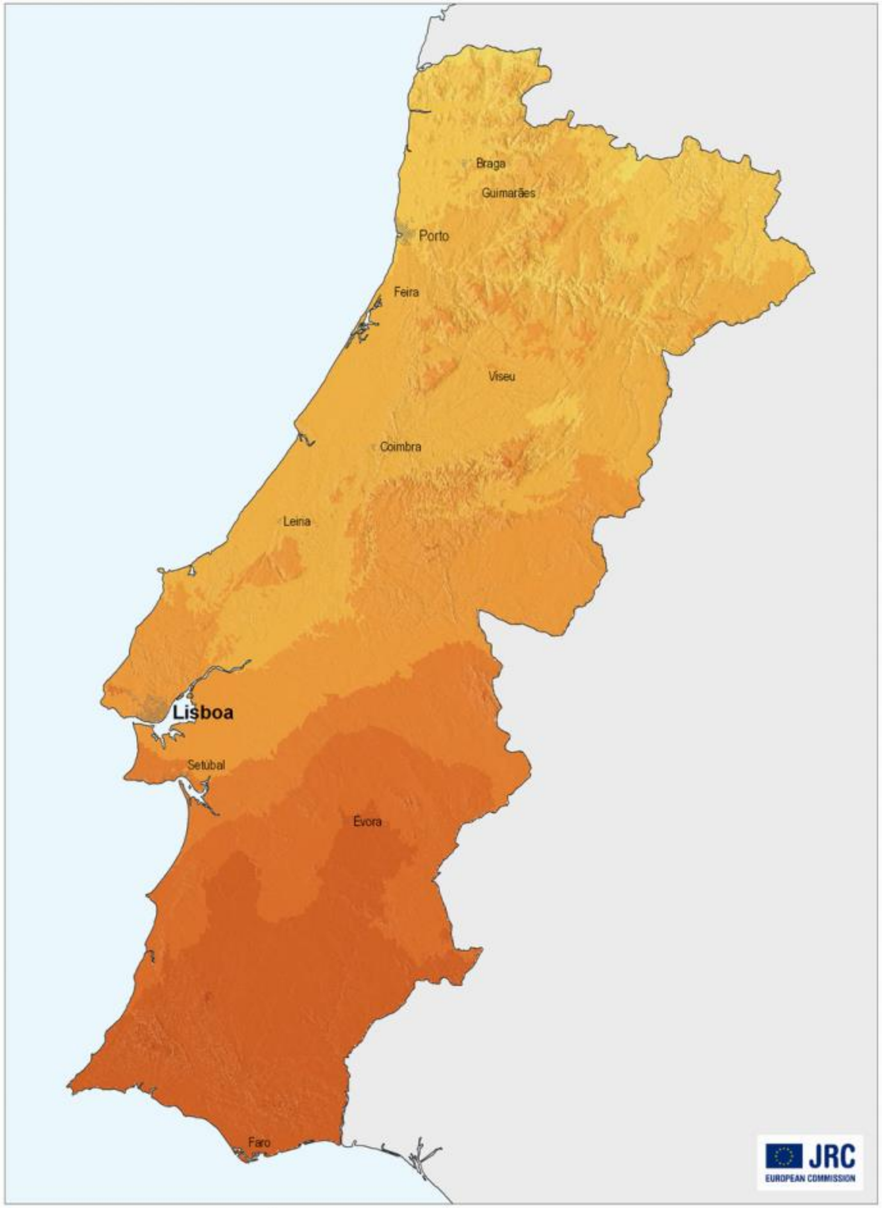
JRC
EUROPEAN COMMISSION

Yearly sum of global irradiation on 2-axis tracking surface (kWh/m²)
period 1981-1990



Global irradiation and solar electricity potential
Horizontally mounted photovoltaic modules

Portugal



Yearly sum of global irradiation [kWh/m²]

<1500 1600 1700 1800

<1125 1200 1275 1350

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

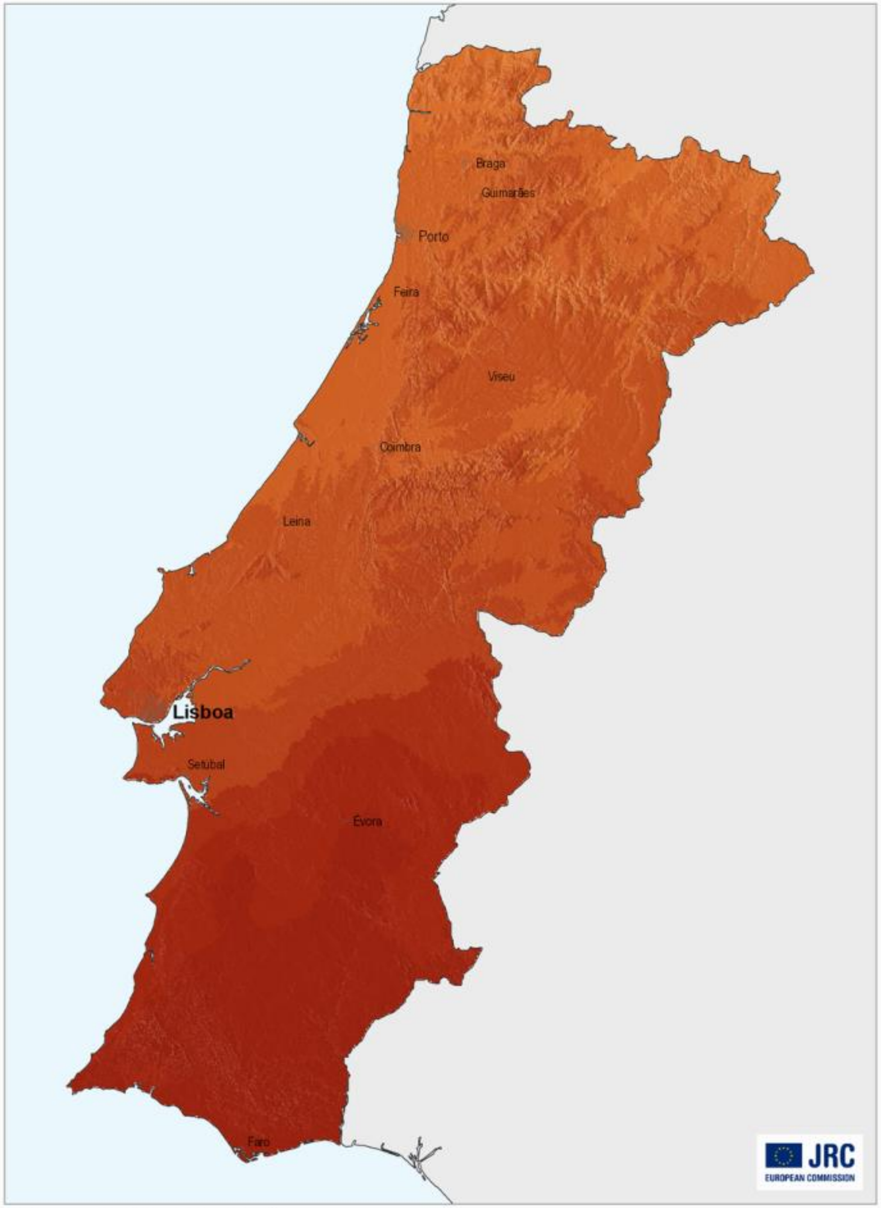
Authors: M. Šúri, T. Cebecauer, T. Huld, E. D. Dunlop

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 [kWh/m²]

1700 1800 1900 2000>

1275 1350 1425 1500>

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

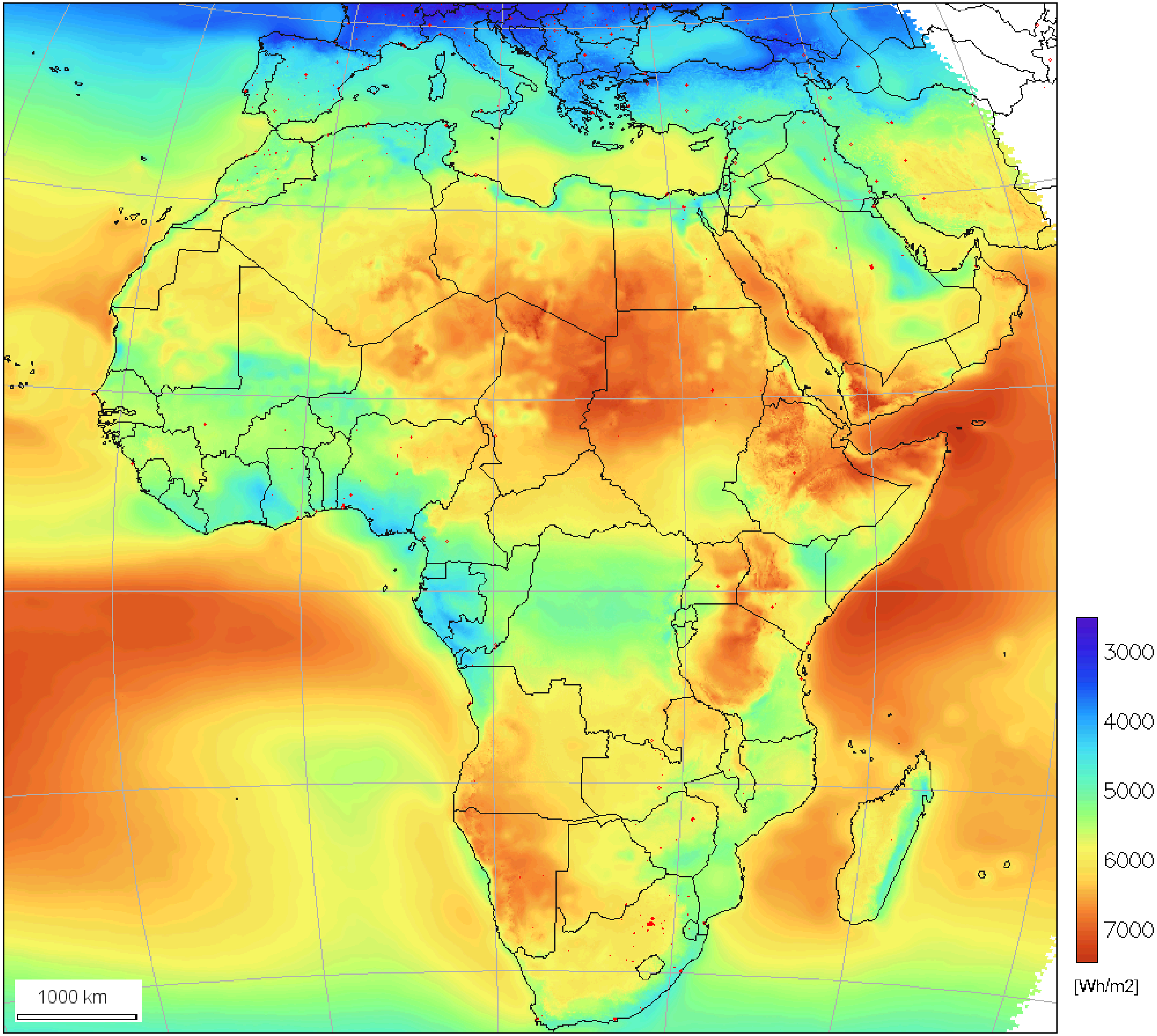
Authors: M. Šúri, T. Cebecauer, T. Huld, E. D. Dunlop
PVGIS © European Communities, 2001-2008
http://re.jrc.ec.europa.eu/pvgis/

0 25 50 km

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

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

MINES PARIS



http://re.jrc.ec.europa.eu/pvgis/

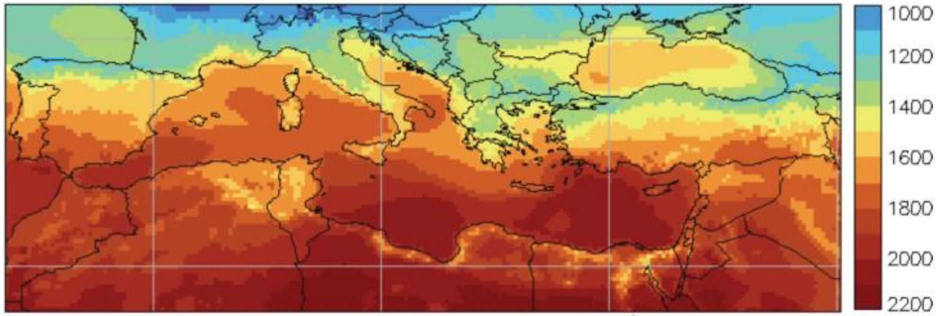


Figure 1: Long-term average of yearly sums of global horizontal irradiation (kWh/m^2, time series representing years 1985, 1987, and 1989-2004)

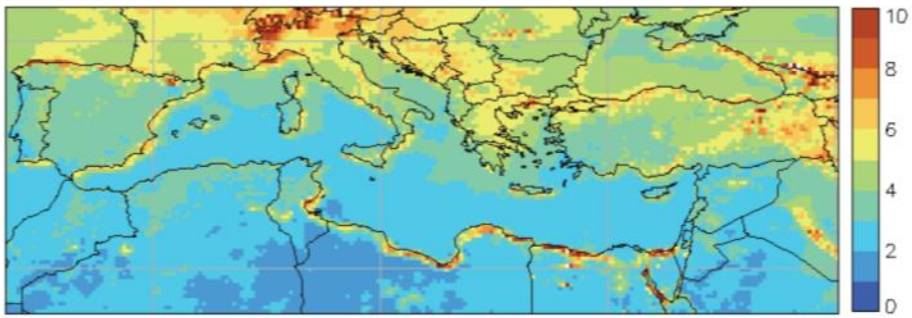


Figure 2: Standard deviation (in %) of yearly sums of global horizontal irradiation (years 1985, 1987, and 1989-2004)

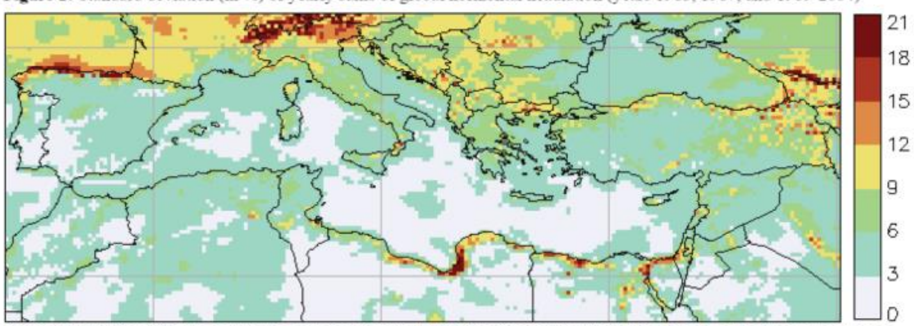


Figure 6: Relative difference of the highest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

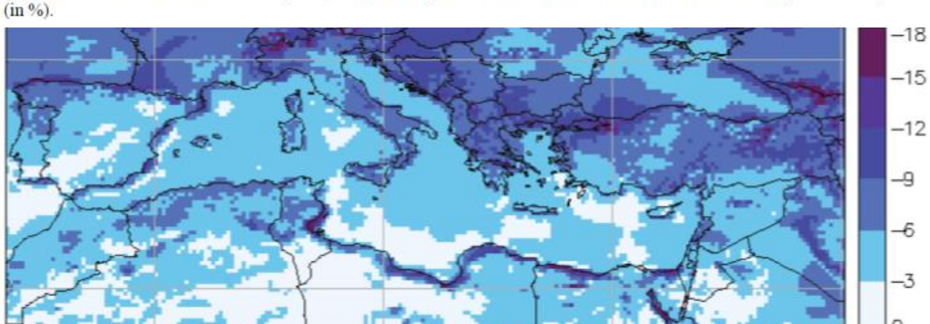


Figure 5: Relative difference of the lowest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

Solar resource

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

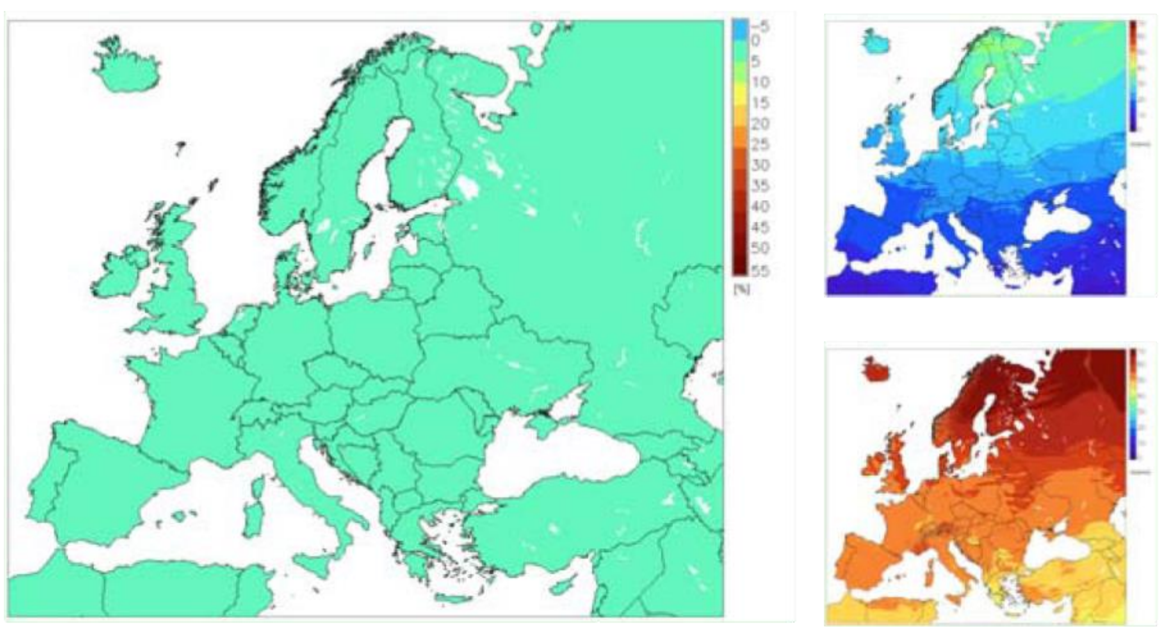
Šúri M., Huld T., Dunlop E.D., Albuisson M., Lefèvre M., Wald L., 2007. *Uncertainties in photovoltaic electricity yield prediction from fluctuation of solar radiation*. Proceedings of the 22nd European Photovoltaic Solar Energy Conference, Milano, Italy 3-7.9.2007

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



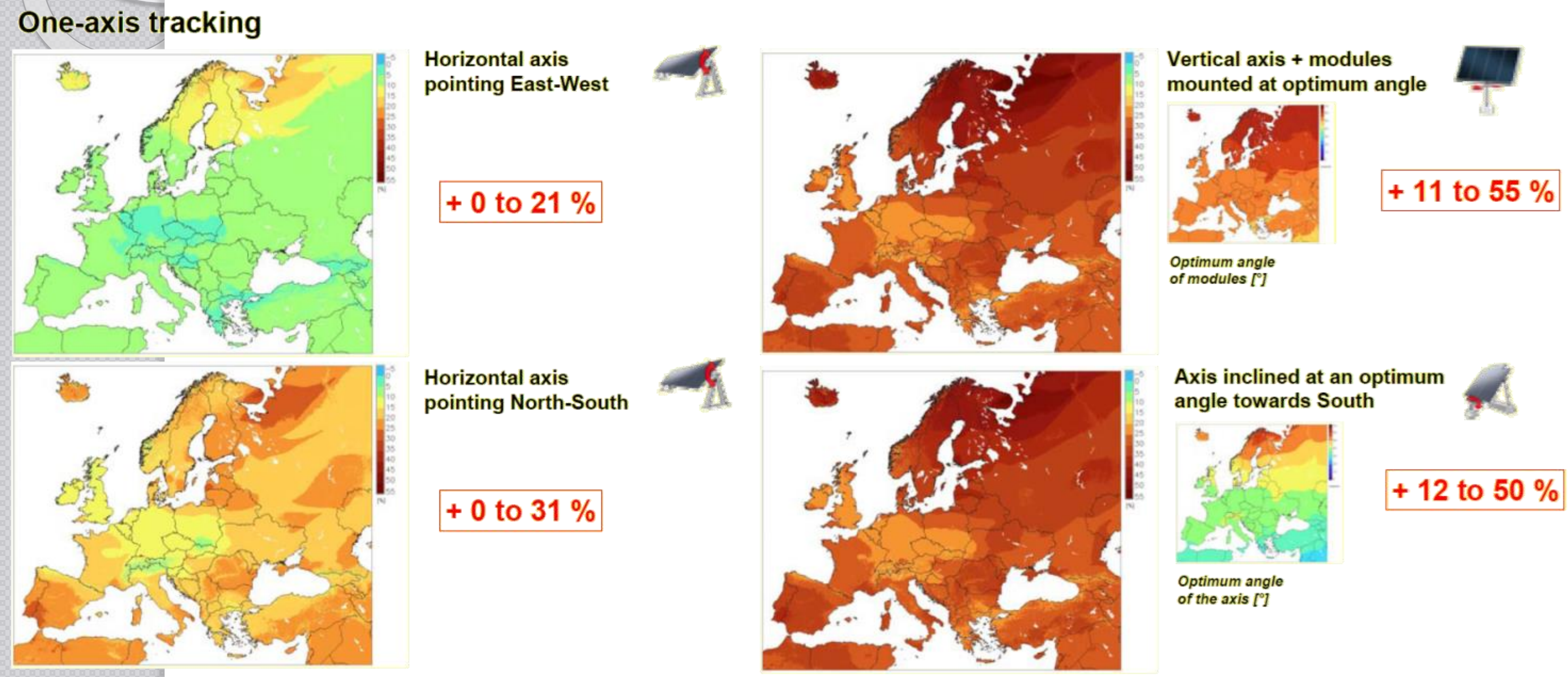
Optimum angle of modules in summer [°]

+ 1.5 to 4.5 %

Optimum angle of modules in winter [°]

Comparison of electricity yield from fixed and suntracking PV systems in Europe [JRC, 2008]

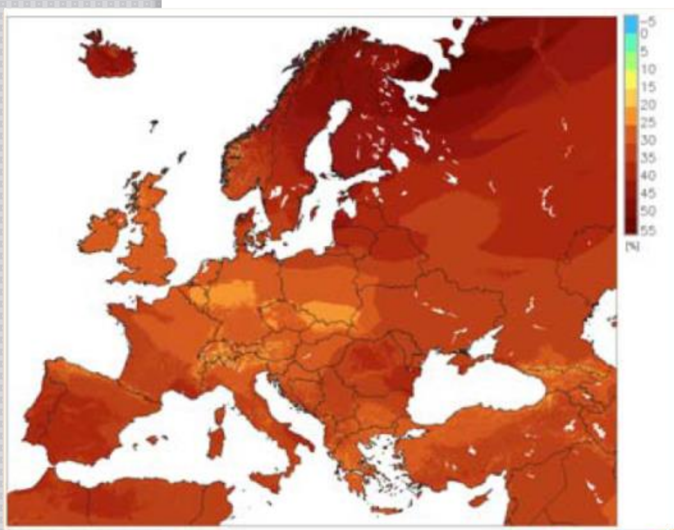
Solar tracking



Comparison of electricity yield from fixed and suntracking PV systems in Europe [JRC, 2008]

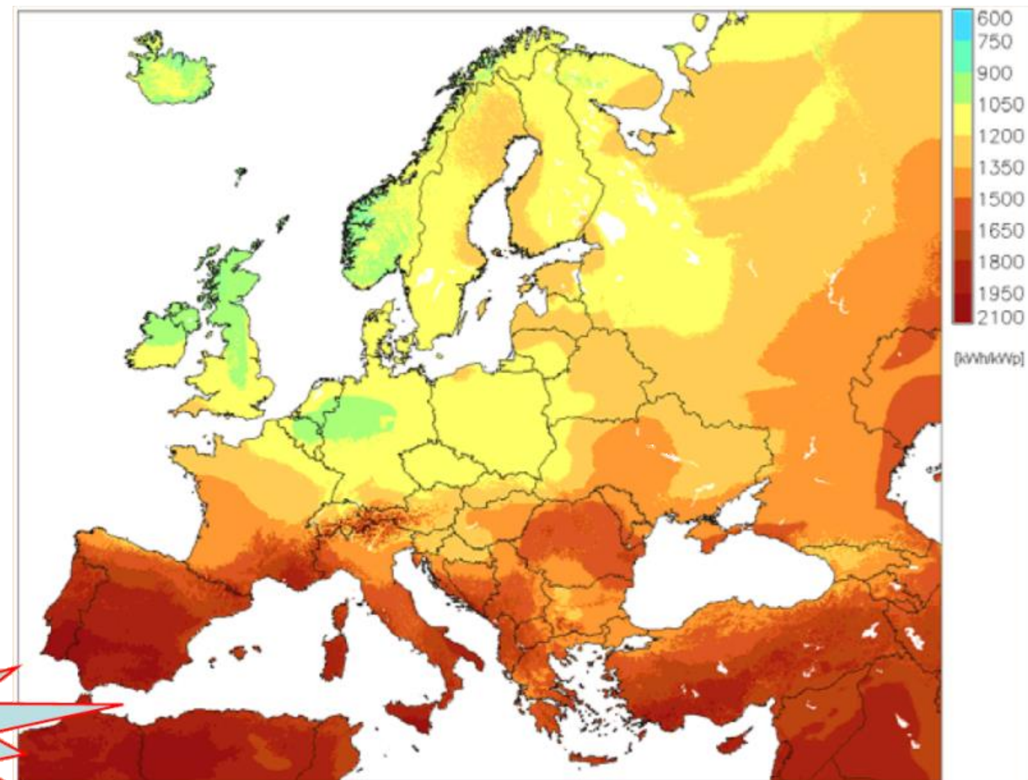
Solar tracking

Two-axis tracking



+13 to 55 %

Highest achievable



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

Comparison of electricity yield from fixed and suntracking PV systems in Europe [JRC, 2008]

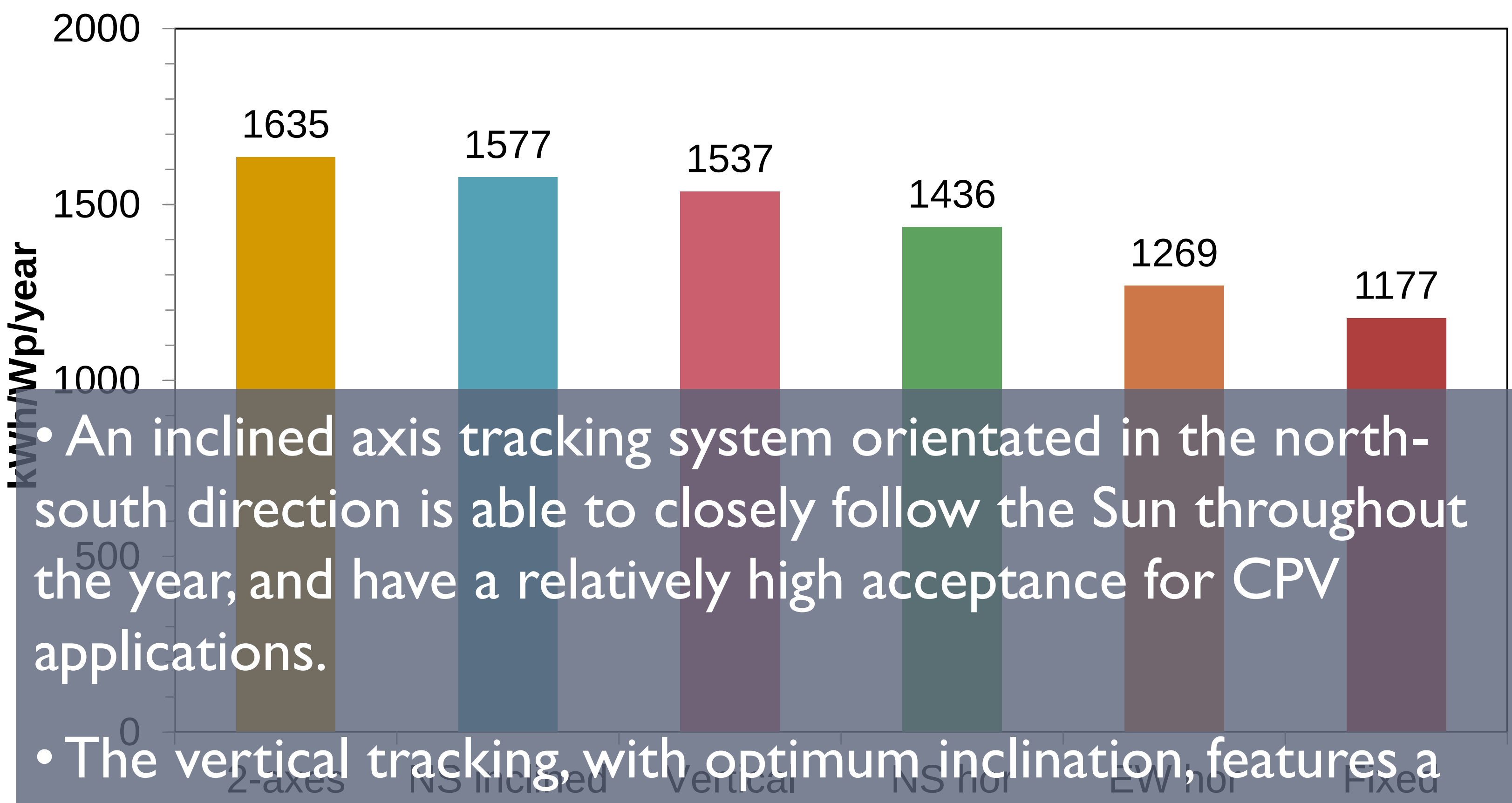
Solar tracking

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

Comparison of electricity yield from fixed and suntracking PV systems in Europe [JRC, 2008]

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.

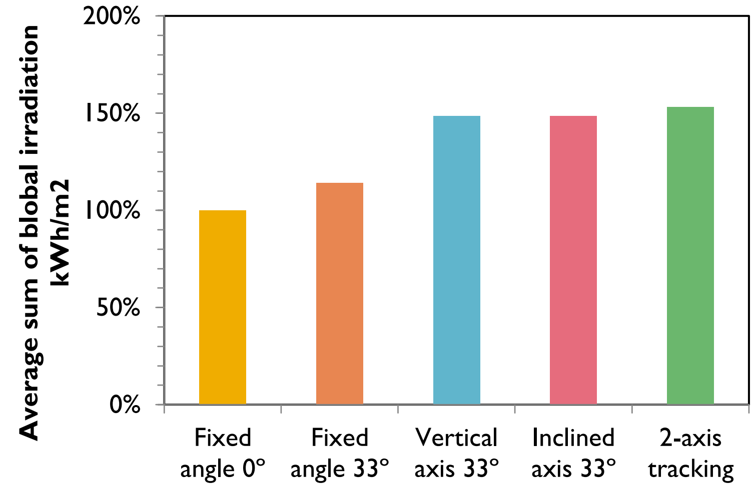
Gaspar et al, *Exploring One-Axis Tracking Configurations For CPV Application,* CPV7, Las Vegas 2011

Solar tracking

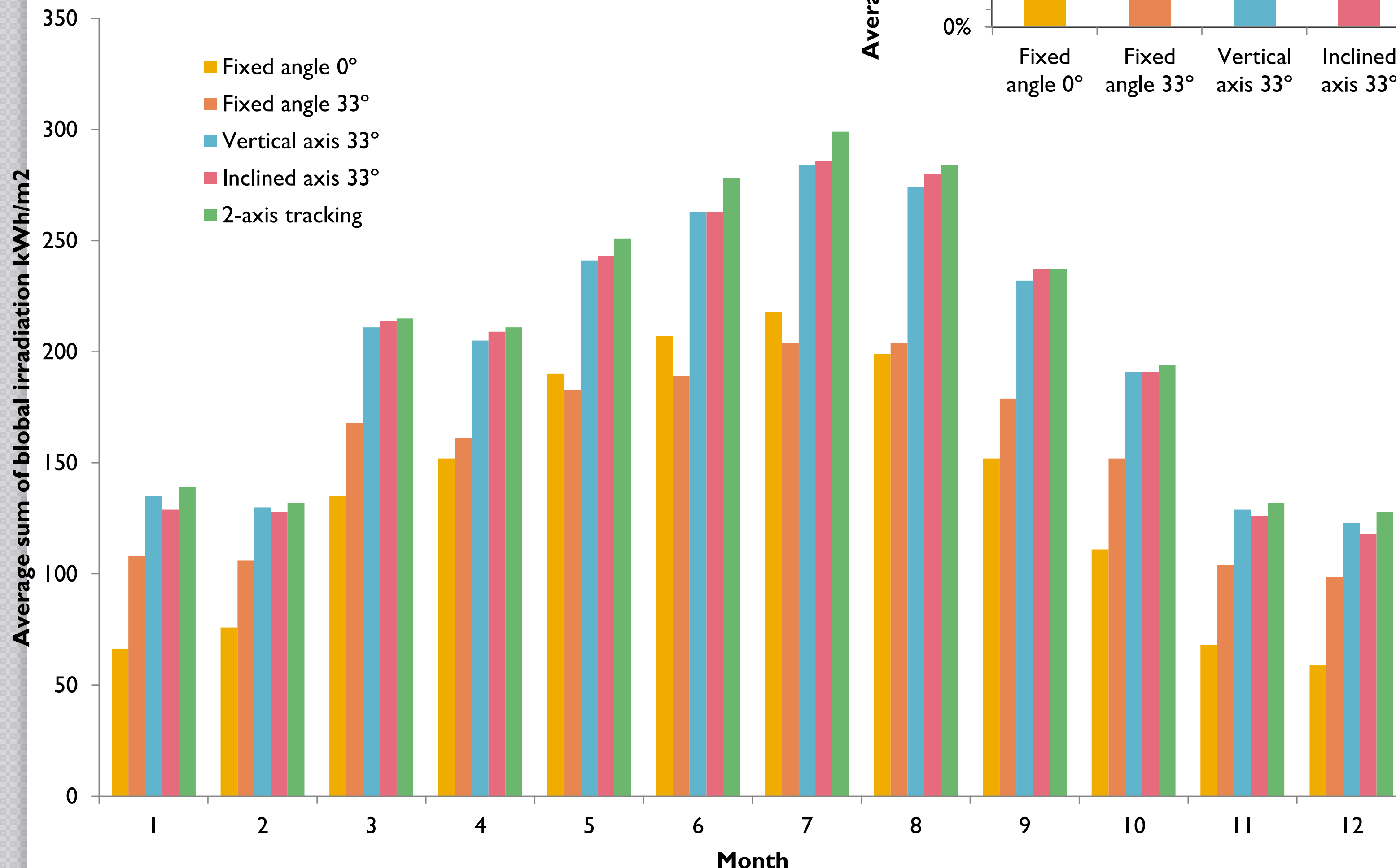
▲ Installing a screw foundation for a dual-axis tracking system (Deger-Traker) at Am Peterswald PV park in Germany: Bftec GmbH pre-drills the ground at the site and then the foundation is installed. The foundation's unusual form, which consists of a smooth side wall with a coil at the bottom (if necessary, 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

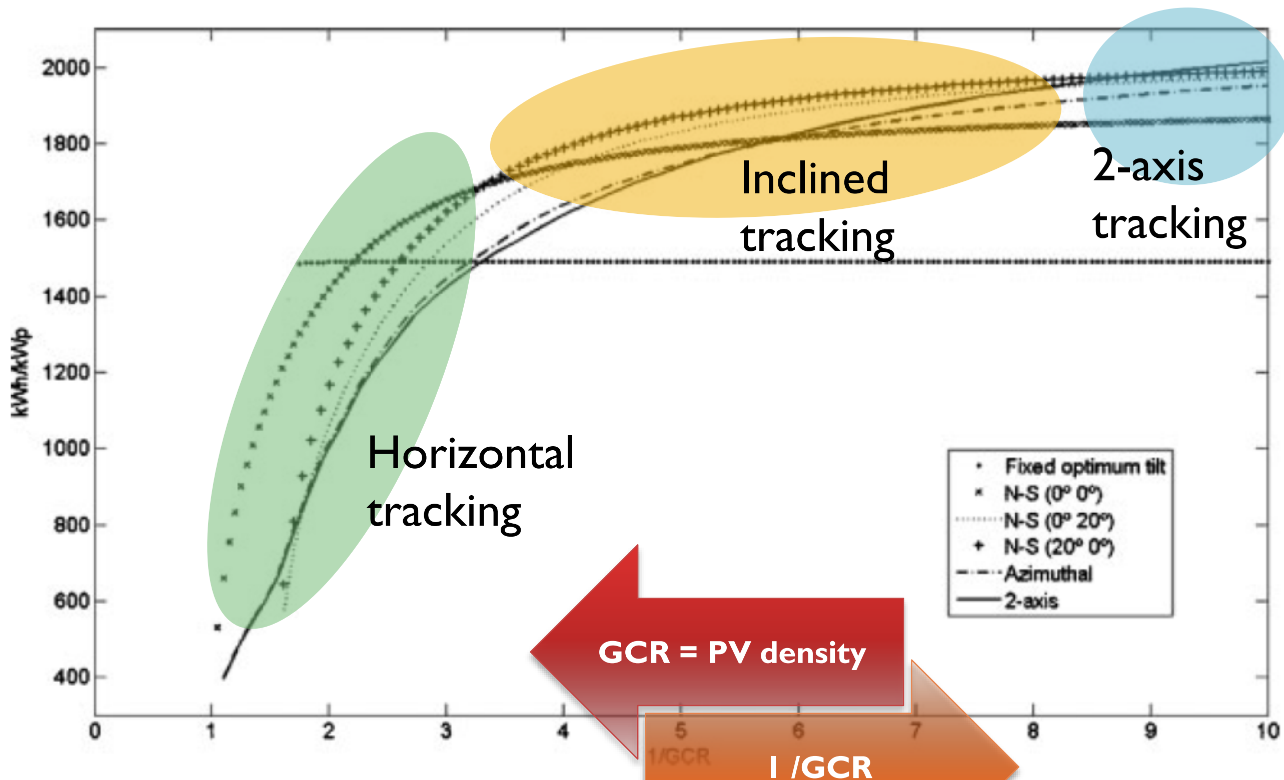


Figure 13. Evolution of yearly energy yield in A[...]ategies considered here, for the pessimistic shading case and assuming a constant dirt[...]ness degree of 3%

E. Narvarte *et al, Tracking and Ground Cover Ratio,* Prog. Photovolt: Res. Appl. 2008; 16:703–714

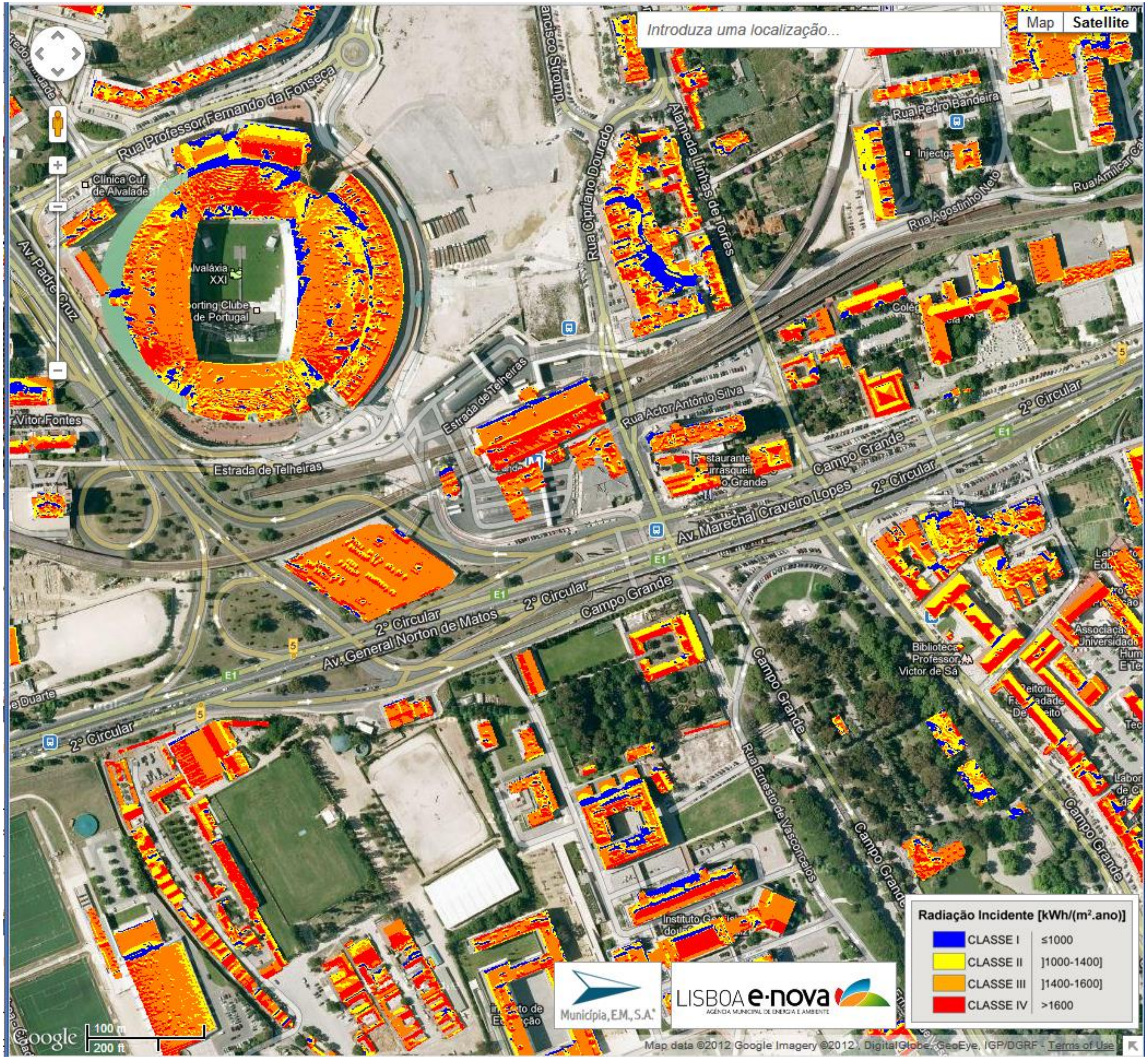
Solar in the city

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

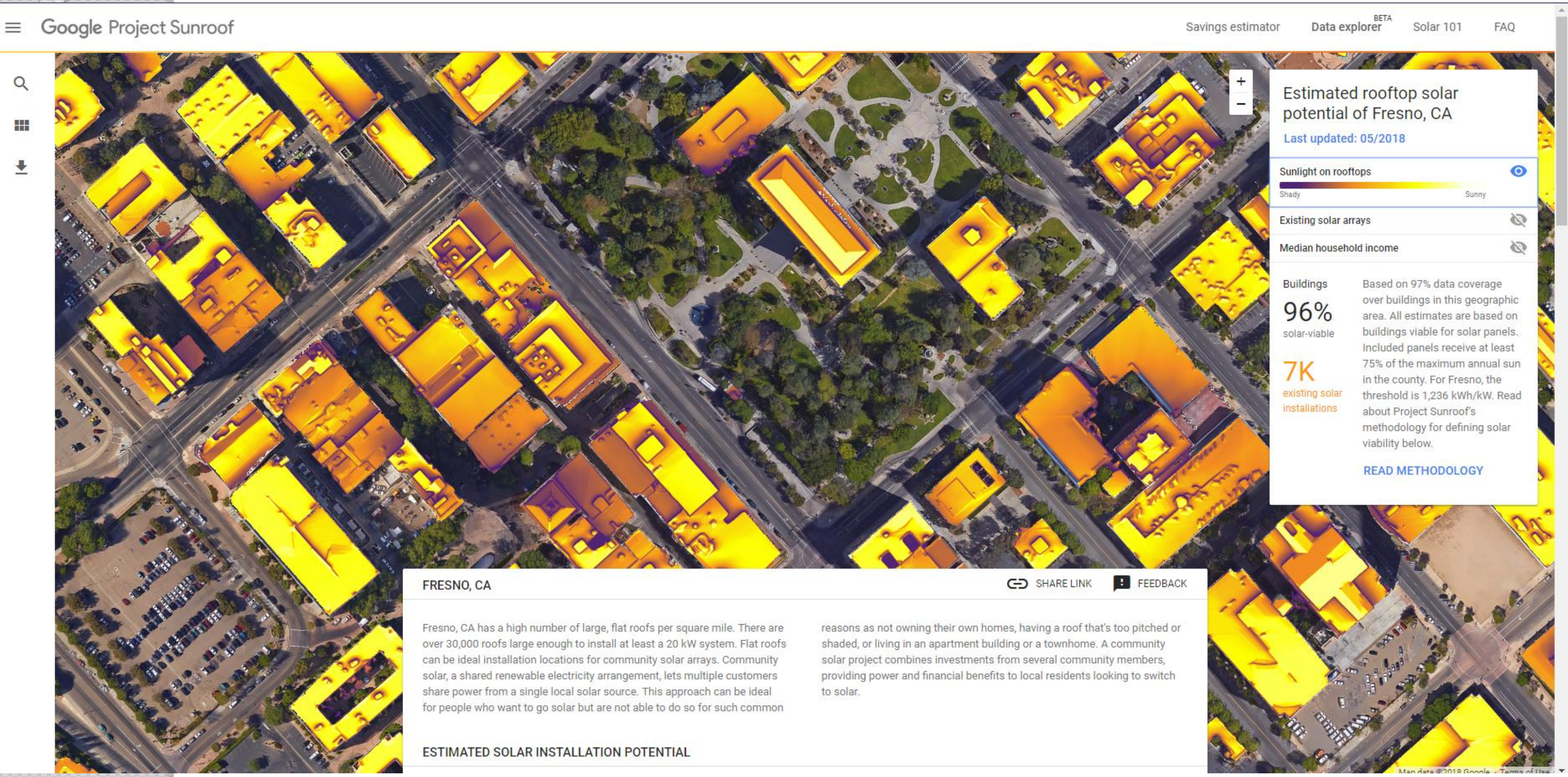
https://doi.org/10.1016/j.solener.2008.03.007


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

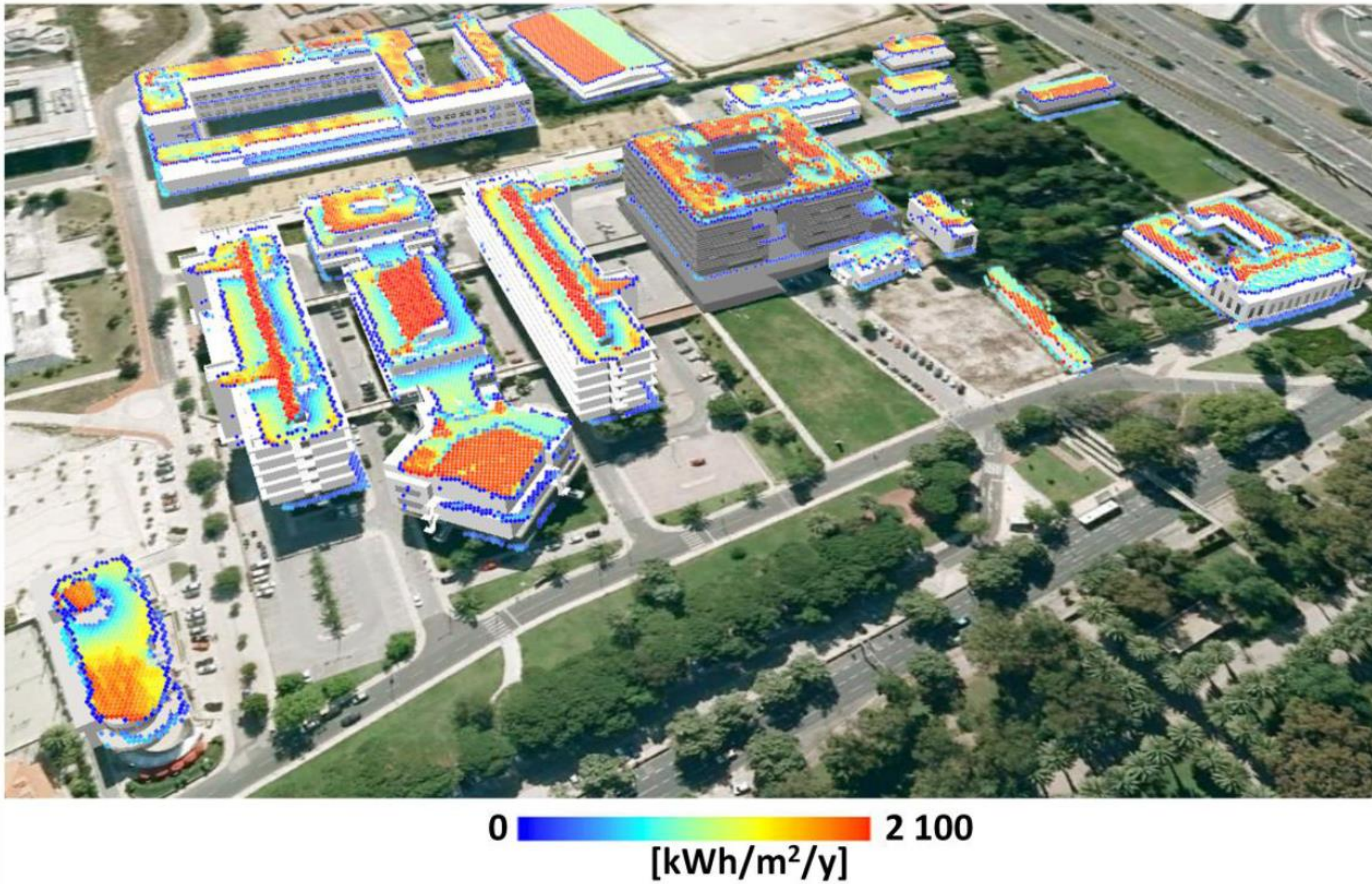


http://www.lisboaenova.org/pt/cartasolarlisboa

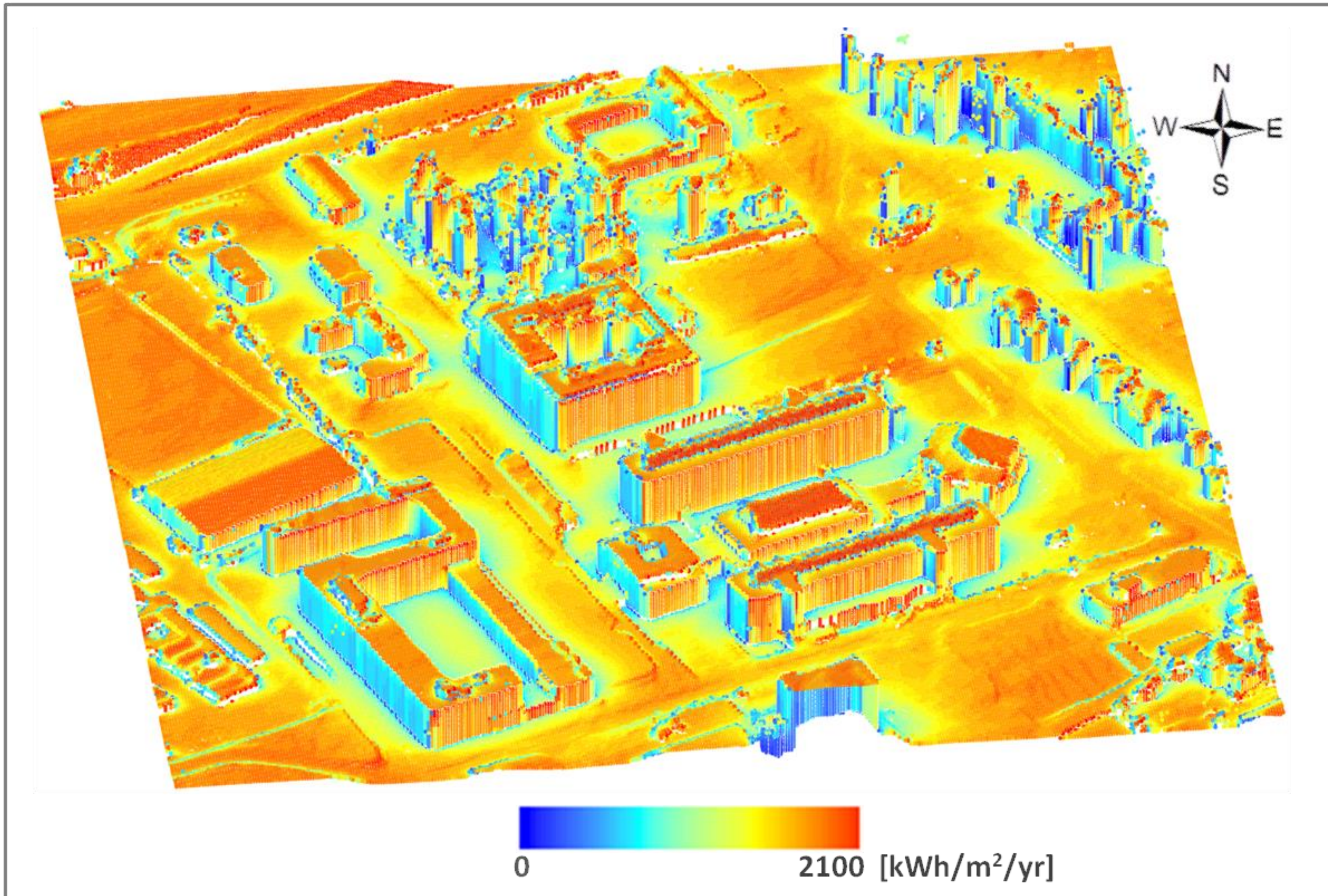
Solar in the city



Solar in the city

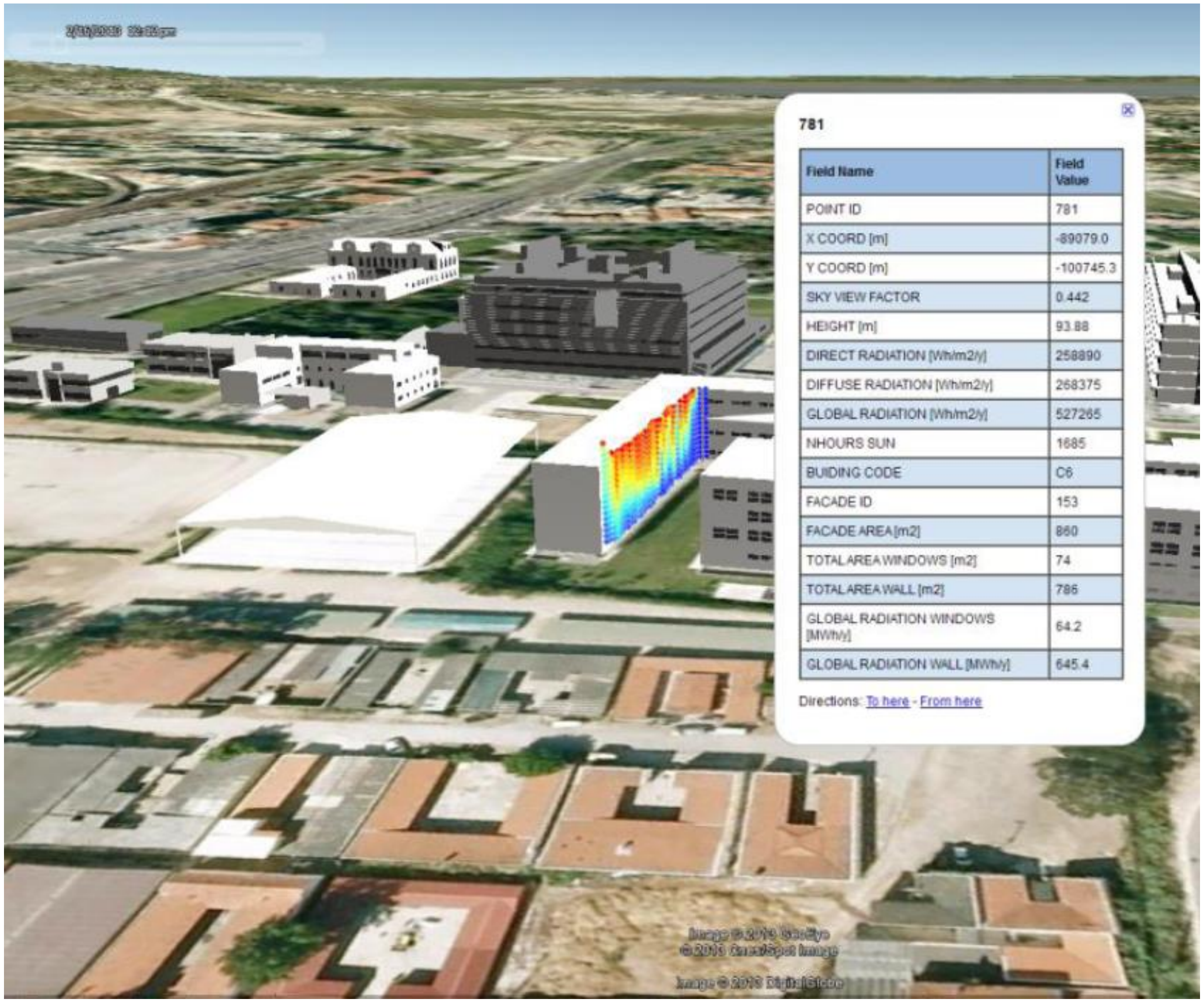


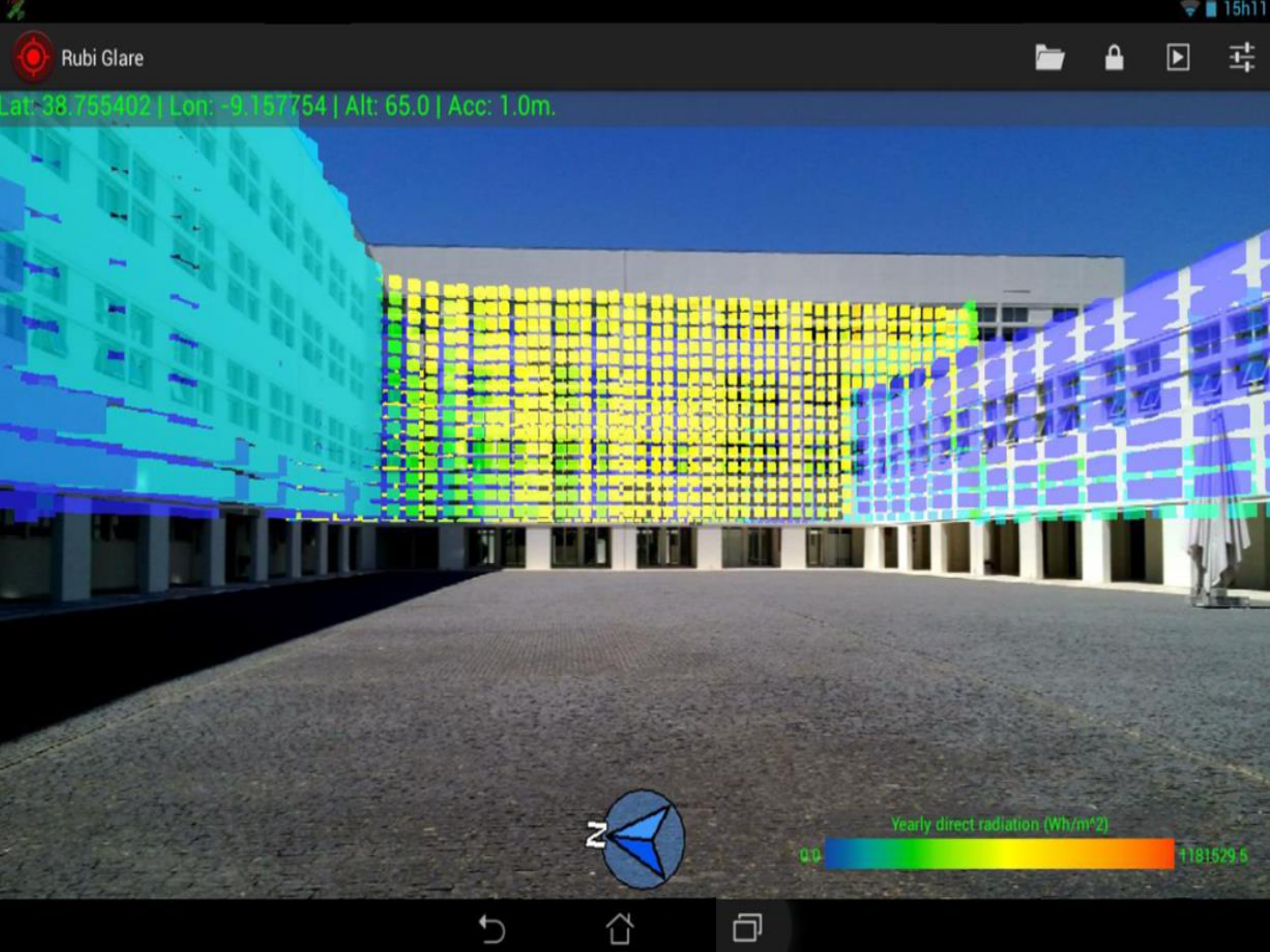
Solar in the city



Redweik et al, Solar Energy 97 (2013) 332–341

Solar in the city




15h11
Rubi Glare
Lat: 38.755402 | Lon: -9.157754 | Alt: 65.0 | Acc: 1.0m.
N
Yearly direct radiation (Wh/m^2)
0.0
1181529.5