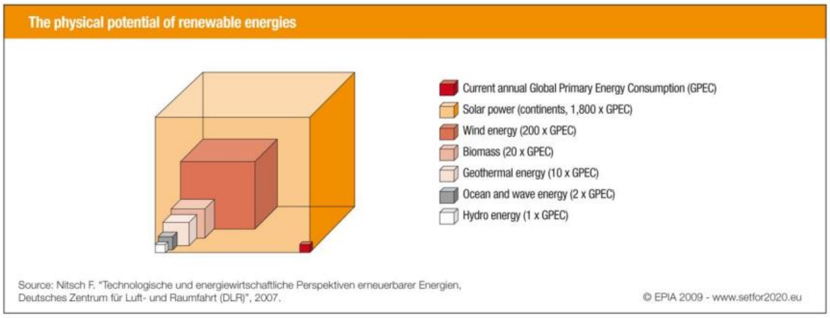
Solar resource

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

Solar resource

- Solar resource is immense
  - Human energy use: 4.0x10^{14} kWh/year
  - Solar resource on Earth's surface: 5.5x10^{17} kWh/year



Solar resource

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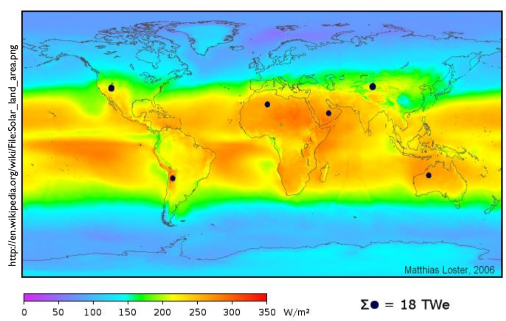


Local solar irradiance averaged over three years from 1991 to 1993 (24 hours a day) taking into account the cloud coverage available from weather satellites

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%).

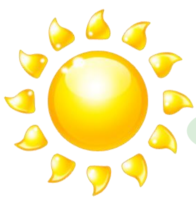
Solar resource

- Solar resource is immense
  - Human energy use: 4.0x10^{14} kWh/year
  - Solar resource on Earth's surface: 5.5x10^{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

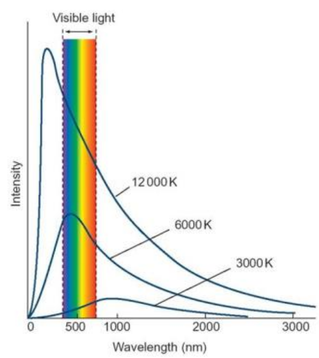


$$P_0 = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

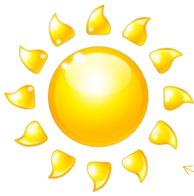
Total radiative power (Stefan Boltzman) T=5762K

Surface area of sun

Power radiated per unit area 5.96x10^7 W/m^2



Solar resource



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

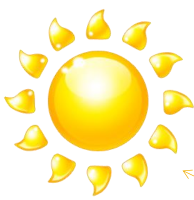
Ratio of surface areas of the 2 spheres

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

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

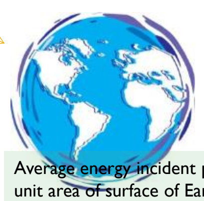
Distance Sun-Earth

Solar resource



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

R_{sun}	6.96x10^5 km
D_{avg}	1.5x10^8 km
R_{Earth}	6.35x10^3 km



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

Energy incident on Earth

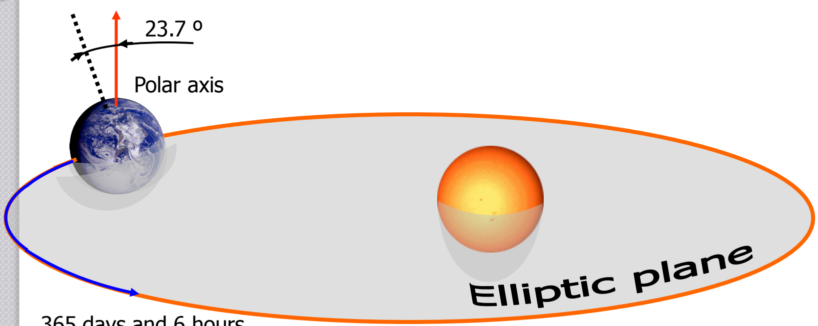
Total area of Earth

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

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

Solar resource

- Earth-Sun motion

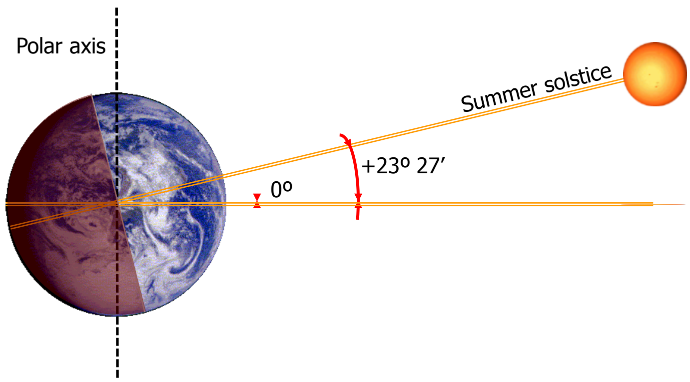


$$\frac{H}{S} = 1 + 0.033\cos\left(\frac{360(n-2)}{365}\right)$$

H(W/m2) is radiant power density outside the atmosphere; S is solar constant; n is day of the year

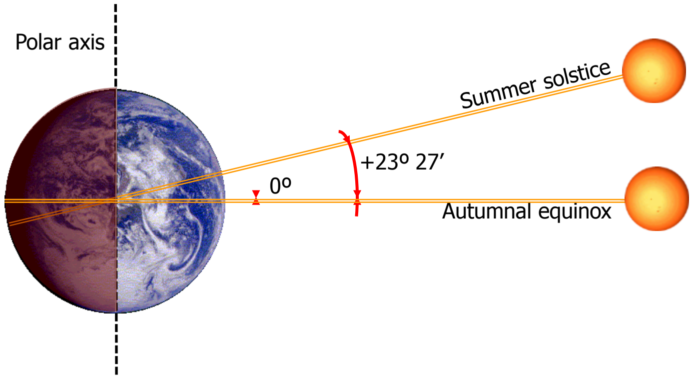
Solar resource

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



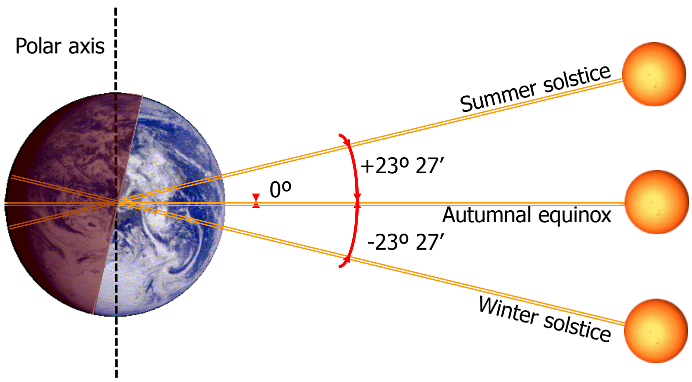
Solar resource

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



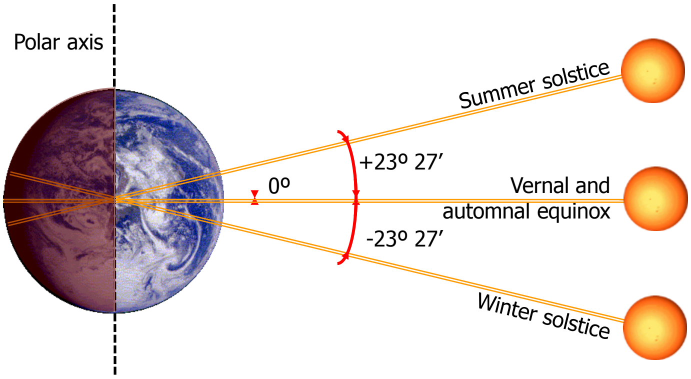
Solar resource

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



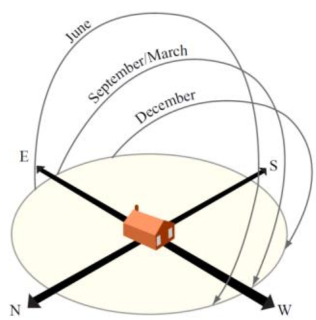
Solar resource

- Earth-Sun motion
  - 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



Building orientation with the long axis facing south

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

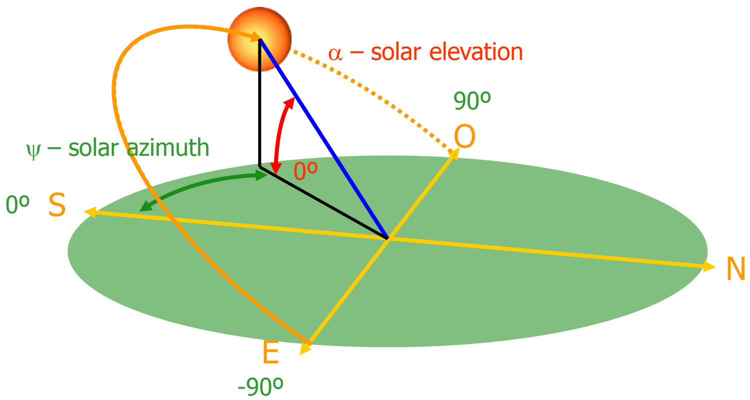
Declination in radians; n is the number of the day (Jan 1st = 1)

Solar resource

- Earth-Sun motion

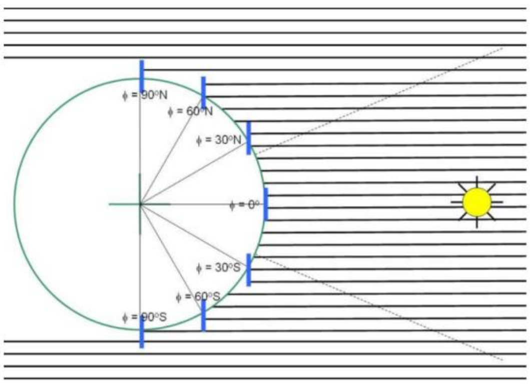
$$\sin\alpha = \sin\delta\sin\phi + \cos\delta\cos\phi$$

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



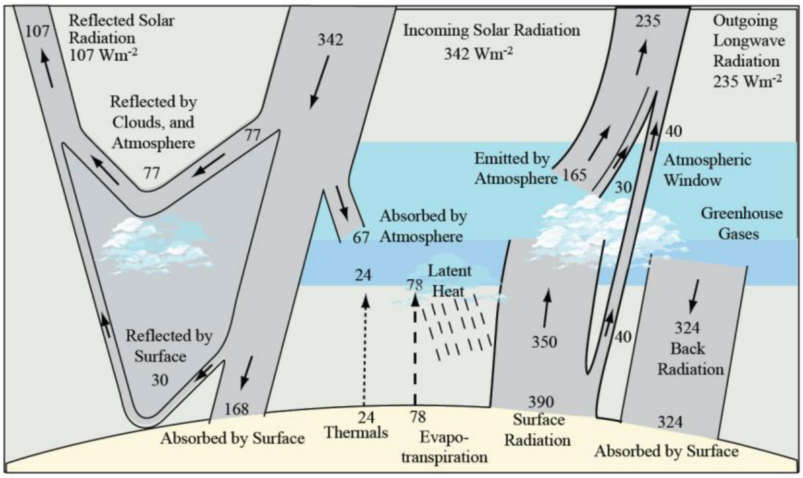
Solar resource

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



Solar resource

Atmospheric effects



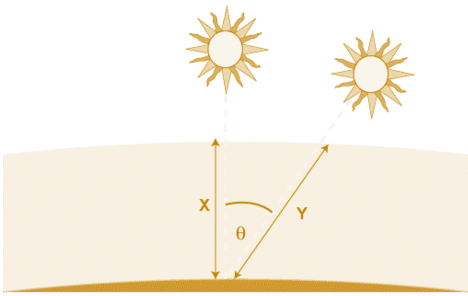
Solar resource

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

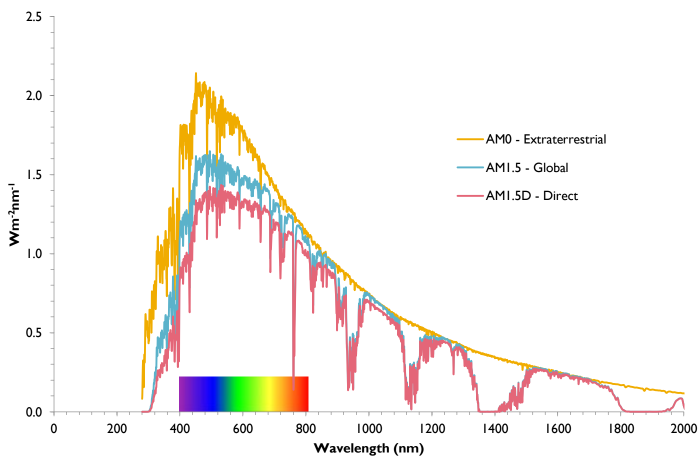
- Air Mass is a measure of the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust



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

19

Solar resource



20

Solar resource

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

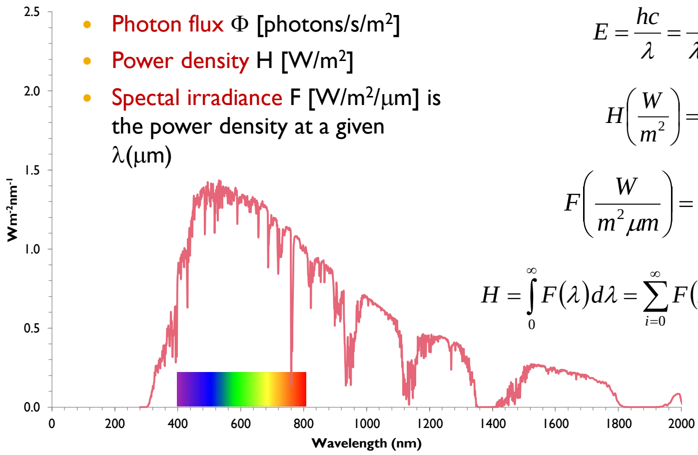
$$E = \frac{hc}{\lambda} = \frac{1.24}{\lambda(\mu m)}$$

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

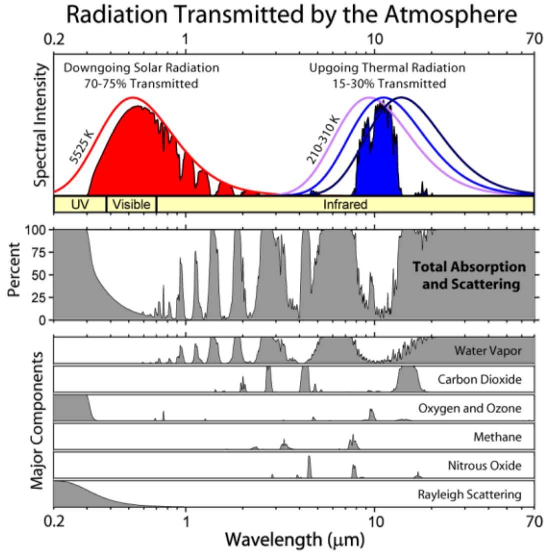
$$F\left(\frac{W}{m^2 \mu m}\right) = \Phi \frac{hc}{\lambda^2}$$

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

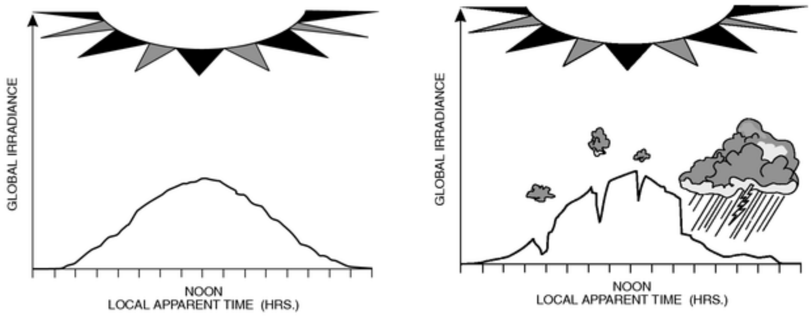
- Photon flux Φ [photons/s/m²]
- Power density H [W/m²]
- Spectral irradiance F [W/m²/μm] is the power density at a given λ(μm)



Solar resource



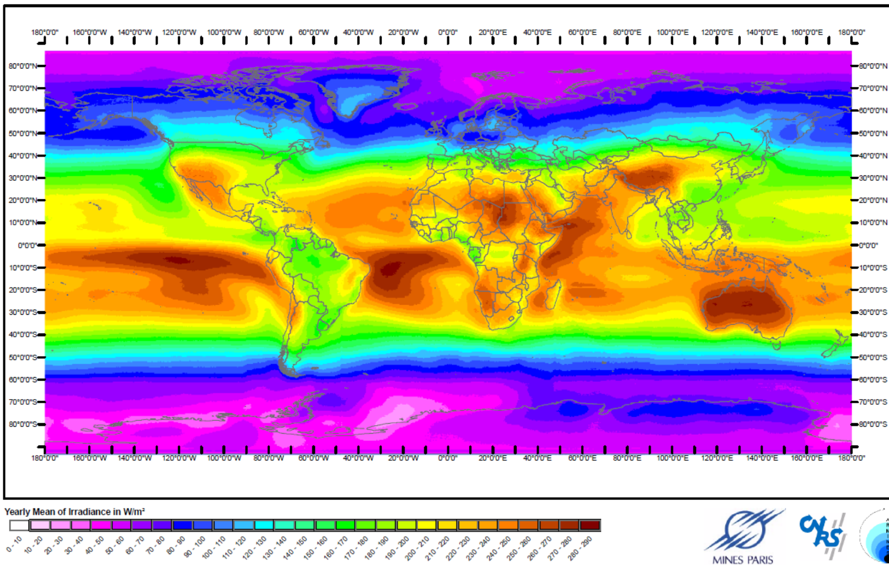
Solar resource



Solar resource

- Insolation: **In**coming **Sola**r 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

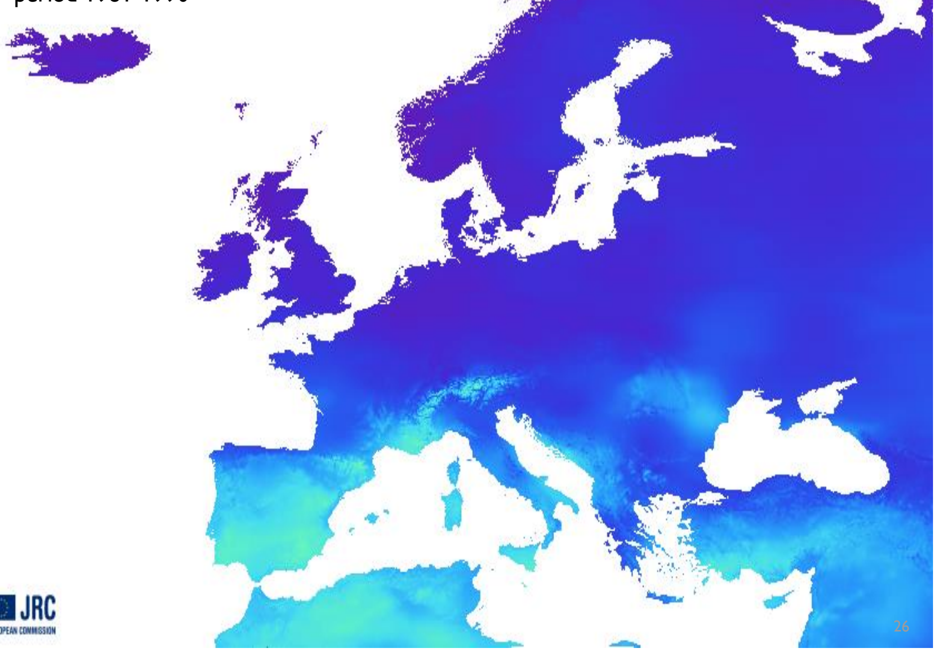


MINES PARIS

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.

25

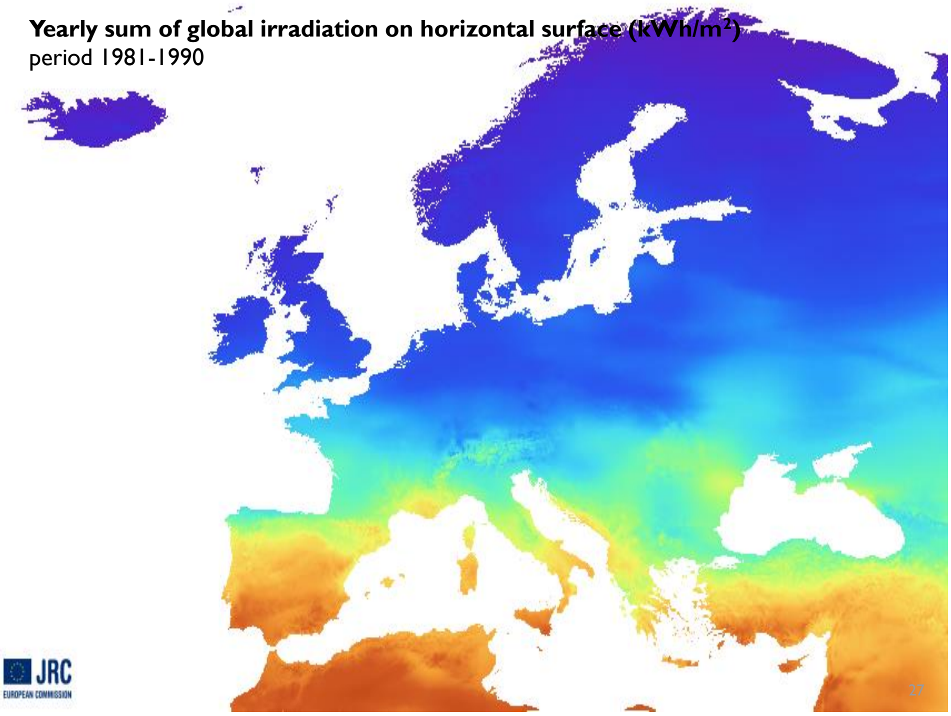
Yearly sum of global irradiation on vertical surface (kWh/m²)
period 1981-1990



JRC
EUROPEAN COMMISSION

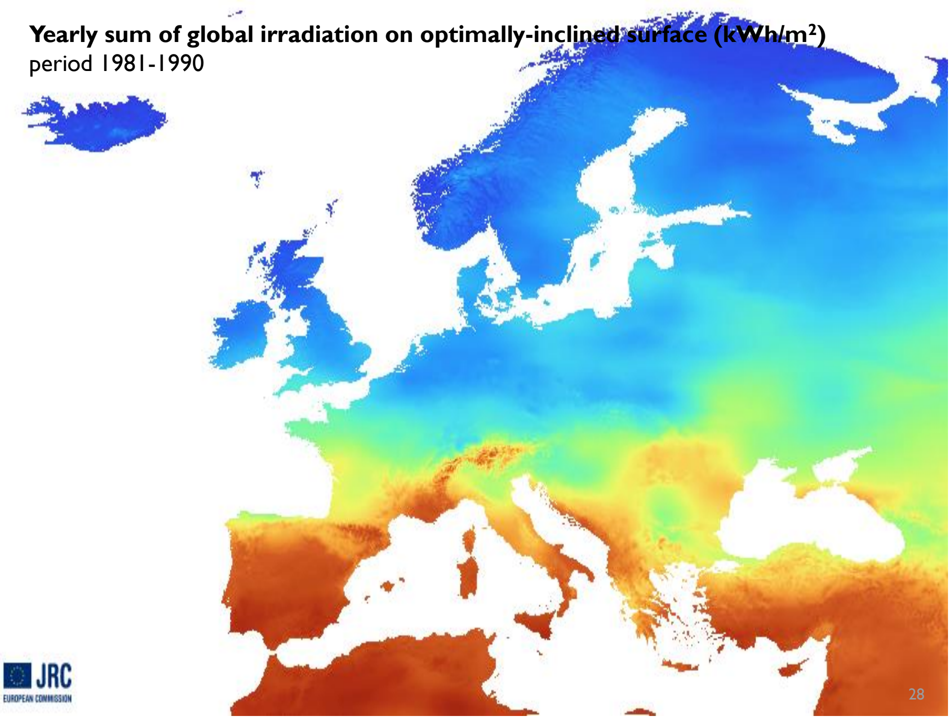
26

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



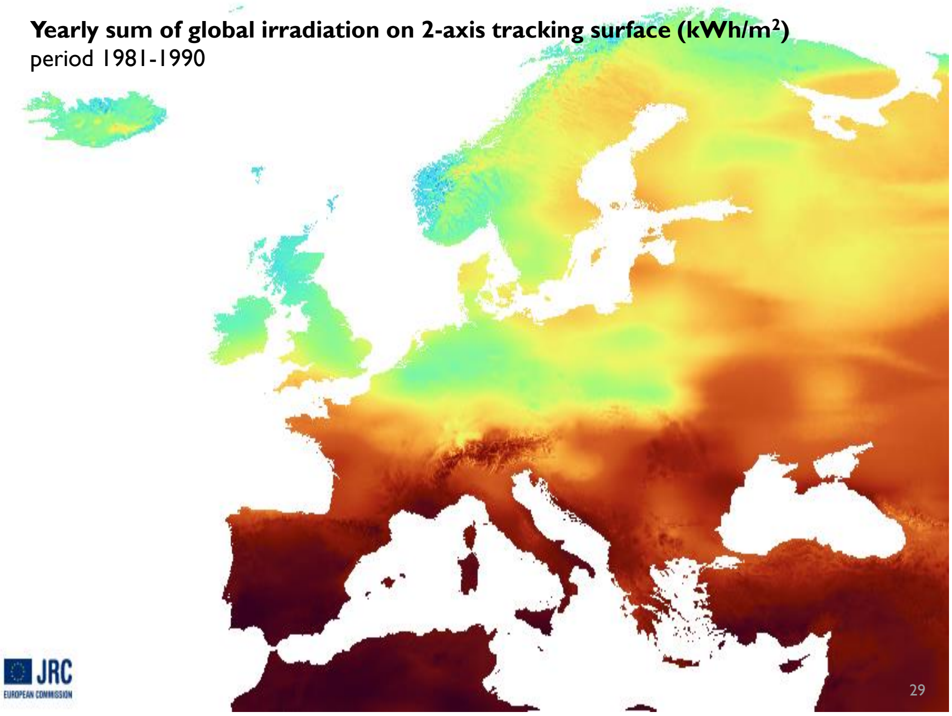
27

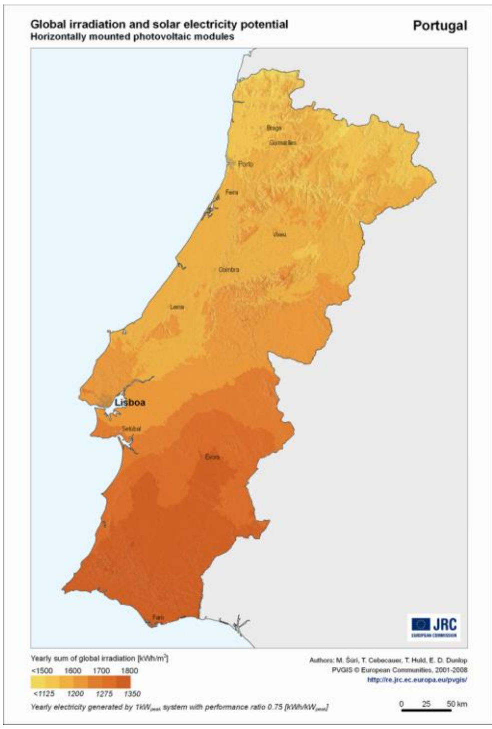
Yearly sum of global irradiation on optimally-inclined surface (kWh/m²)
period 1981-1990

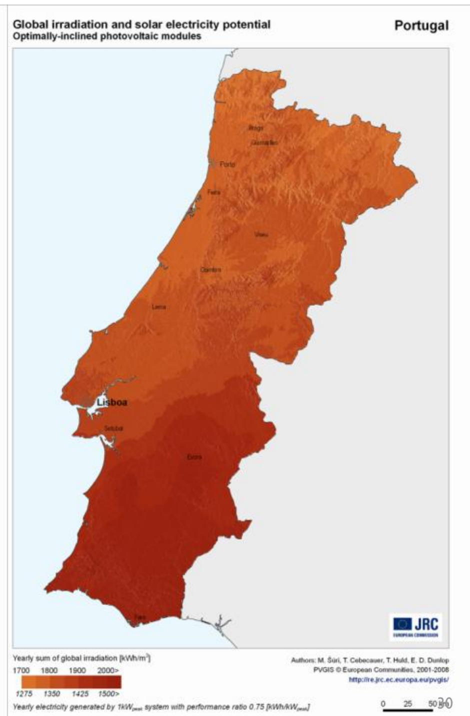


28

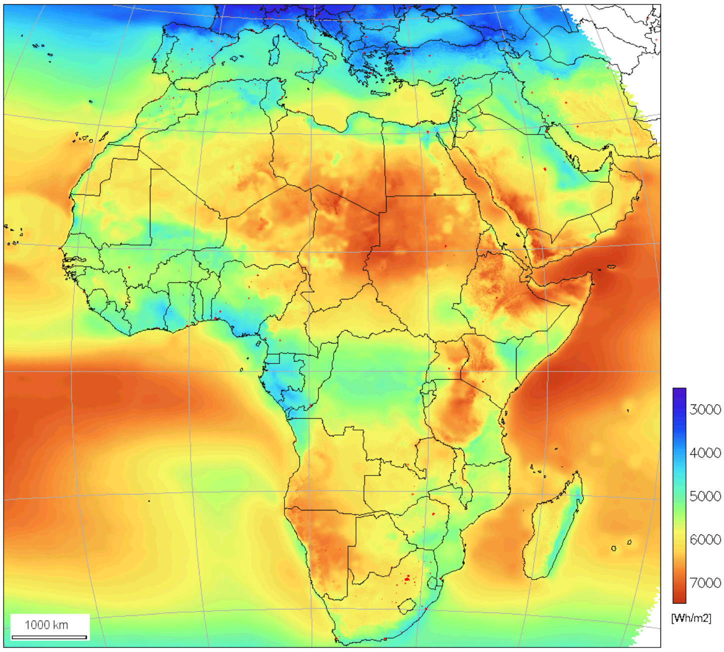
Yearly sum of global irradiation on 2-axis tracking surface (kWh/m²)
period 1981-1990







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



PVGIS (c) European Communities 2002-2006
HelioClim-1 (c) Ecole des Mines de Paris/ARMINES 1985-2005

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

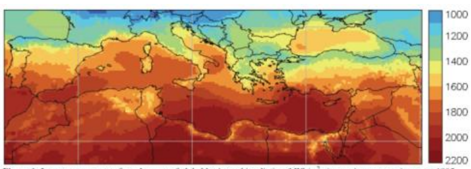


Figure 1: Long-term average of yearly sums of global horizontal irradiation (kWh/m², time series representing years 1985, 1987, and 1989-2004)

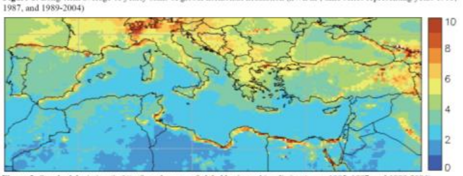


Figure 2: Standard deviation (in %) of yearly sums of global horizontal irradiation (years 1985, 1987, and 1989-2004)

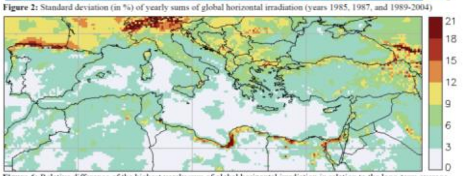


Figure 6: Relative difference of the highest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

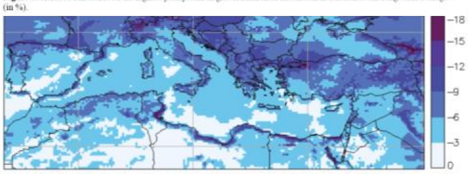


Figure 5: Relative difference of the lowest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

Solar resource

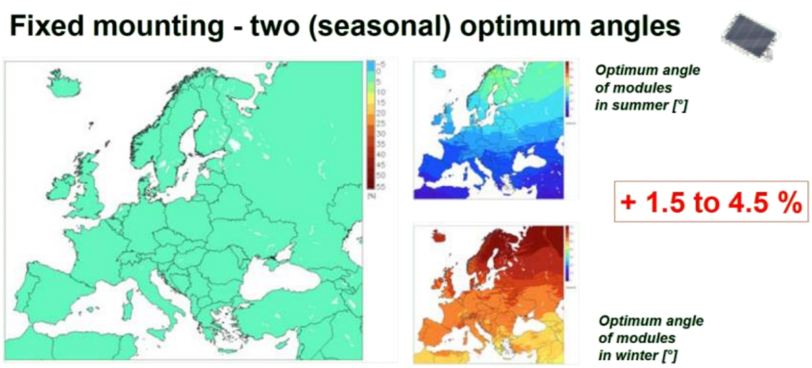
- Coastal areas and higher mountains face wider variations (up to 10%)
- Winter is much more variable (up to x6) than summer months

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

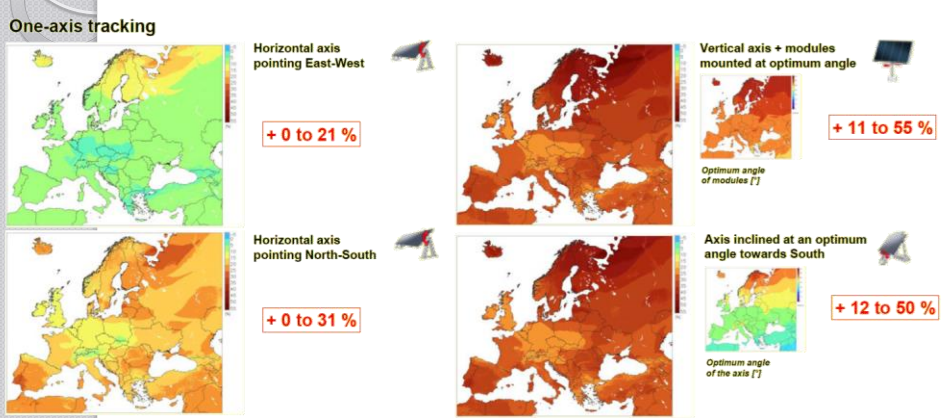
Compared to PV with modules fixed at optimum angle:

- Changing inclination twice a year contributes only marginally



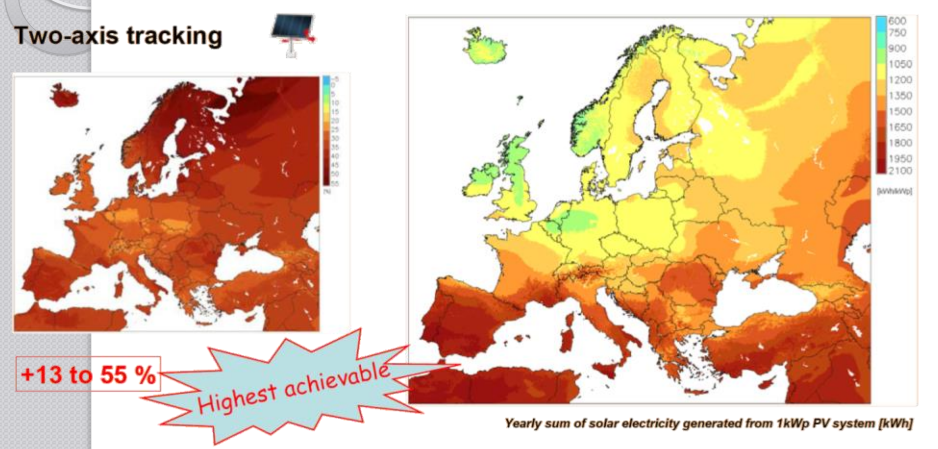
Comparison of electricity yield from fixed and suntracking PV systems in Europe [JRC, 2008]

Solar tracking



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

Solar tracking



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

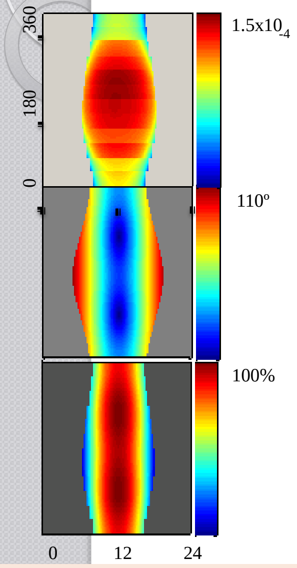
Solar tracking

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]

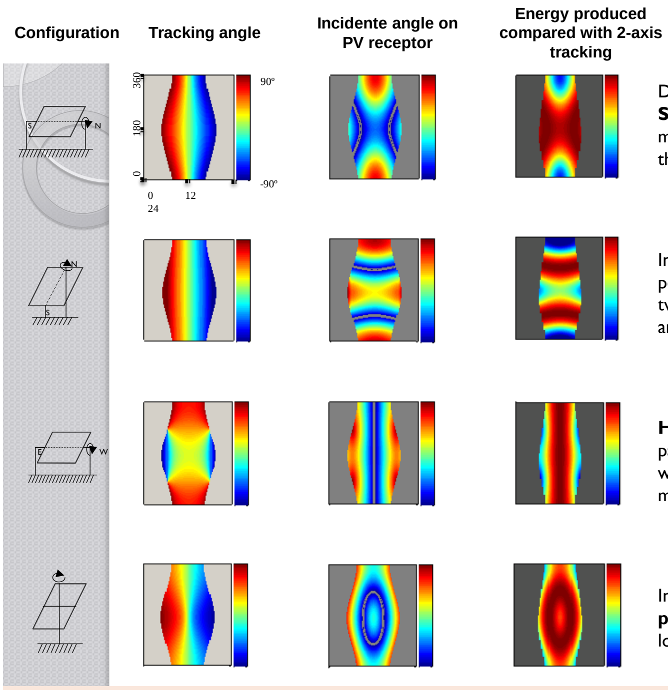
Solar tracking



Hourly energy produced by PV system with 2-axes tracking [kWh/Wp]

Incidence angle on fixed panel with optimum inclination

Ratio between energy produced using system with 2-axes tracking and fixed panel with optimum inclination.



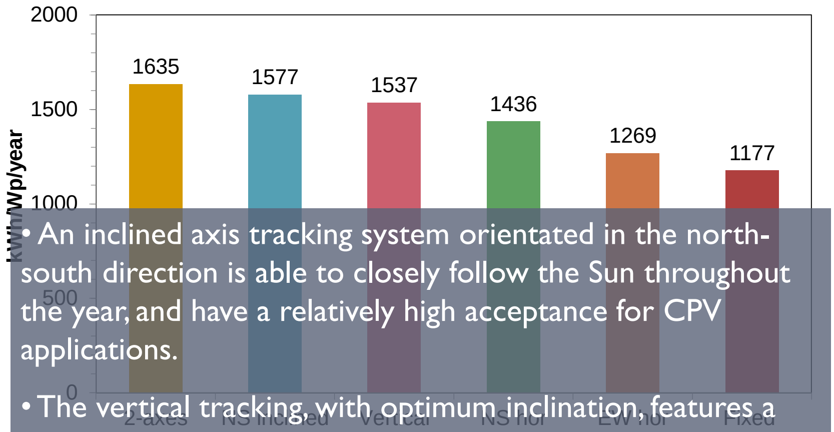
During the summer, in the **North-South horizontal axis**, the misalignment between module and the position of the sun reaches 40º.

In a **North-South inclined axis**, the position of the module is perfect twice a year, in spring and autumn, and misalignment never exceeds 30º.

Horizontal East-West axis is particularly suitable for midday hours, when insolation is at a maximum, but misses early and late hours.

In a **vertical axis with inclined panel**, the misalignment will be lowest when the insolation is highest.

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.

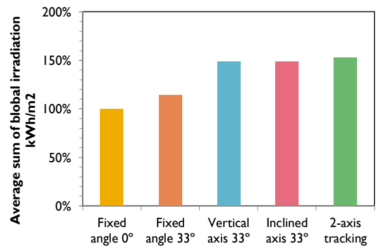
Gaspar *et al*, *Exploring One-Axis Tracking Configurations For CPV Application*, CPV7, Las Vegas 2011

Solar tracking

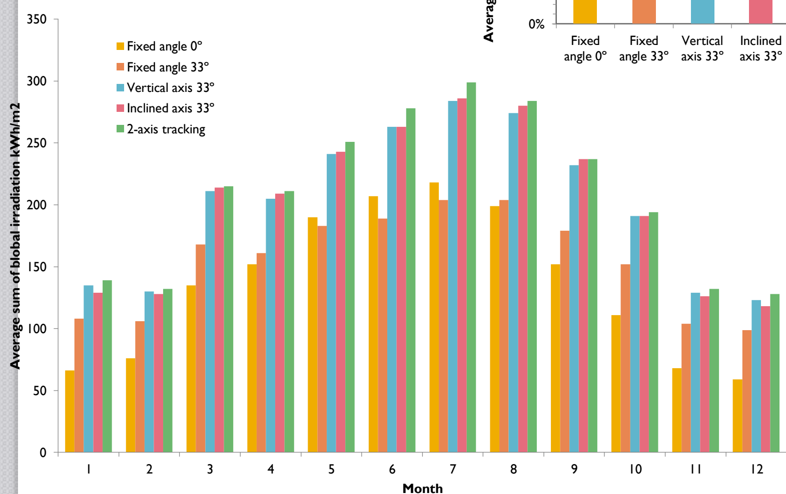
▲ Installing a screw foundation for a dual-axis tracking system (Deger-Traker) at Am Peterswald PV park in Germany: Bftec GmbH pre-drills the ground at the site and then the foundation is installed. The foundation's unusual form, which consists of a smooth side wall with a coil at the bottom (if necessary,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

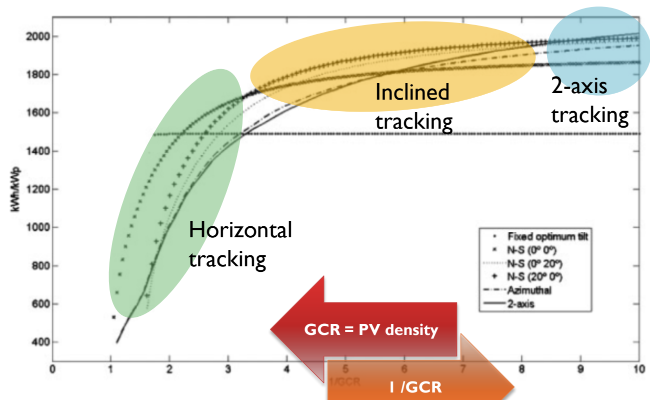


Figure 13. Evolution of yearly energy yield in A[illegible]ategies considered here, for the pessimistic shading case and assuming a constant dir[illegible]ness degree of 3%

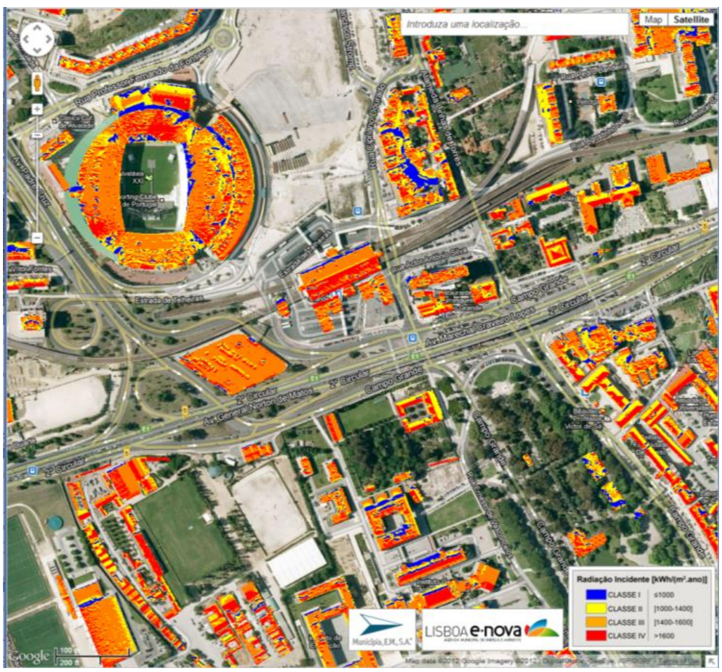
E. Narvarte *et al, Tracking and Ground Cover Ratio,* Prog. Photovolt: Res. Appl. 2008; 16:703–714

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

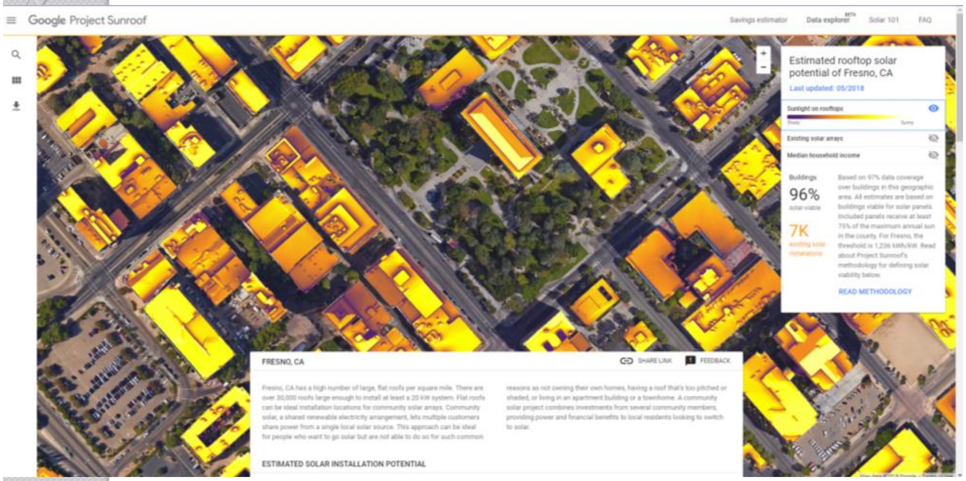
https://doi.org/10.1016/j.solener.2008.03.007



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

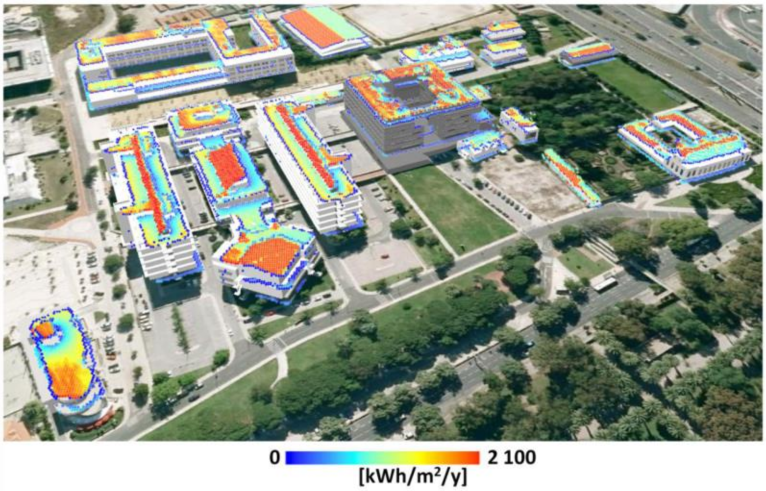
46

Solar in the city



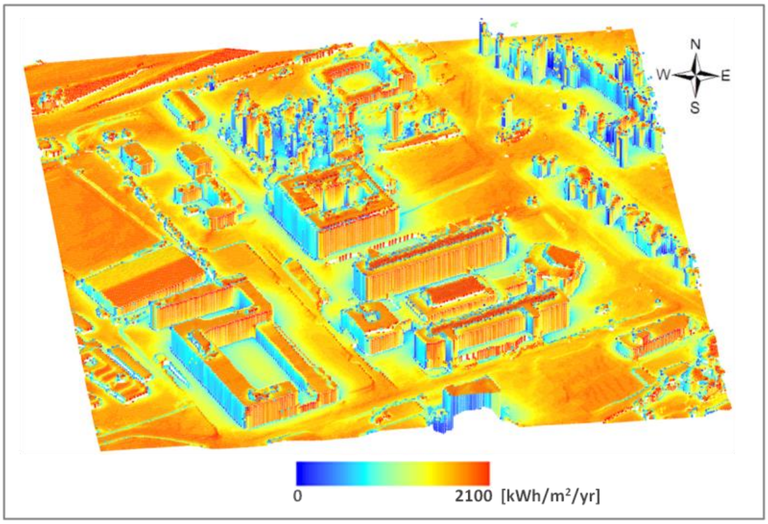
47

Solar in the city



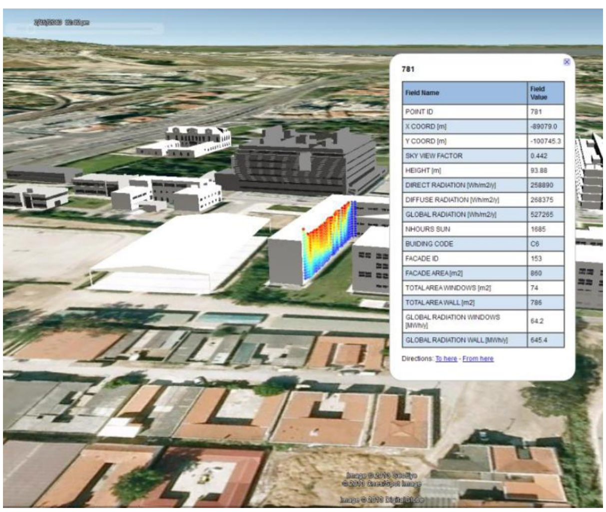
48

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
1181529.6