

# SOLAR RESOURCE



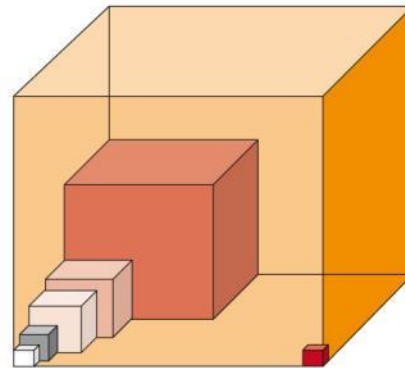
# Solar resource

- 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



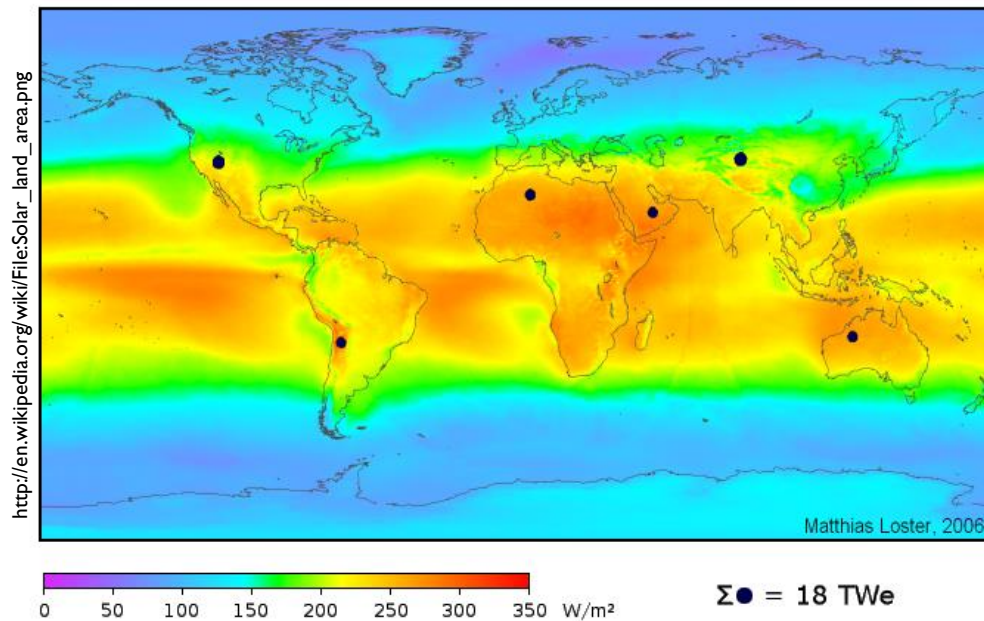
- Current annual Global Primary Energy Consumption (GPEC)
- Solar power (continents, 1,800 x GPEC)
- Wind energy (200 x GPEC)
- Biomass (20 x GPEC)
- Geothermal energy (10 x GPEC)
- Ocean and wave energy (2 x GPEC)
- Hydro energy (1 x GPEC)

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

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# Solar resource

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



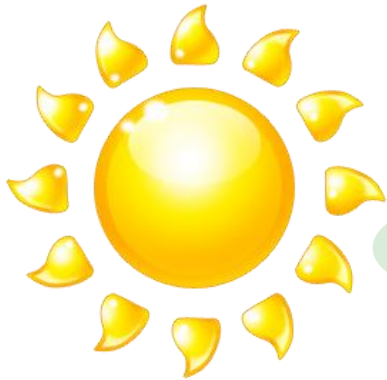
Local solar irradiance averaged over three years from 1991 to 1993 (24 hours a day) taking into account the cloud coverage available from weather satellites

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

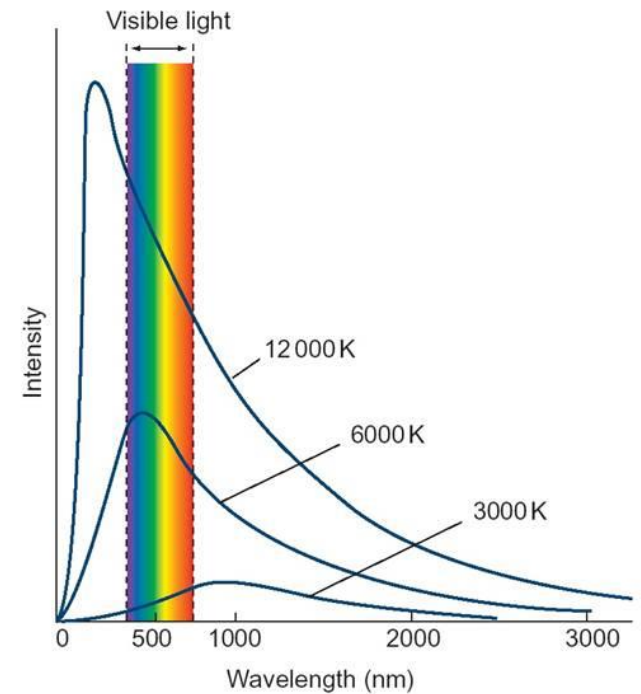


$$P_0 = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

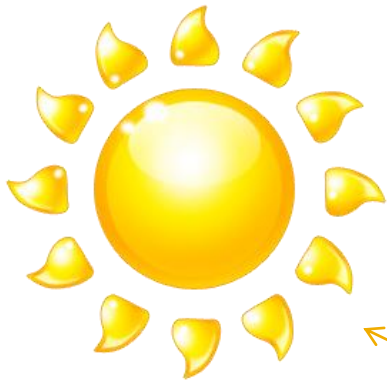
Total radiative power (Stefan Boltzman)  $T=5762\text{K}$

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

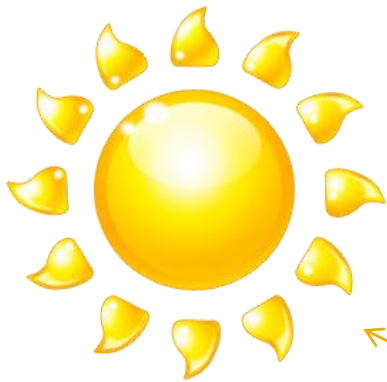
**Solar constant** average energy flux incident at the Earth's orbit:  
**1366 W/m<sup>2</sup>**

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

Distance Sun-Earth

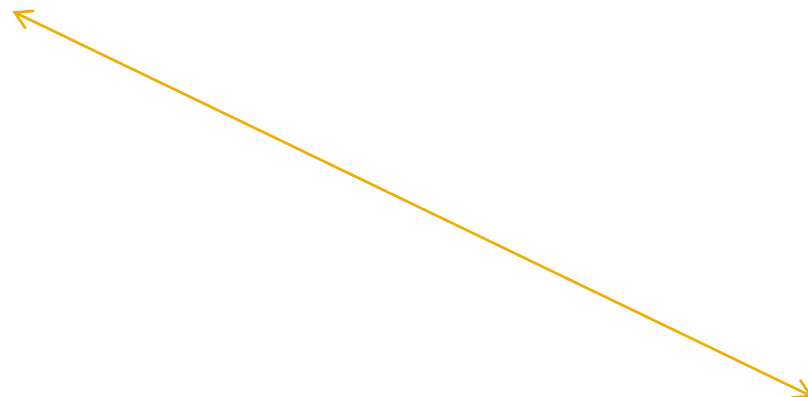


# Solar resource



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

$R_{sun}$      $6.96 \times 10^5$  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

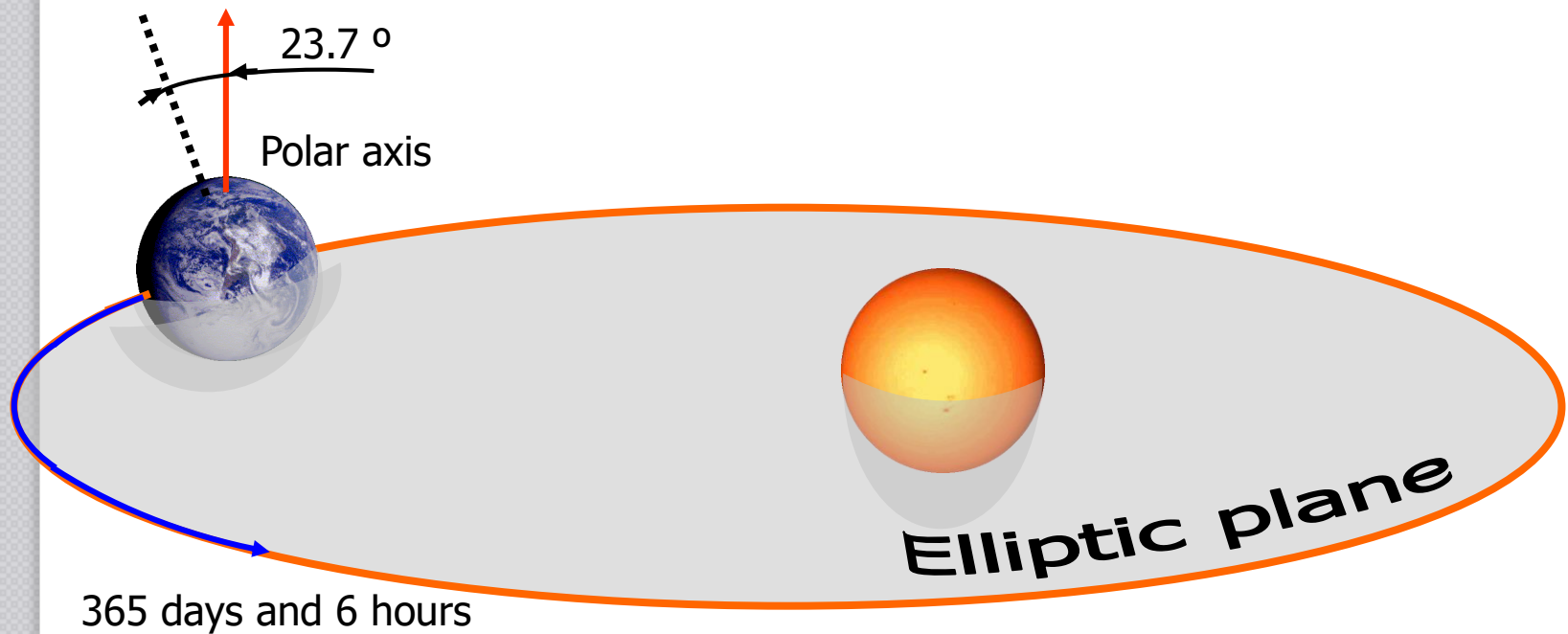
Total area of Earth

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

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

# Solar resource

- Earth-Sun motion

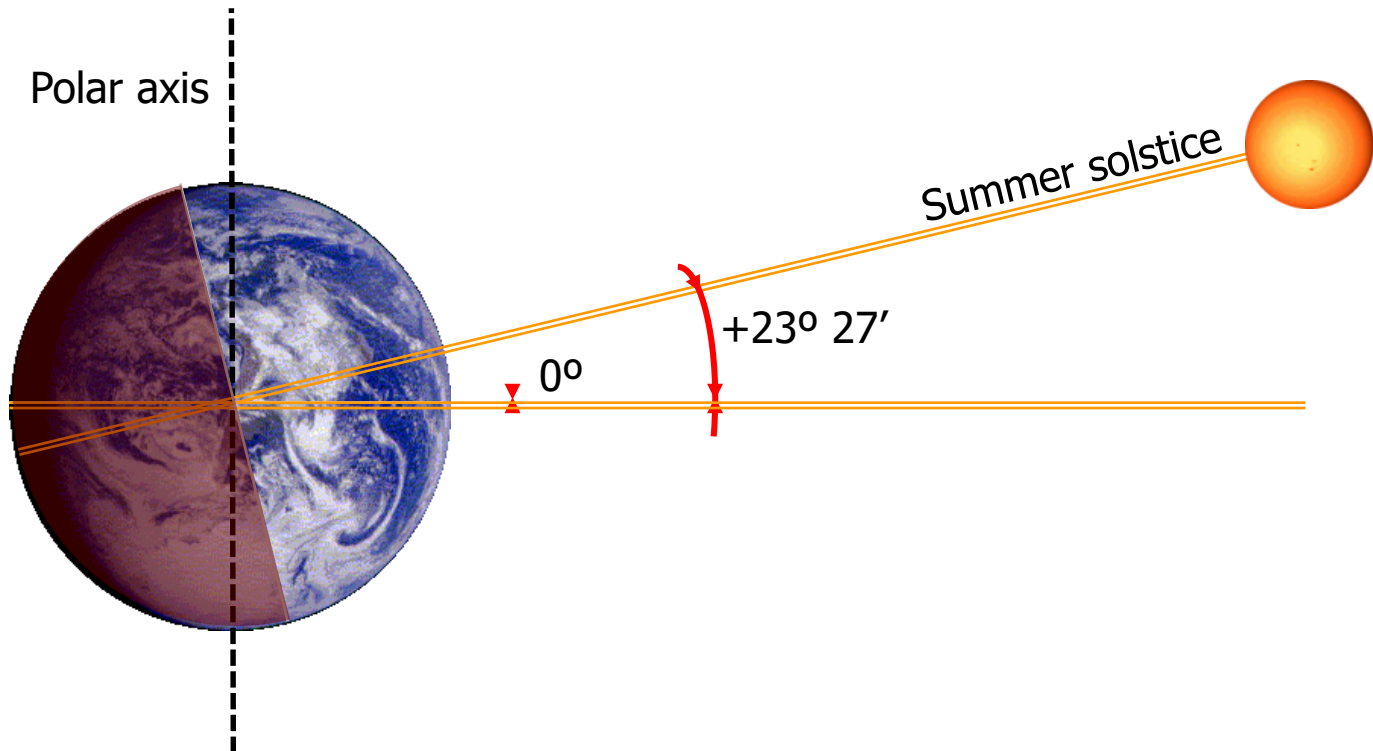


$$\frac{H}{S} = 1 + 0.033 \cos\left(\frac{360(n-2)}{365}\right)$$

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

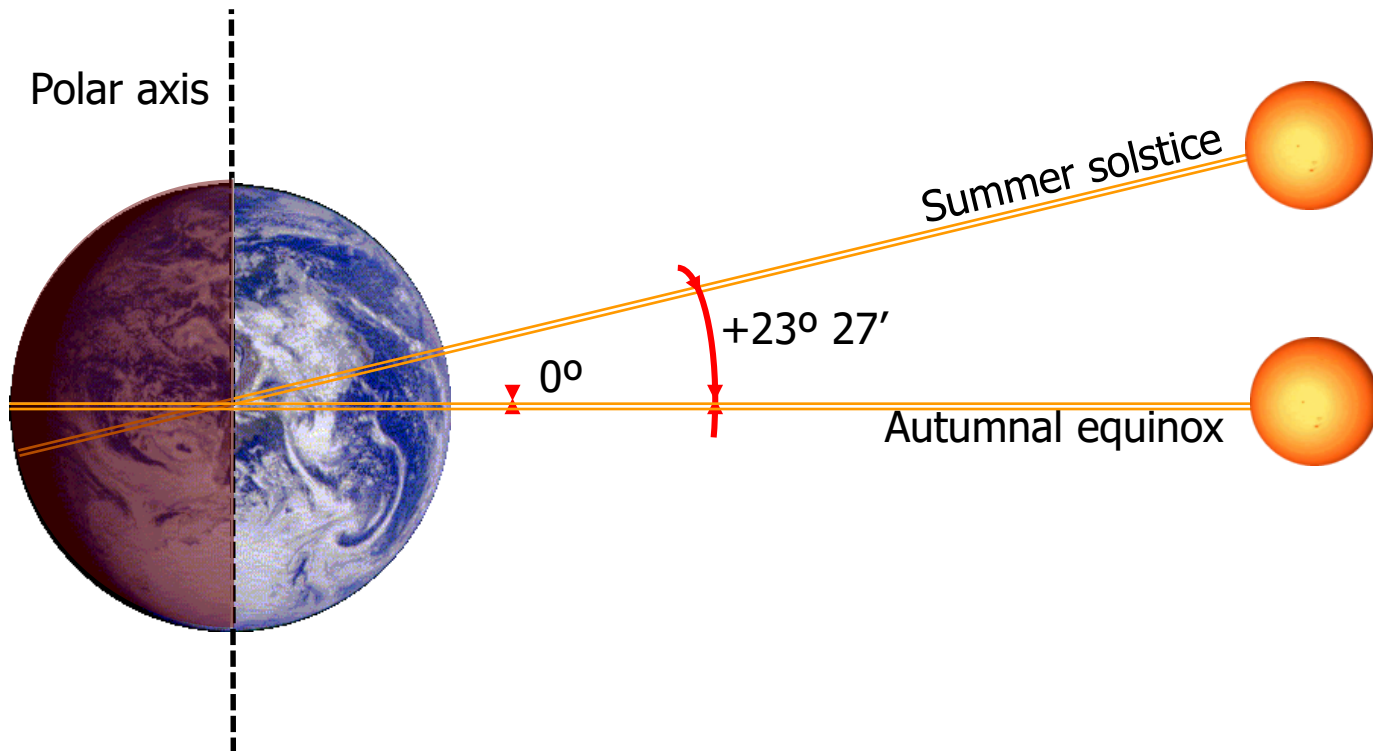
# Solar resource

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



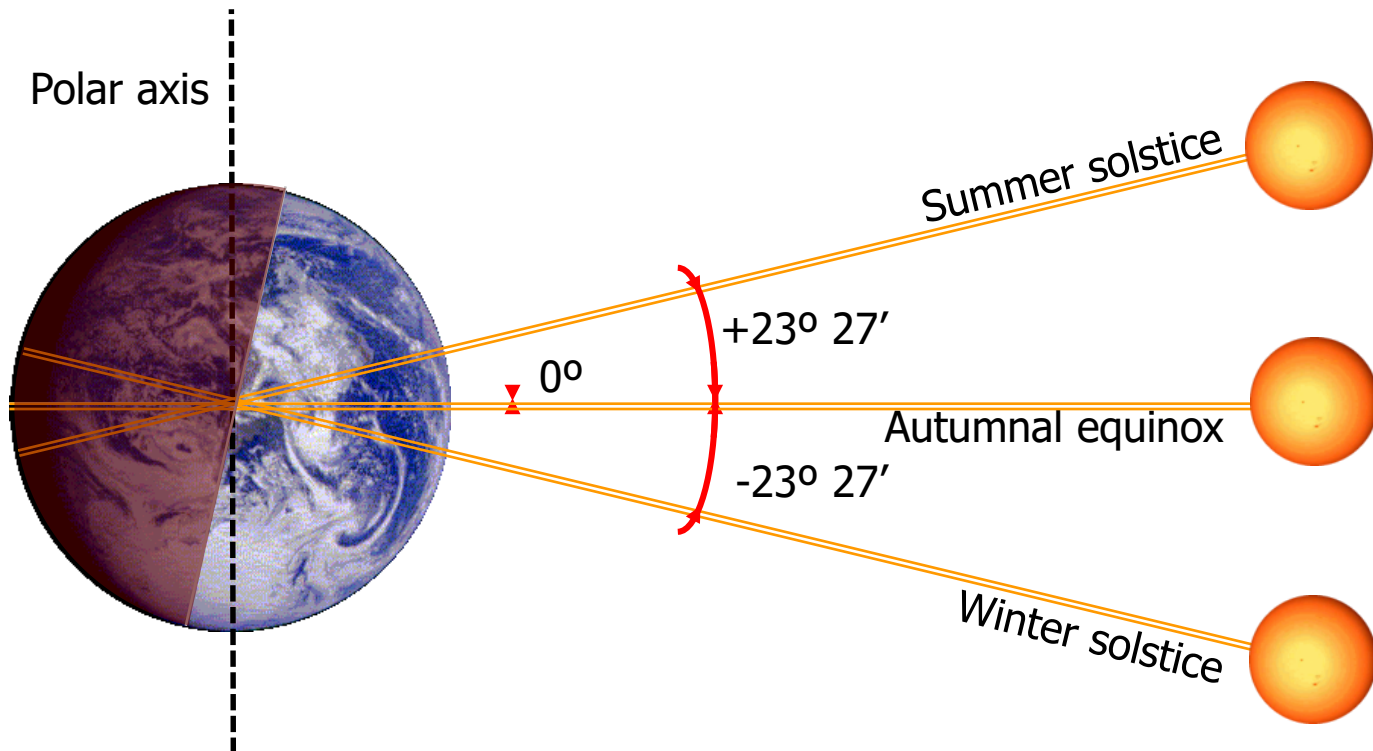
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# Solar resource

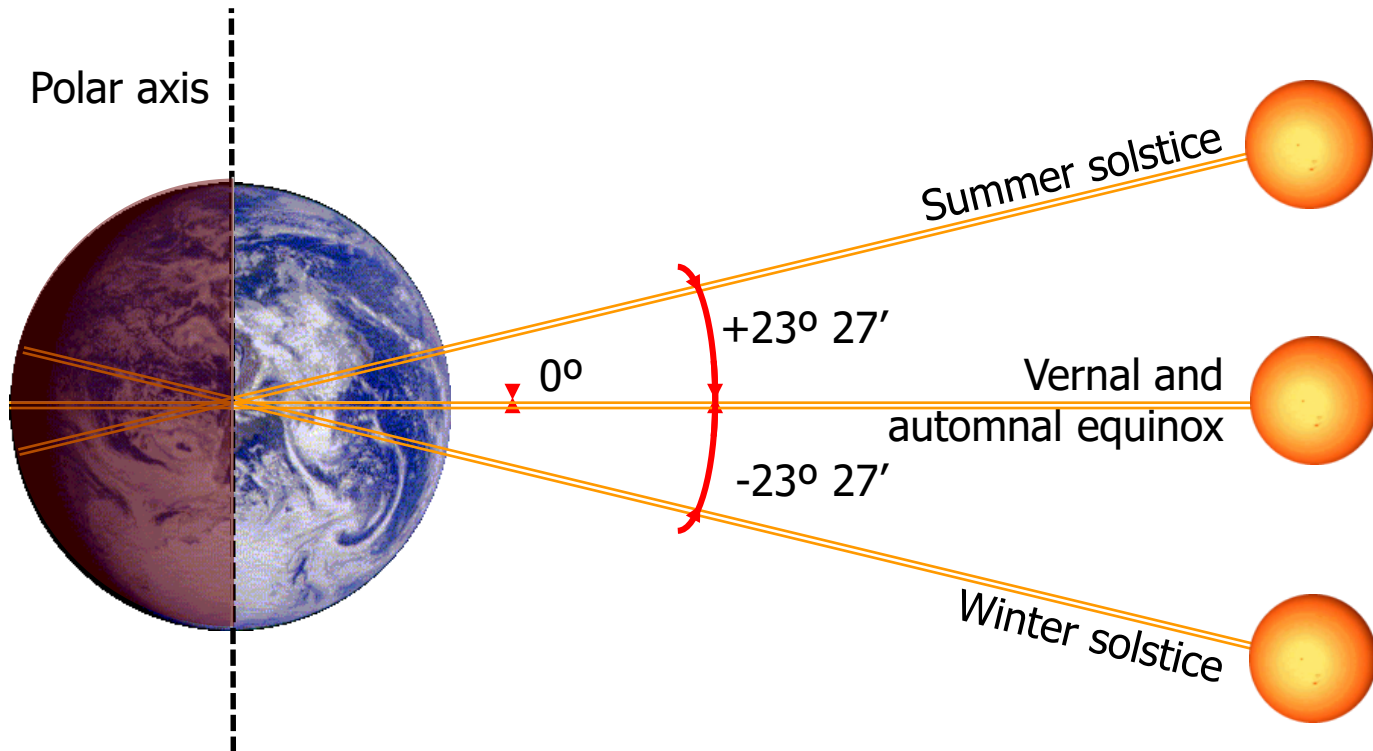
- Earth-Sun motion
  - **Solar declination:** angle between line joining centres of Earth and Sun and the equatorial plane



# Solar resource

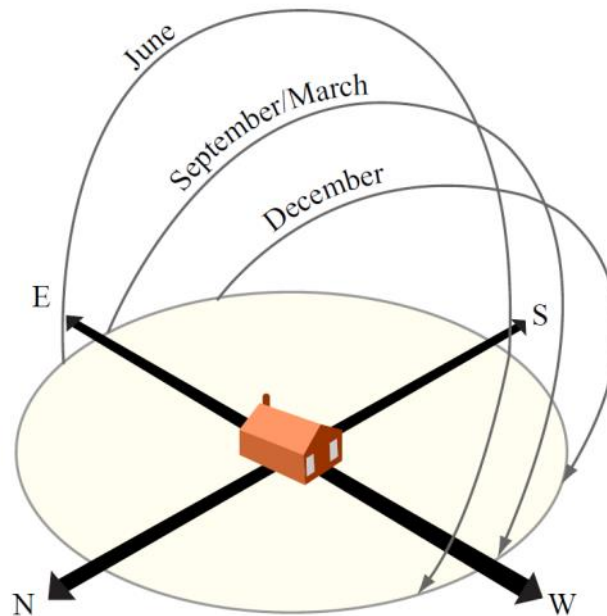
- Earth-Sun motion

- **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*

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

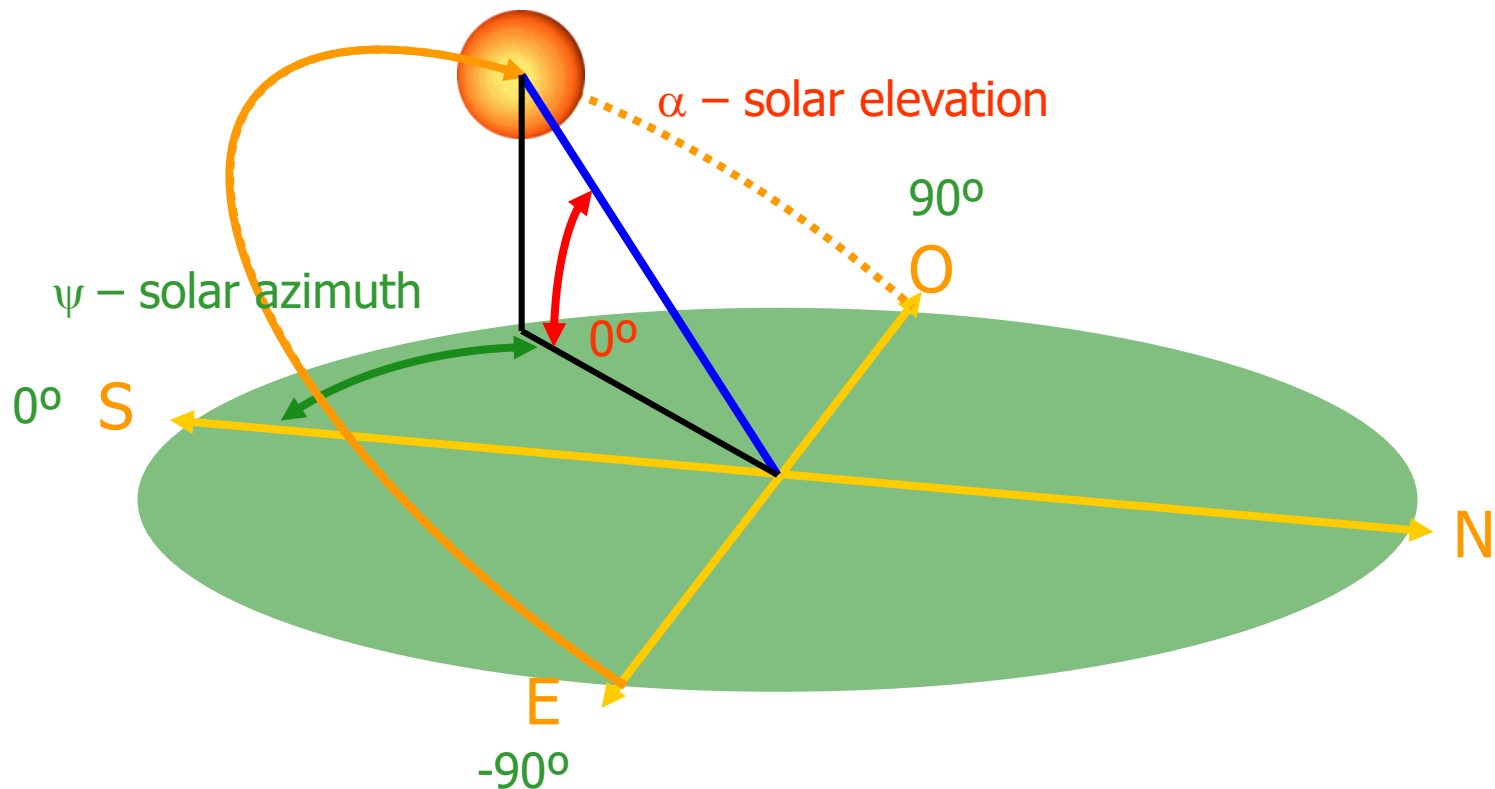
Declination in radians; n is the number of the day (Jan 1st = 1)

# Solar resource

- Earth-Sun motion

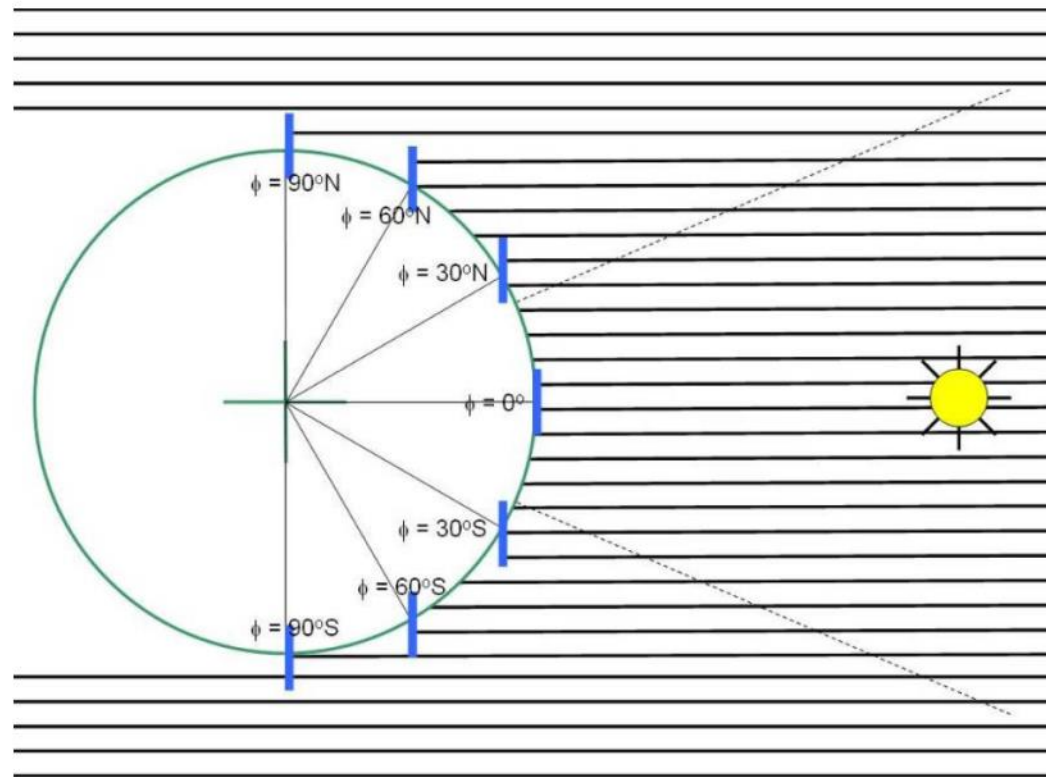
$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi$$

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



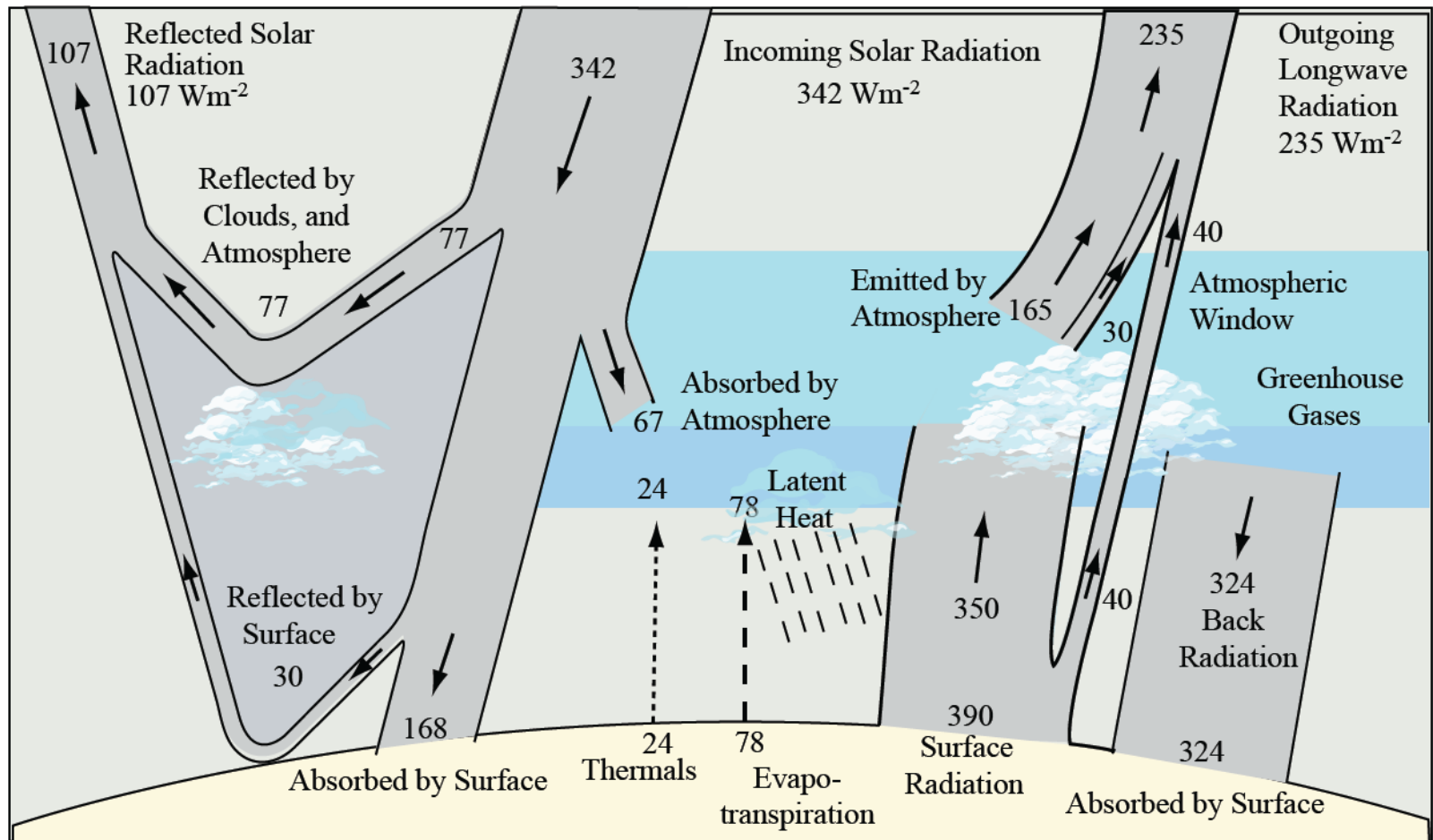
# Solar resource

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



# Solar resource

## Atmospheric effects



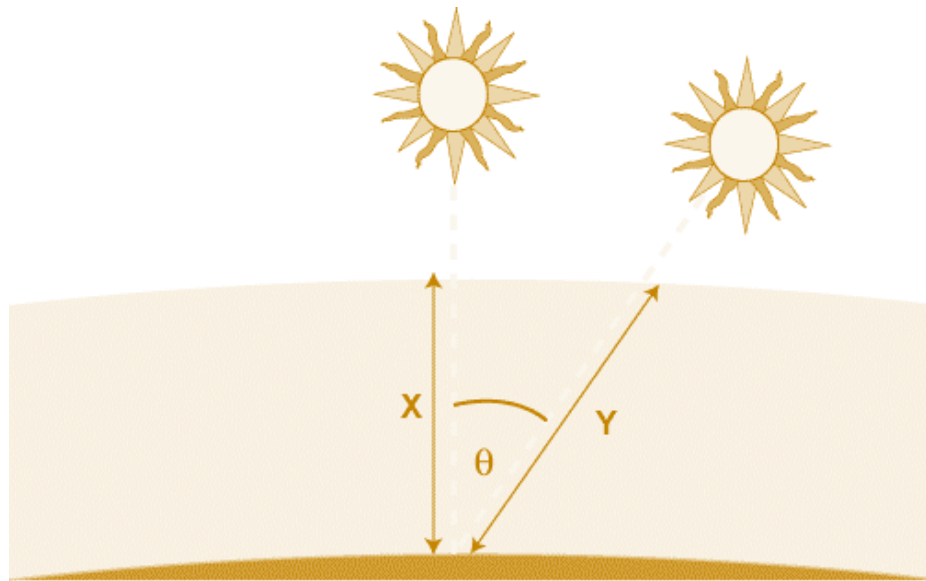
# Solar resource

## **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.

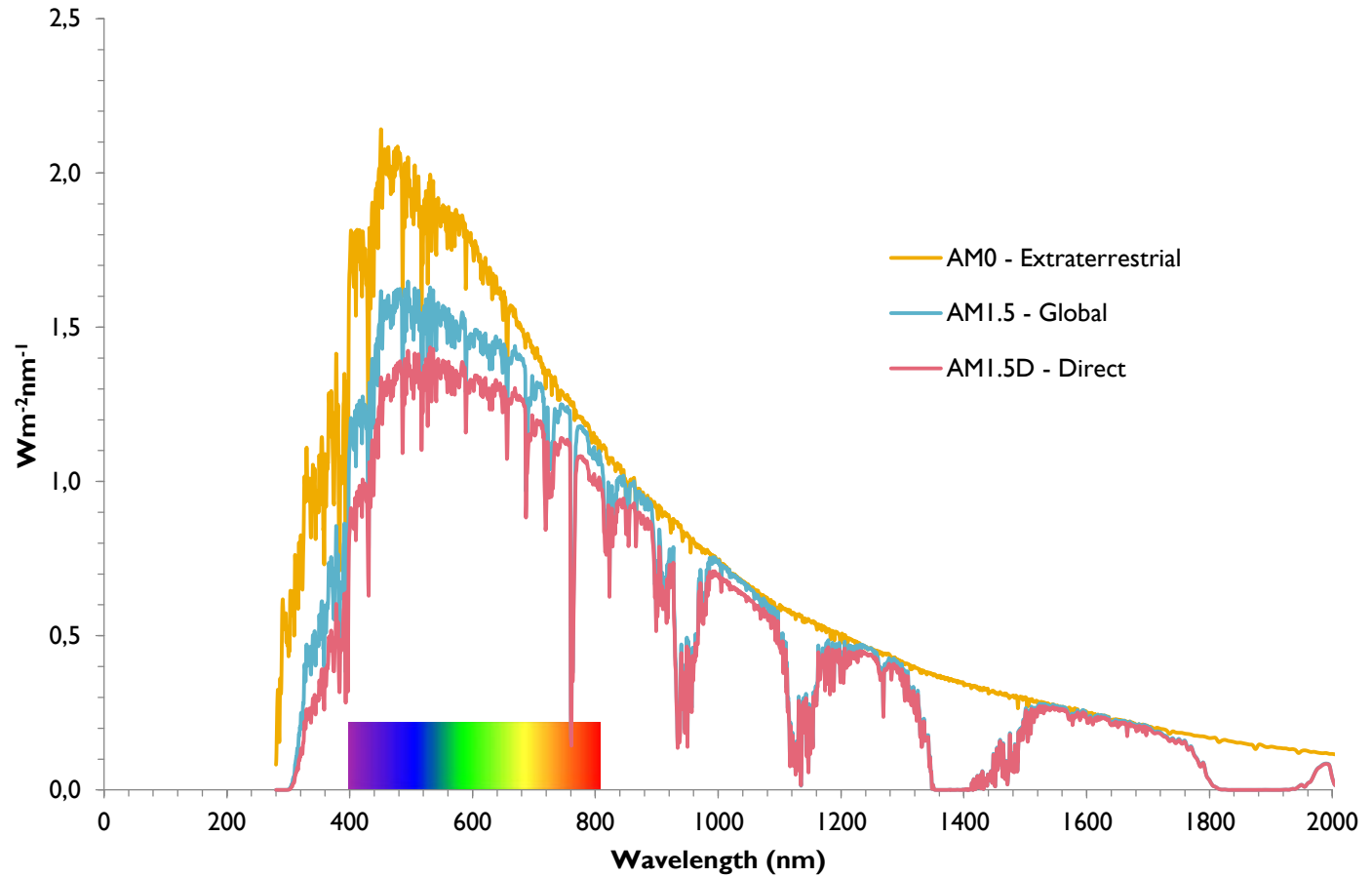
# Solar resource

- **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



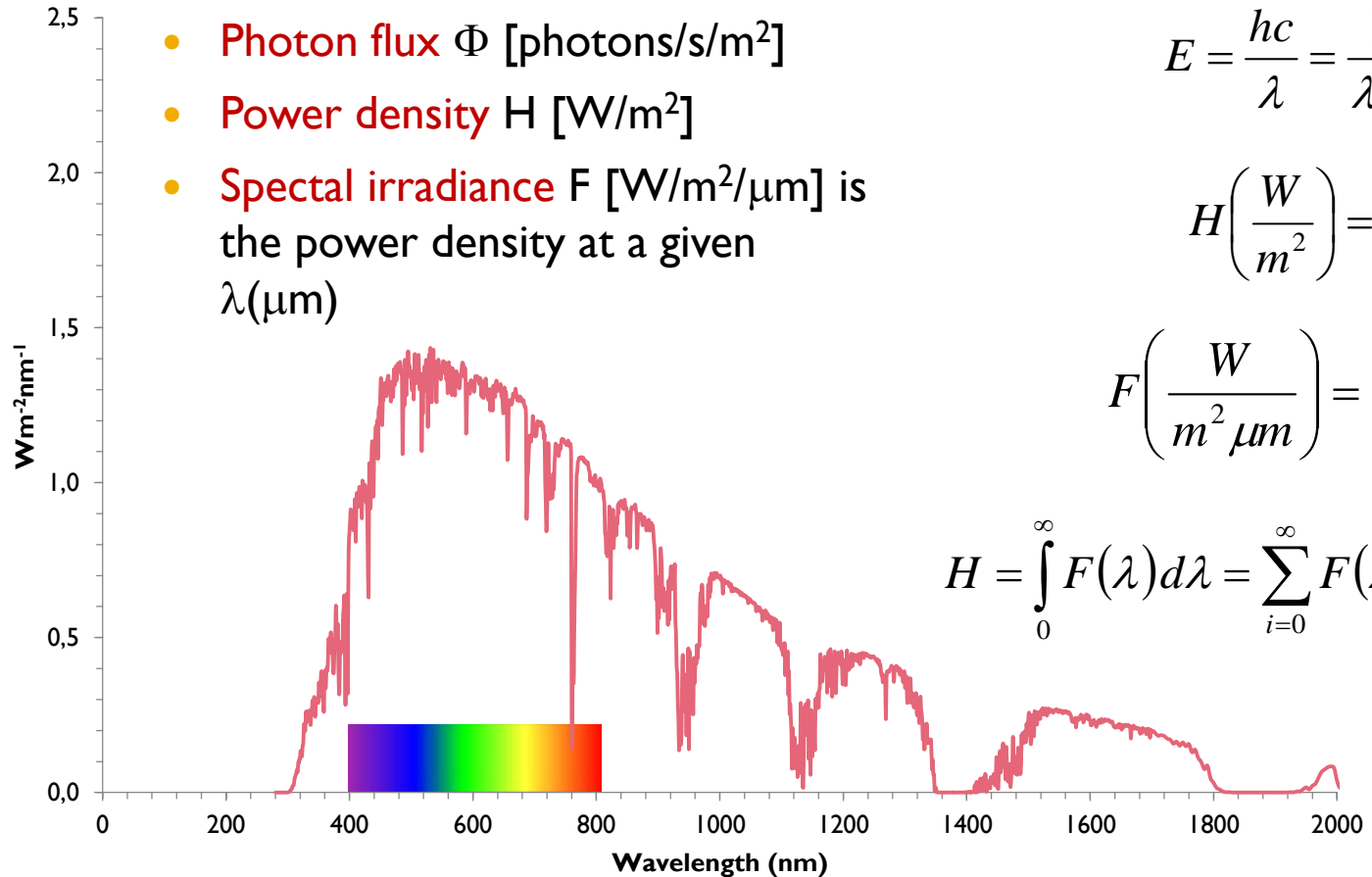
$$AM = \frac{1}{\cos \theta}$$

# 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)



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

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

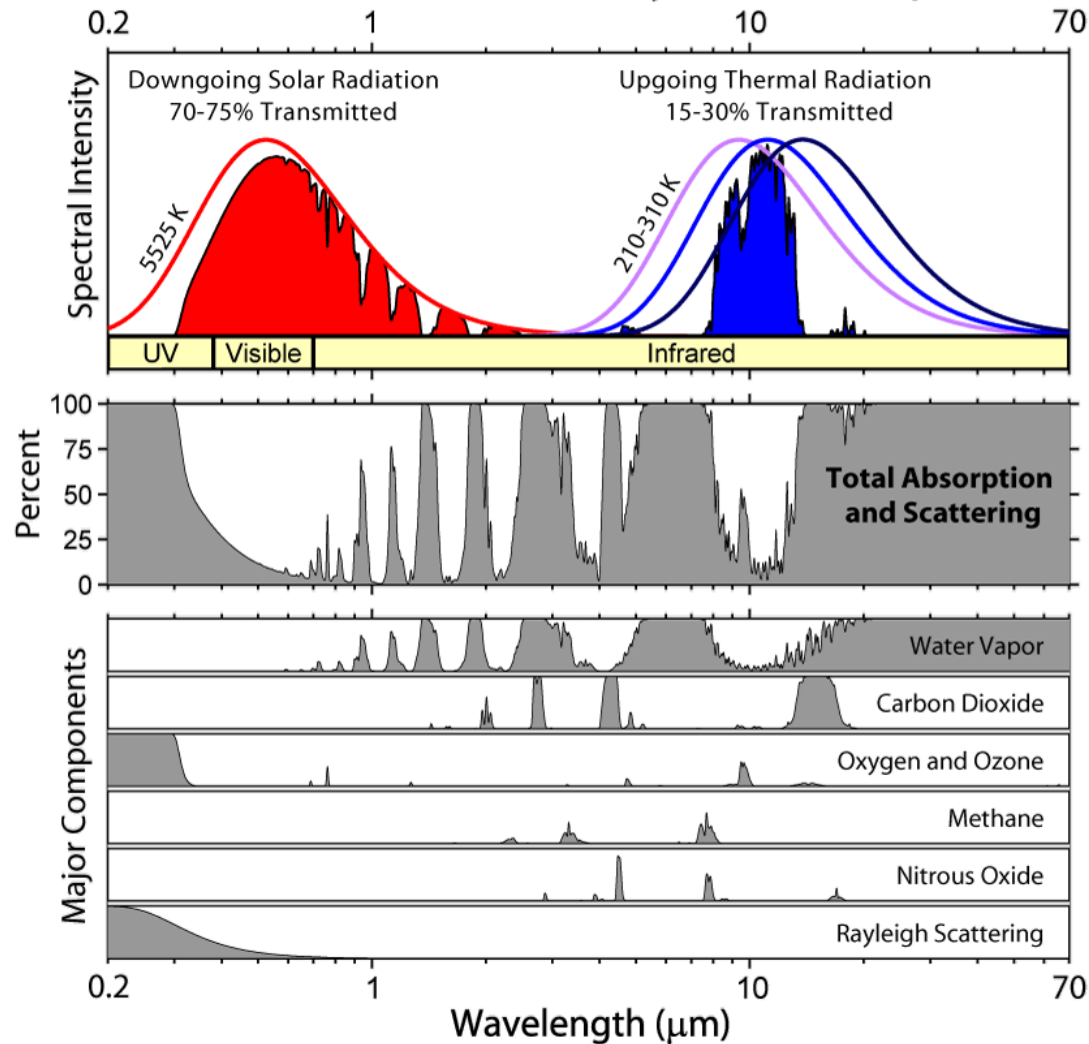
$$H\left(\frac{\text{W}}{\text{m}^2}\right) = \Phi \frac{hc}{\lambda}$$

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

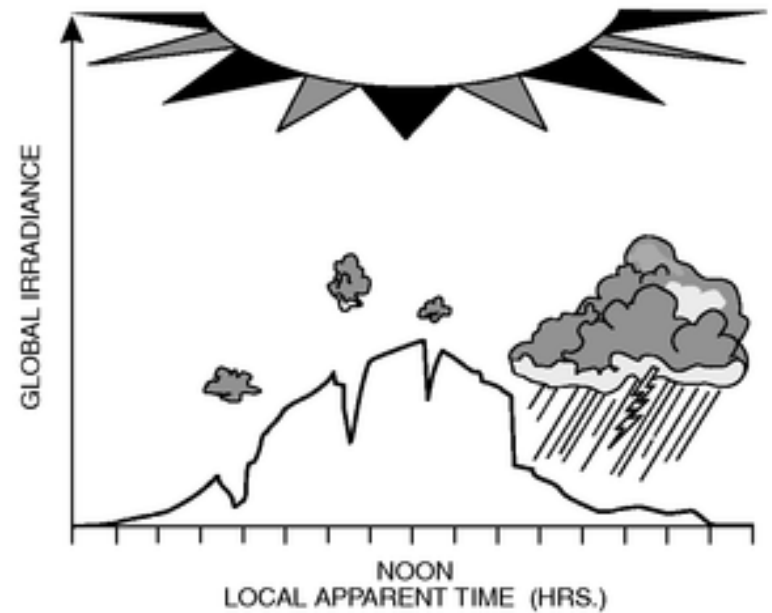
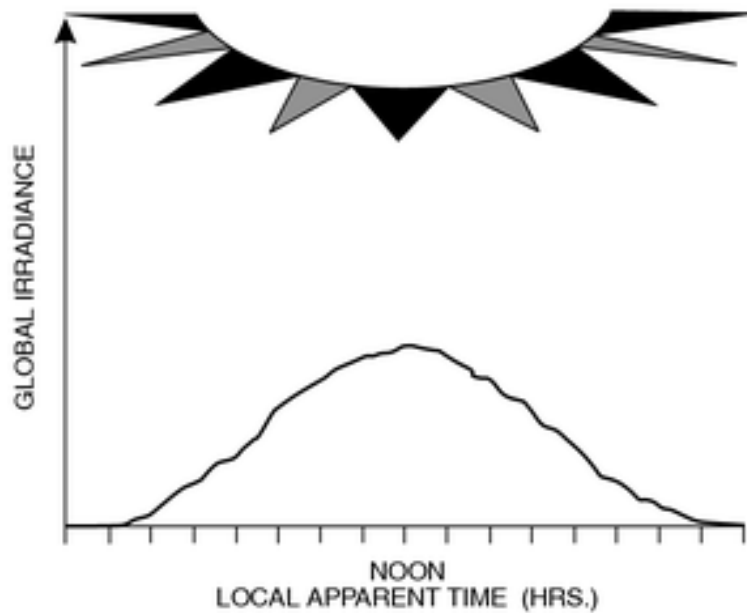
$$H = \int_0^{\infty} F(\lambda) d\lambda = \sum_{i=0}^{\infty} F(\lambda) \Delta\lambda$$

# Solar resource

## Radiation Transmitted by the Atmosphere



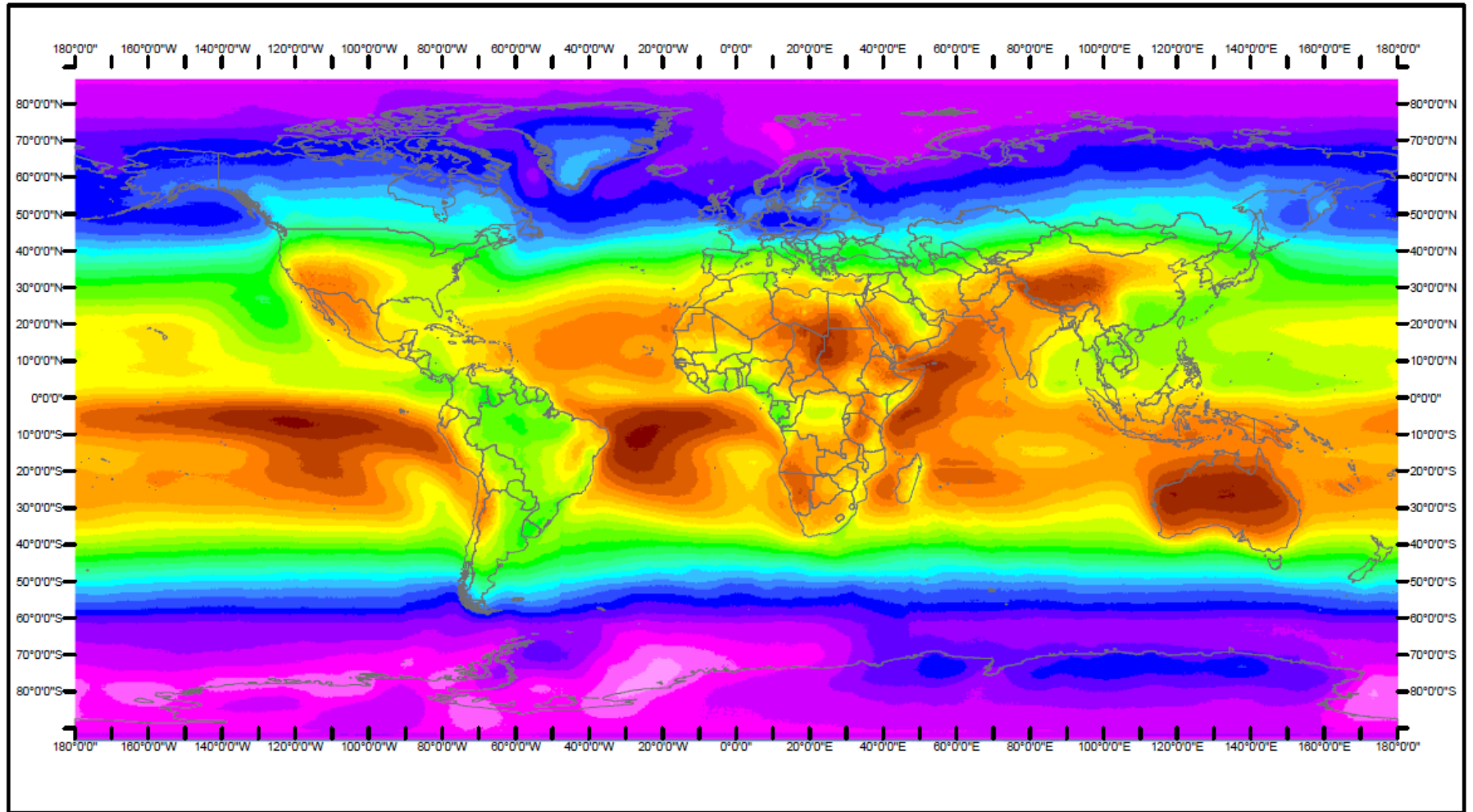
# Solar resource



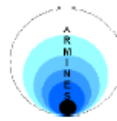
# Solar resource

- 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

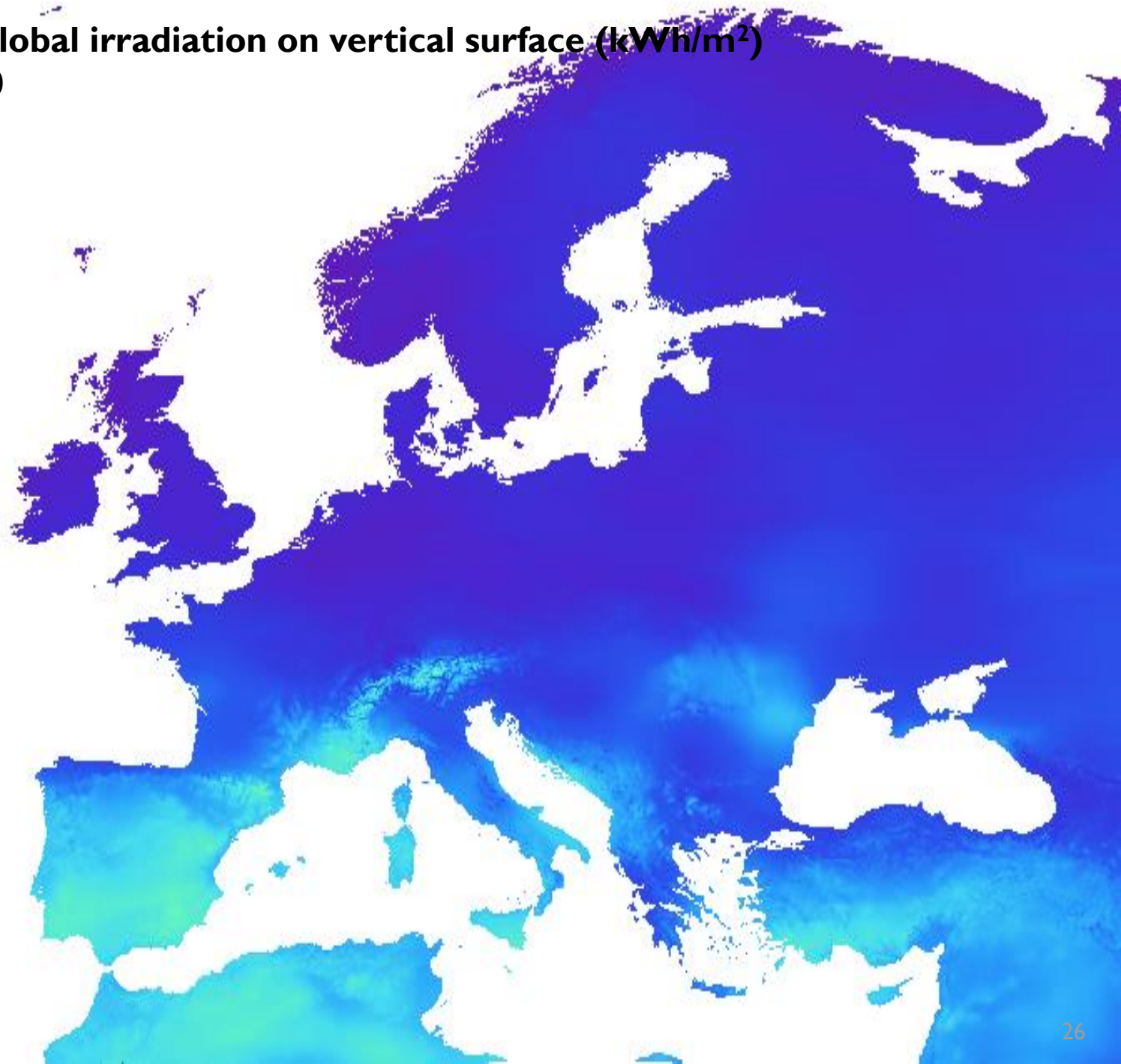


Yearly Mean of Irradiance in W/m<sup>2</sup>

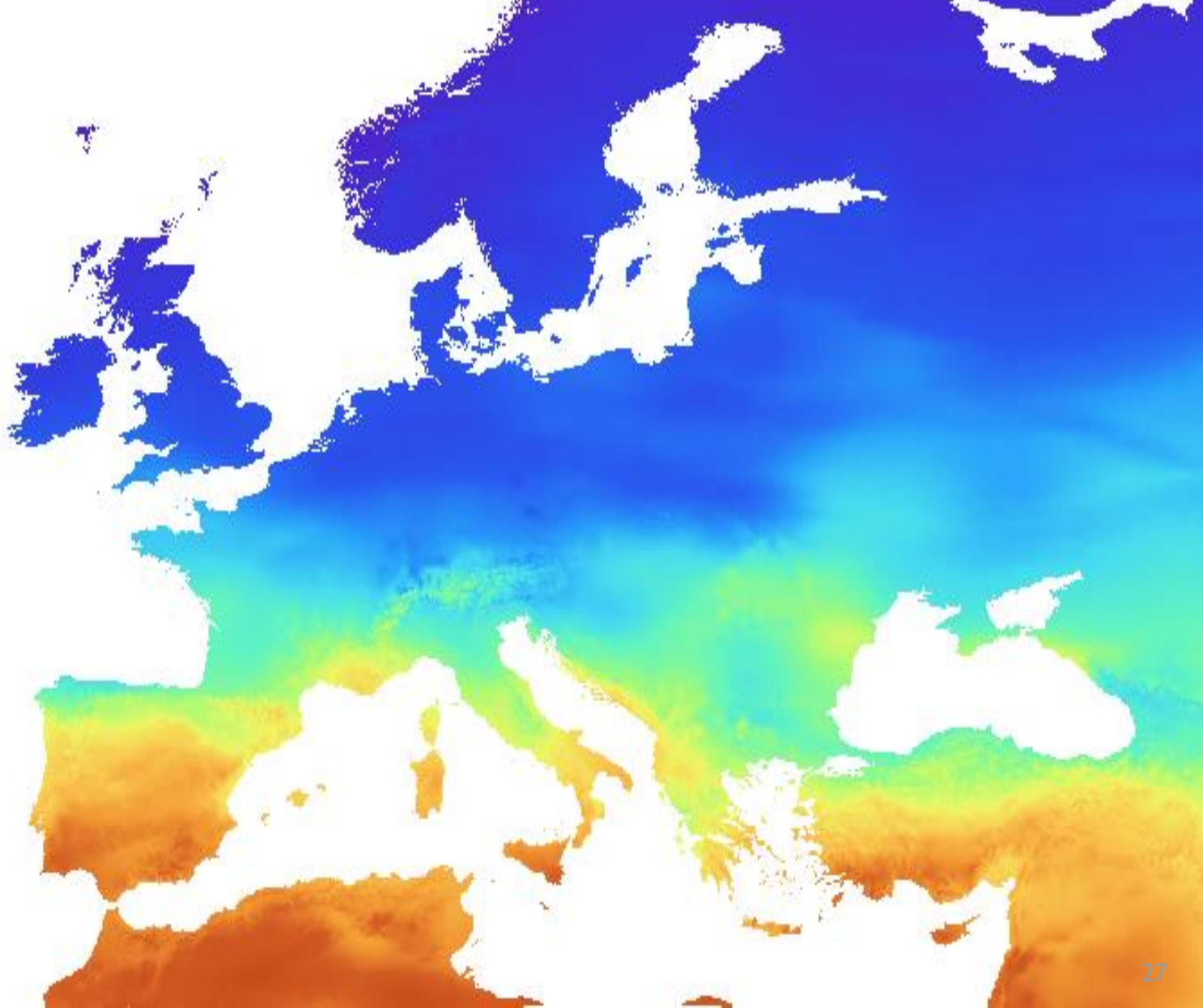


Realized by Michel Albuissou, Mireille Lefèvre, Lucien Wald.  
Edited and produced by Thierry Ranchin. Date of production: 23 November 2006.  
Centre for Energy and Processes, Ecole des Mines de Paris / Ammines / CNRS.  
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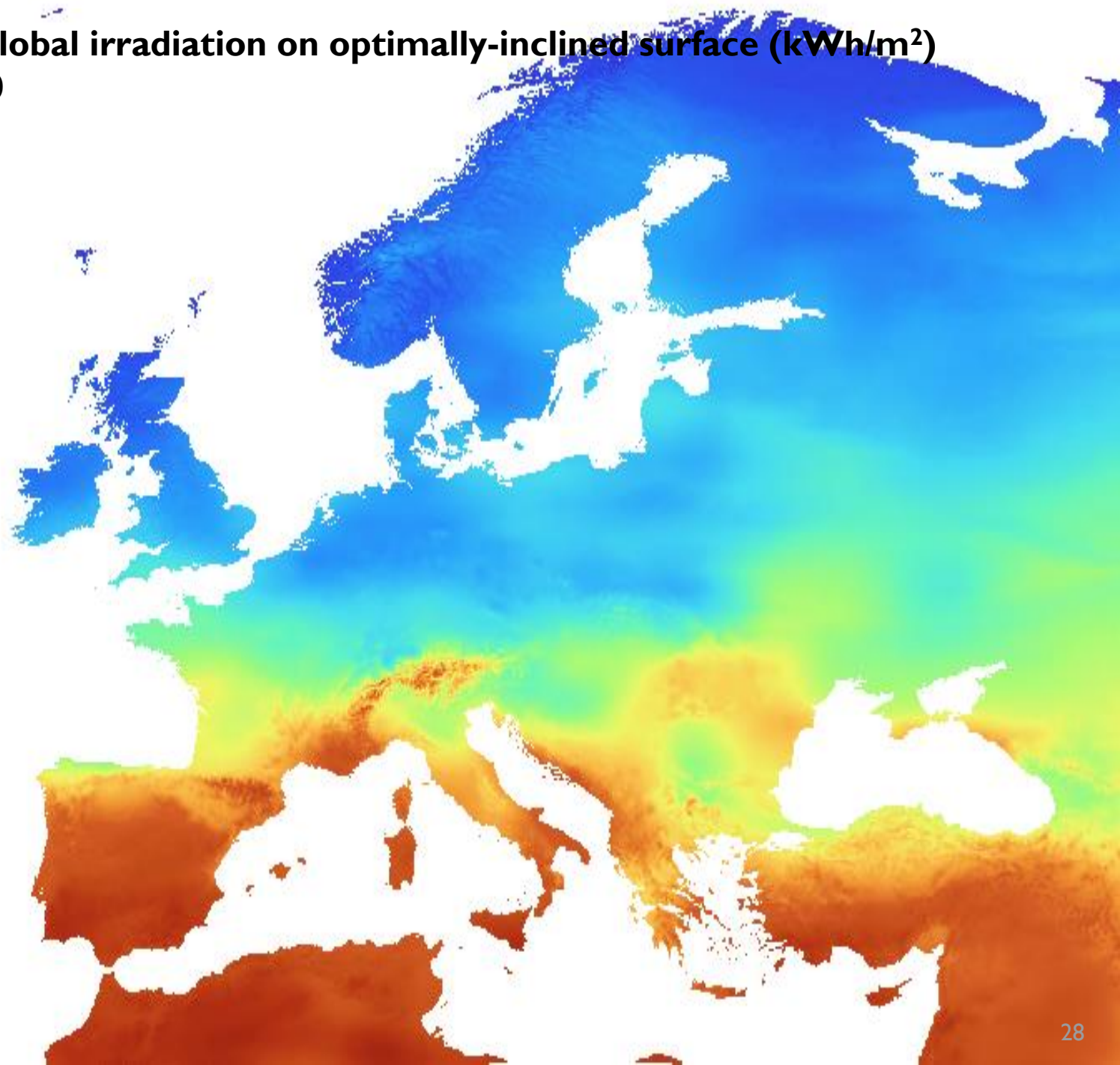
# Yearly sum of global irradiation on vertical surface (kWh/m<sup>2</sup>) period 1981-1990



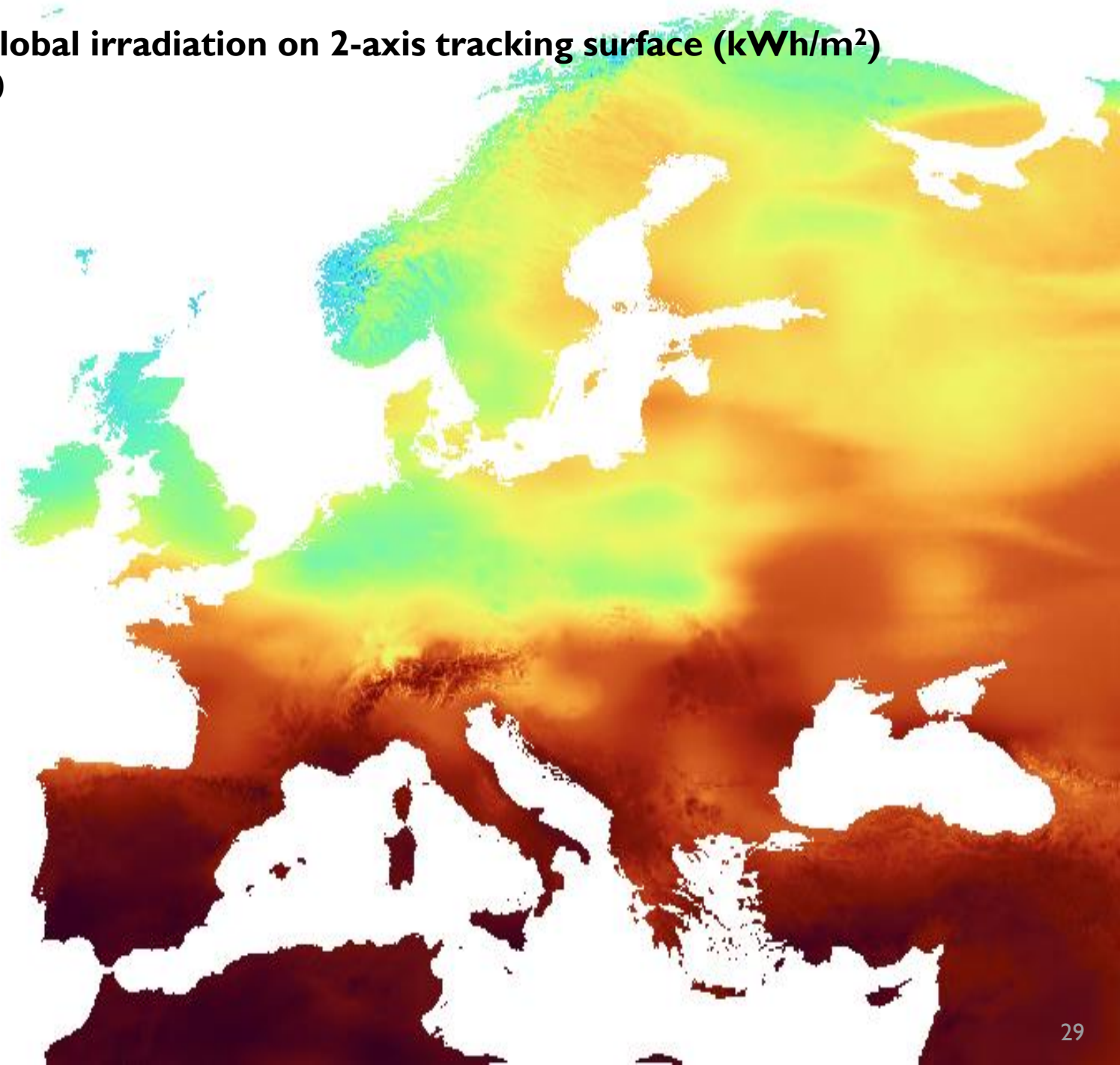
# Yearly sum of global irradiation on horizontal surface (kWh/m<sup>2</sup>) period 1981-1990



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

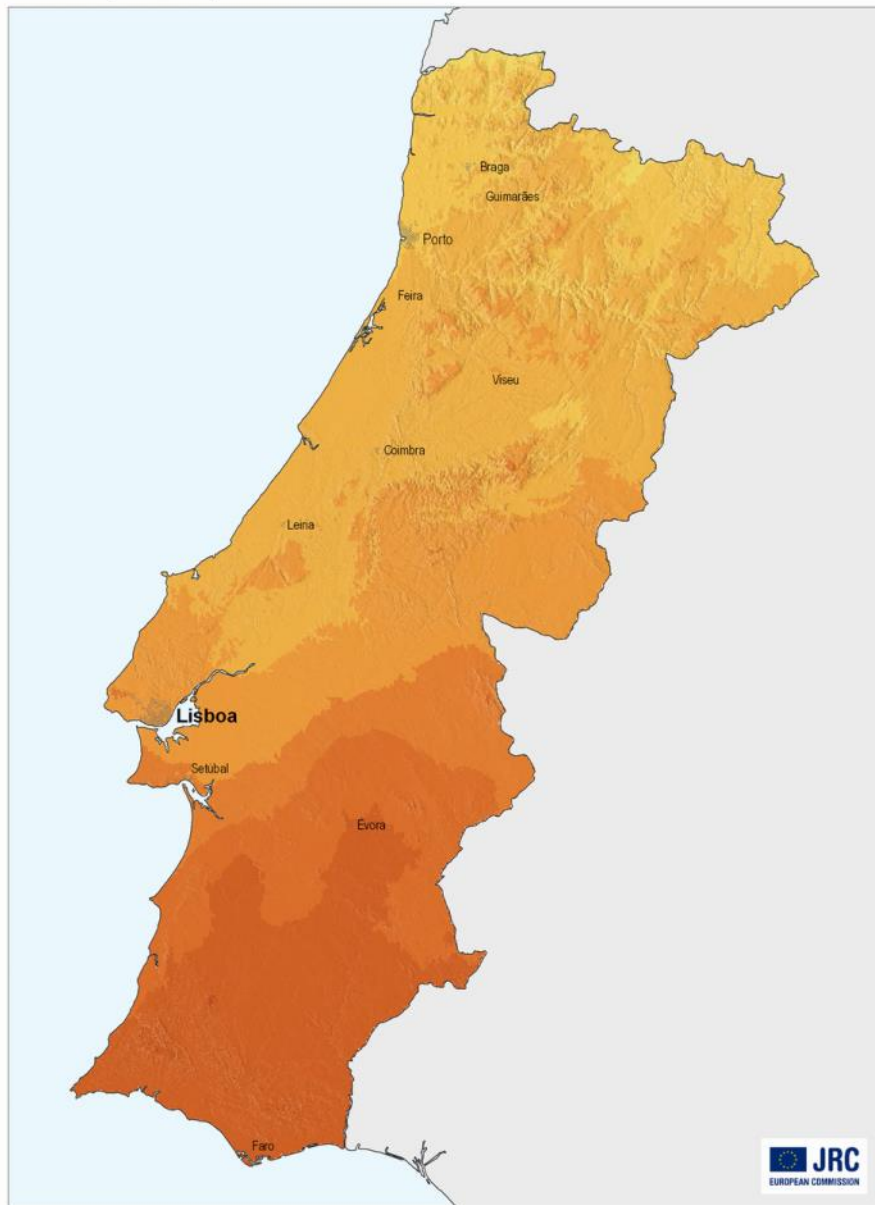


**Yearly sum of global irradiation on 2-axis tracking surface (kWh/m<sup>2</sup>)  
period 1981-1990**



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

**Portugal**



Yearly sum of global irradiation [kWh/m<sup>2</sup>]

<1500 1600 1700 1800

<1125 1200 1275 1350

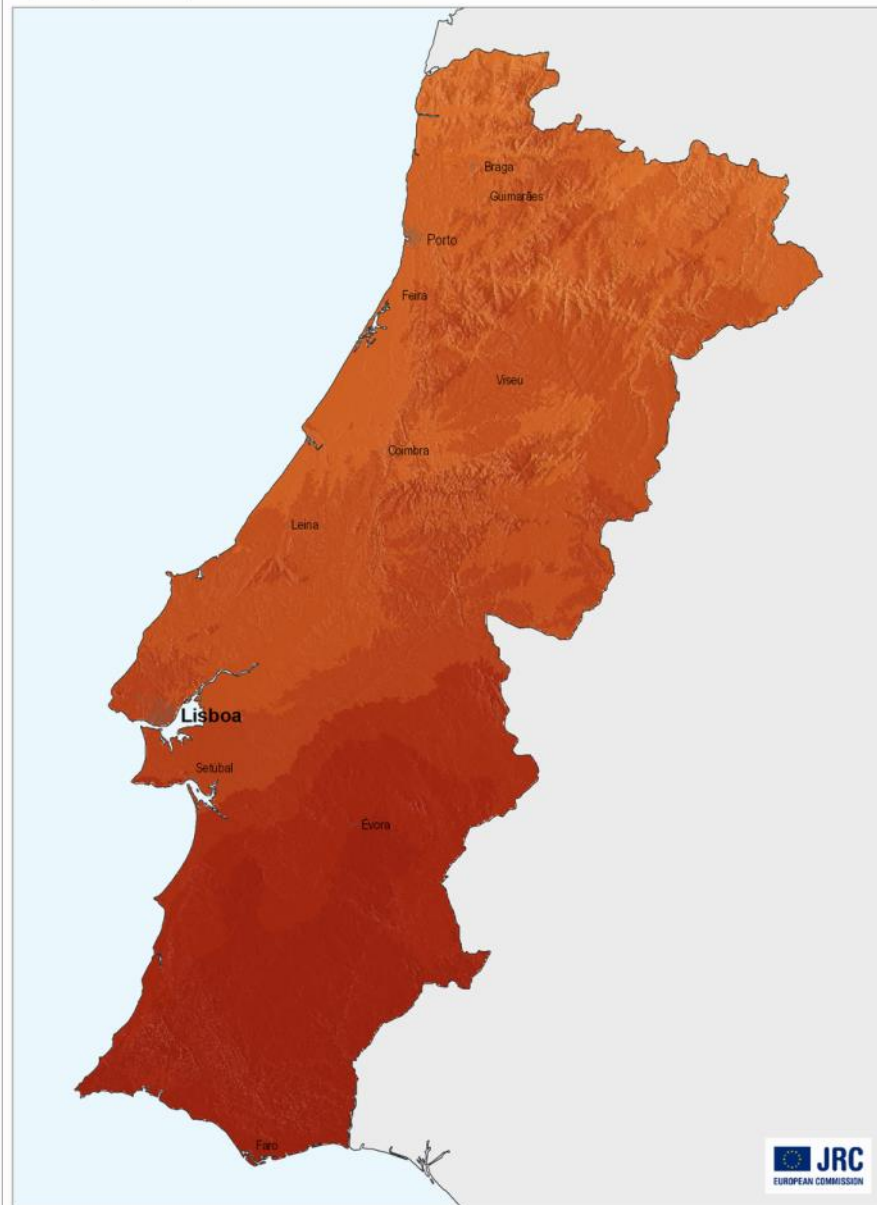
Yearly electricity generated by 1kW<sub>peak</sub> system with performance ratio 0.75 [kWh/kW<sub>peak</sub>]

Authors: M. Šuri, 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 [kWh/m<sup>2</sup>]

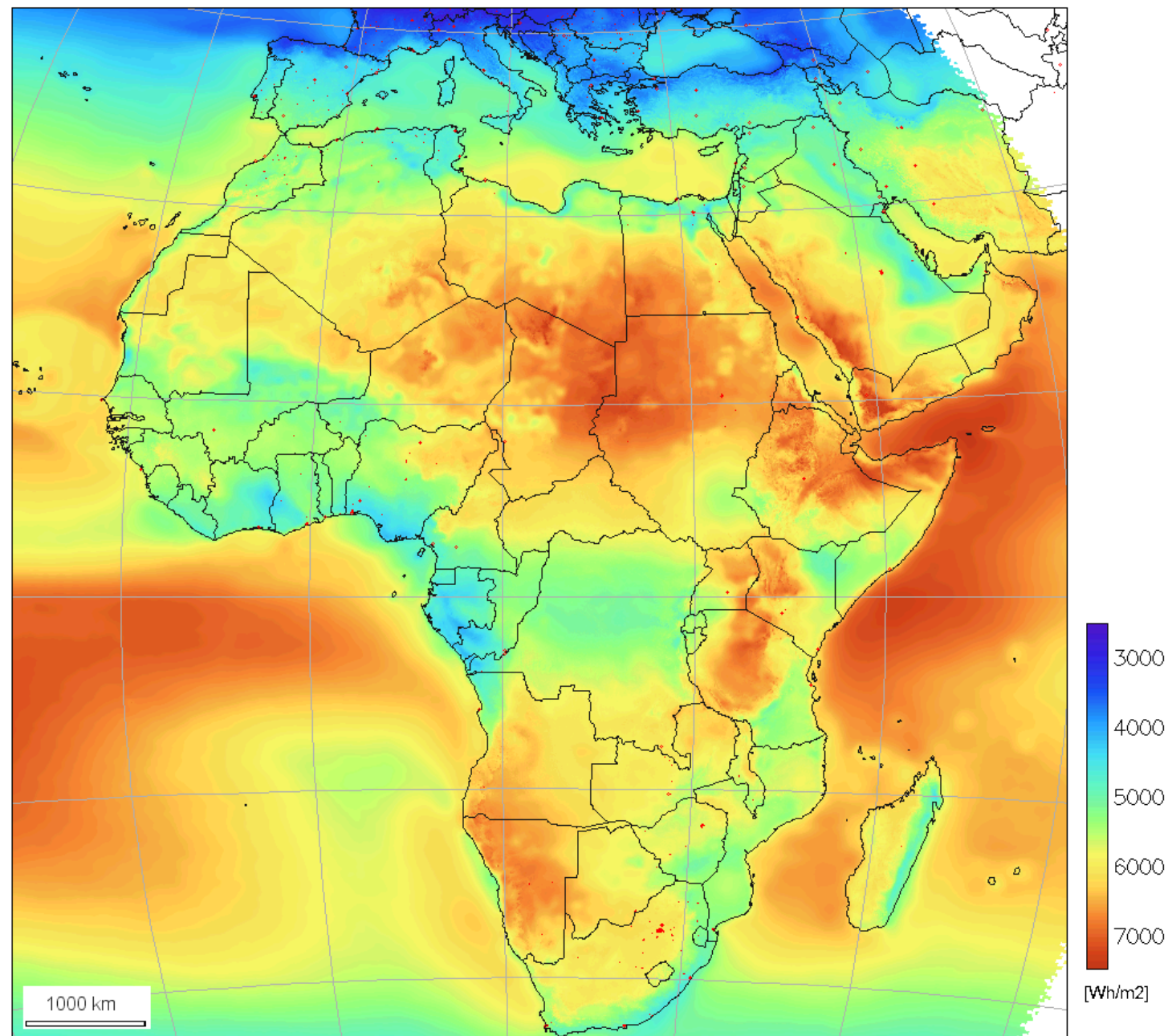
1700 1800 1900 2000>

1275 1350 1425 1500>

Yearly electricity generated by 1kW<sub>peak</sub> system with performance ratio 0.75 [kWh/kW<sub>peak</sub>]

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



# Solar resource

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

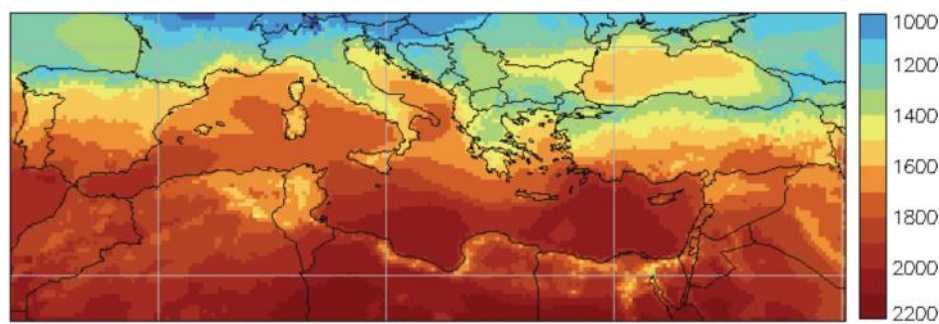


Figure 1: Long-term average of yearly sums of global horizontal irradiation (kWh/m<sup>2</sup>, time series representing years 1985, 1987, and 1989-2004)

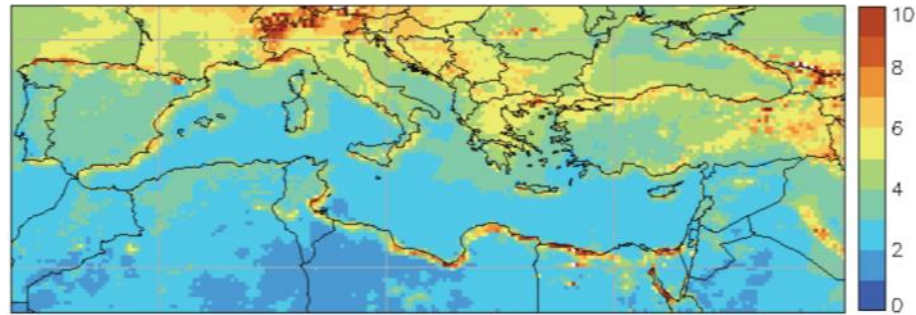


Figure 2: Standard deviation (in %) of yearly sums of global horizontal irradiation (years 1985, 1987, and 1989-2004)

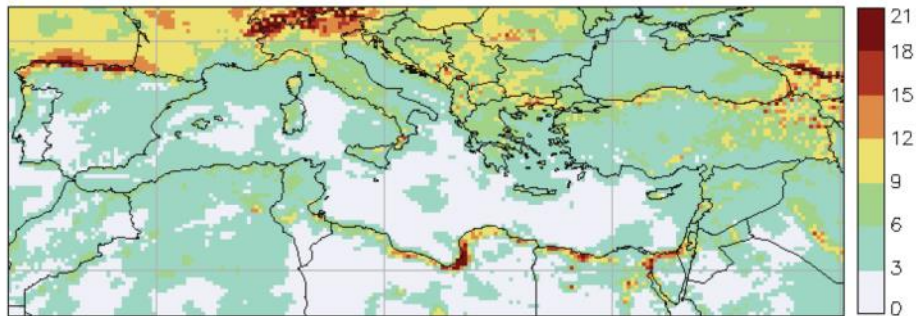


Figure 6: Relative difference of the highest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

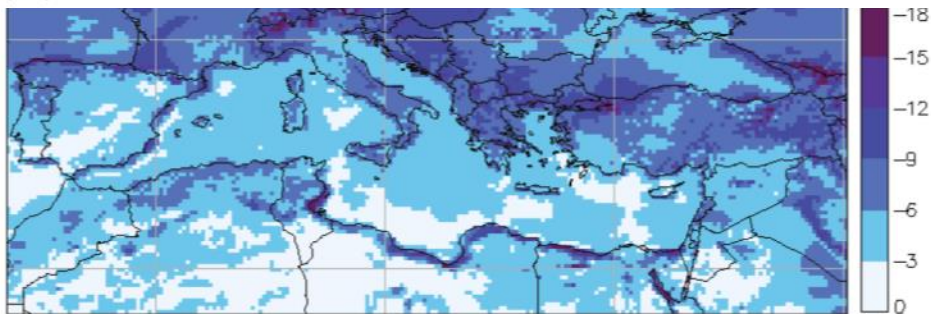


Figure 5: Relative difference of the lowest yearly sum of global horizontal irradiation in relation to the long-term average (in %).

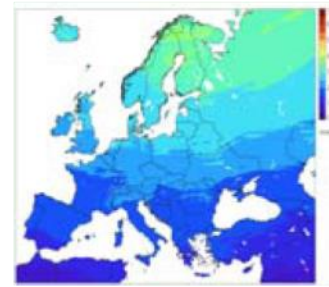
Šúri M., Huld T., Dunlop E.D., Albuissou M., Lefèvre M., Wald L., 2007. *Uncertainties in photovoltaic electricity yield prediction from fluctuation of solar radiation*. Proceedings of the 22nd European Photovoltaic Solar Energy Conference, Milano, Italy 3-7.9.2007

# Solar tracking

Compared to PV with modules fixed at optimum angle:

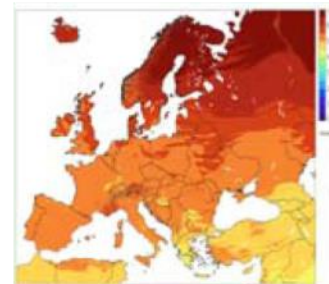
- Changing inclination twice a year contributes only marginally

## Fixed mounting - two (seasonal) optimum angles



*Optimum angle  
of modules  
in summer [°]*

**+ 1.5 to 4.5 %**

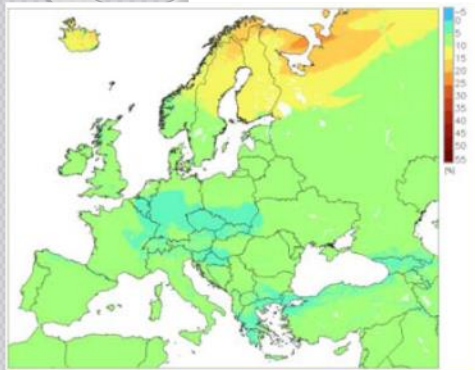


*Optimum angle  
of modules  
in winter [°]*



# Solar tracking

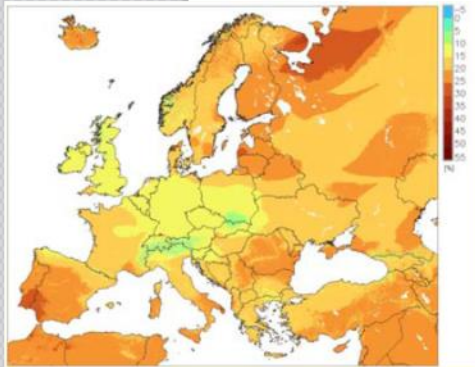
## One-axis tracking



Horizontal axis pointing East-West



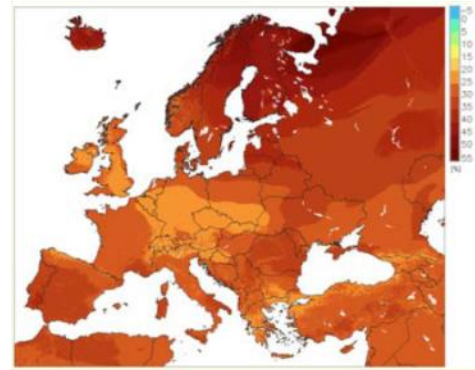
+ 0 to 21 %



Horizontal axis pointing North-South



+ 0 to 31 %



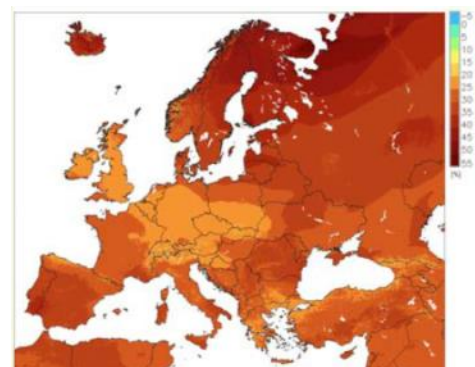
Vertical axis + modules mounted at optimum angle



+ 11 to 55 %



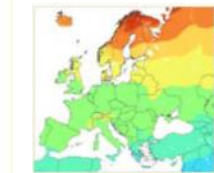
Optimum angle of modules [°]



Axis inclined at an optimum angle towards South



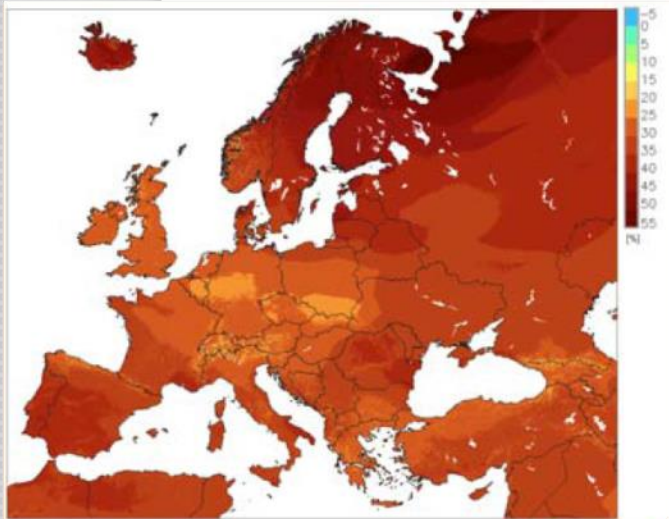
+ 12 to 50 %



Optimum angle of the axis [°]

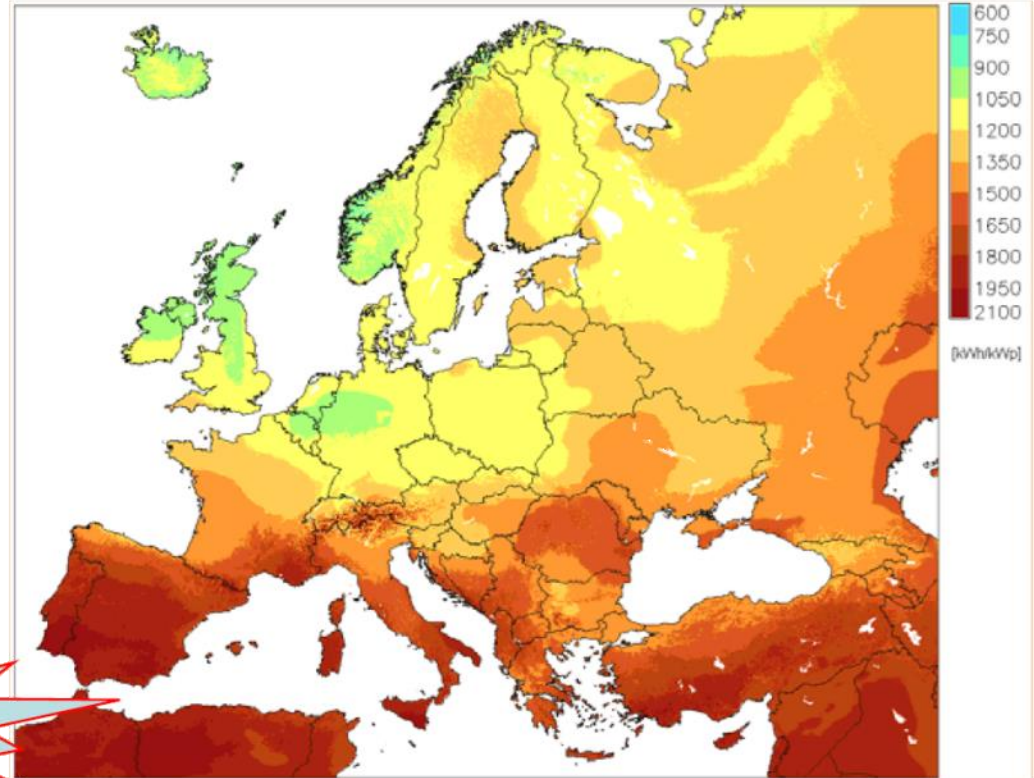
# Solar tracking

Two-axis tracking



+13 to 55 %

Highest achievable



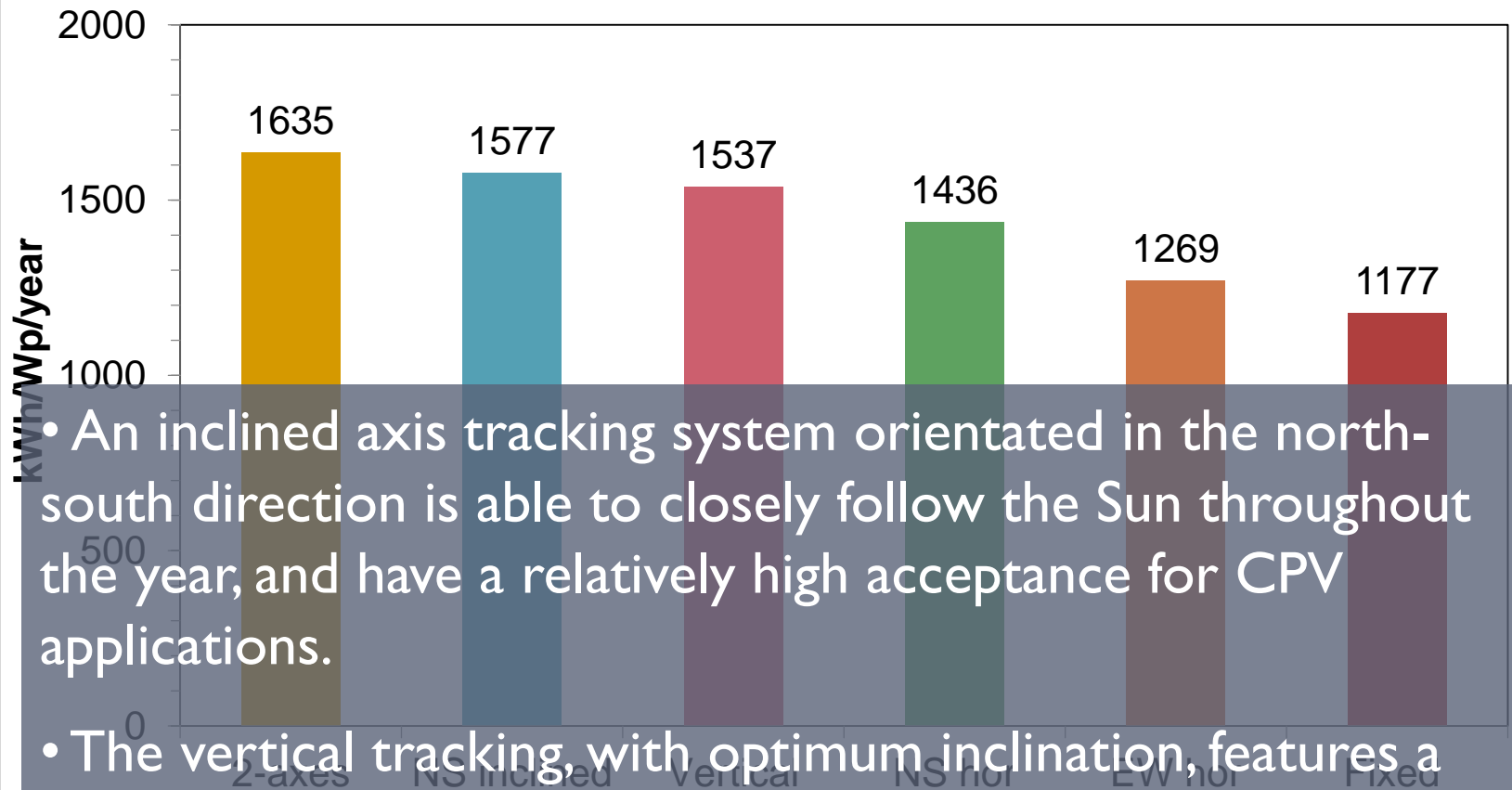
Yearly sum of solar electricity generated from 1kWp PV system [kWh]

# 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



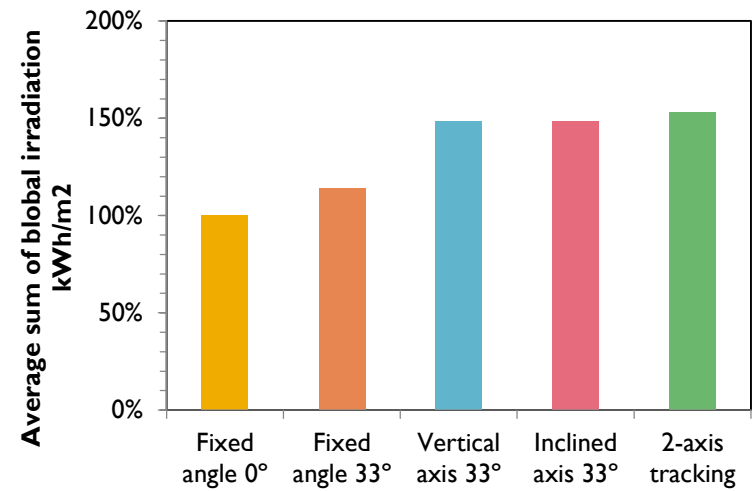
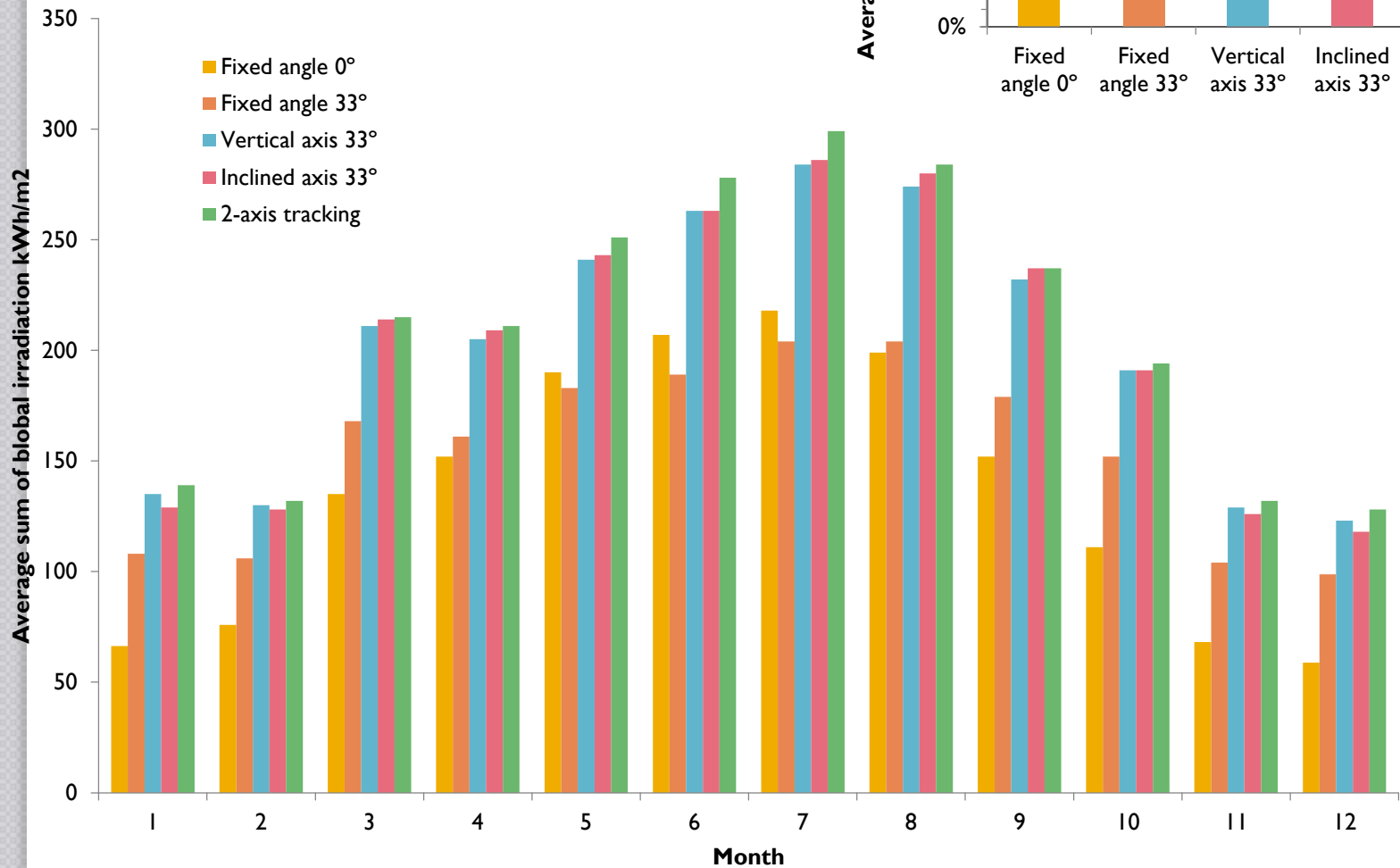
▲ Installing a screw foundation for a dual-axis tracking system (Deger-Traker) at Am Peterswald PV park in Germany: Bftec GmbH pre-drills the ground at the site and then the foundation is installed. The foundation's unusual form, which consists of a smooth side wall with a coil at the bottom (if necessary,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

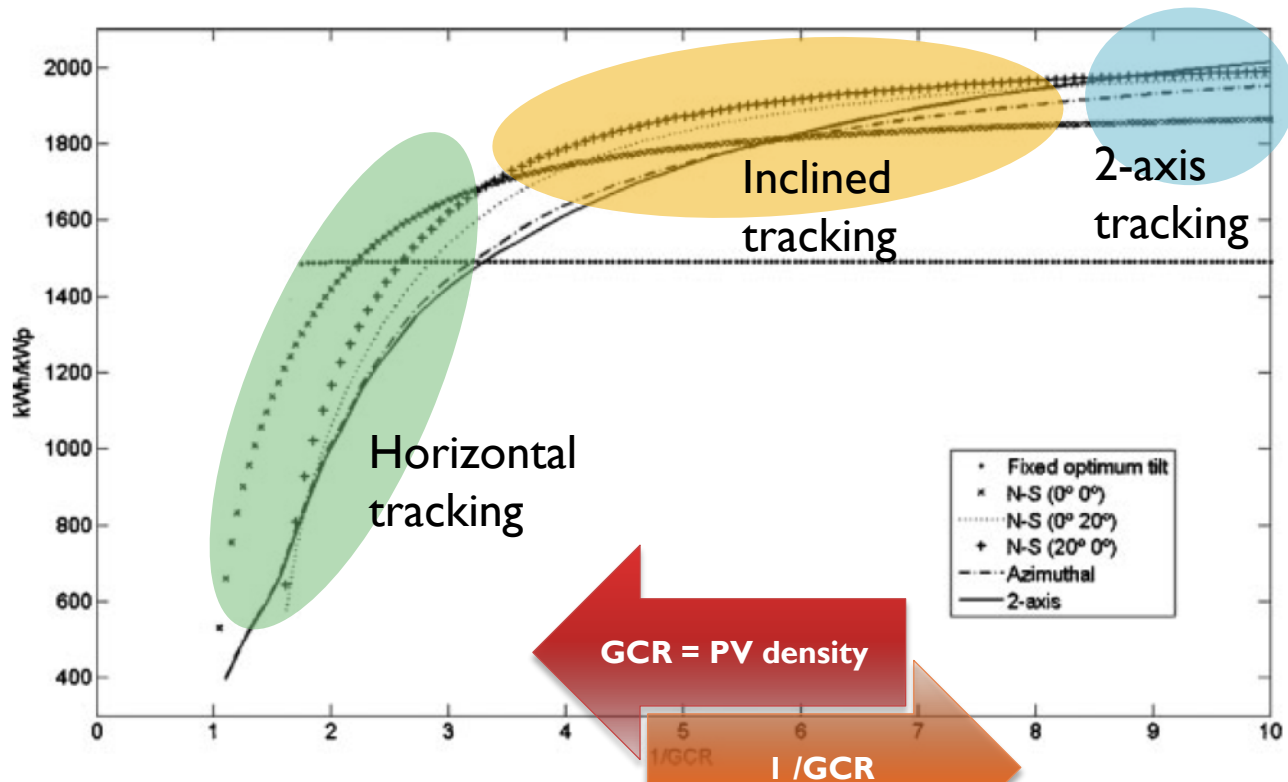



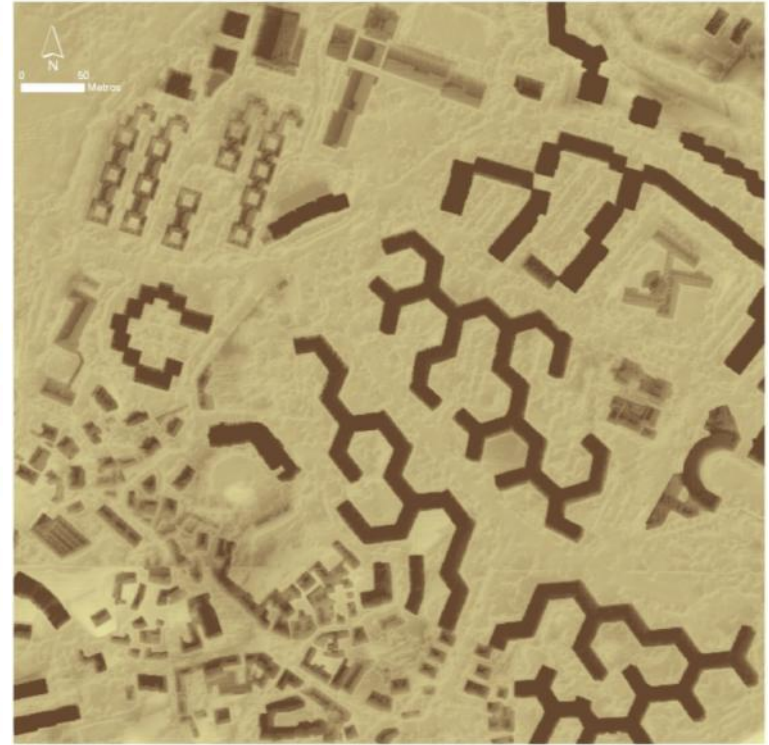
Figure 13. Evolution of yearly energy yield in Almería for the tracking strategies considered here, for the pessimistic shading case and assuming a constant dirtiness degree of 3%

# PV in urban environment



Localização da área de estudo

 Área de estudo

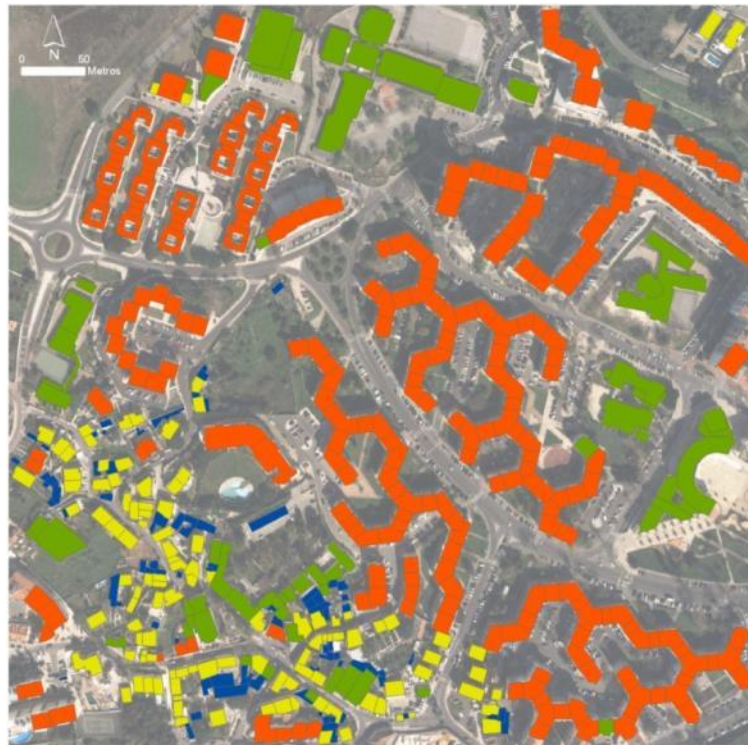


Modelo Digital de Superfície Normalizado (MDSn)

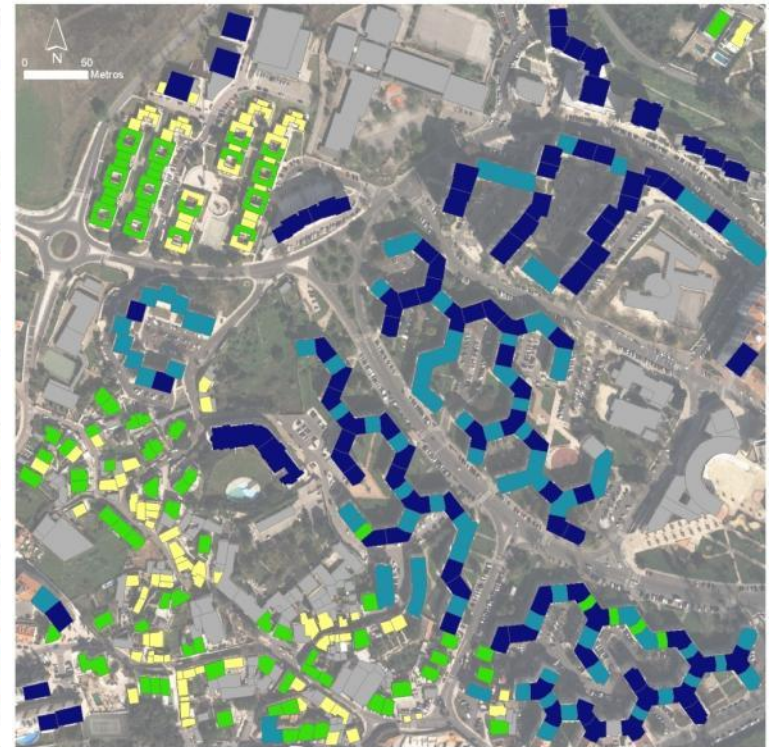
Altura  
Alto : 40,3  
Baixo : -4,9

Carnaxide (38.43° N, 9.8 W)

# PV in urban environment



- Plurifamiliar
- Unifamiliar
- Anexo
- Serviços



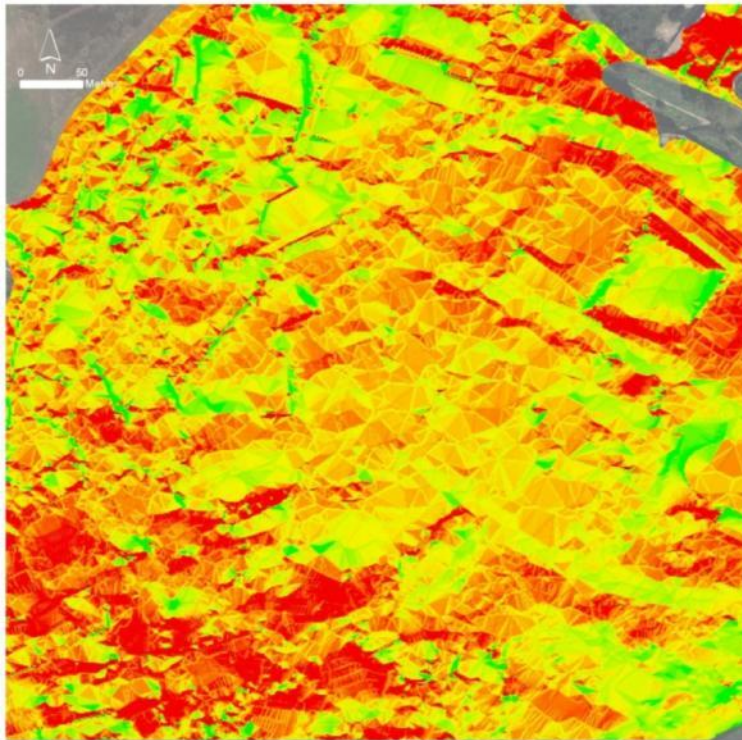
#### N.º de habitantes

- 1 - 3
- 4 - 10
- 11 - 18
- 19 - 81

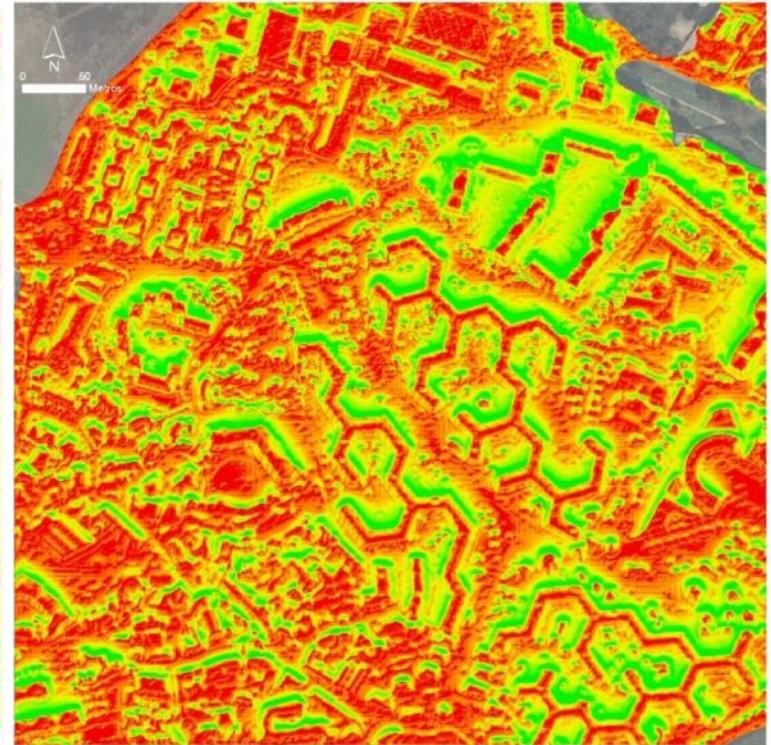
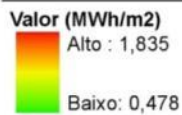
Edifício de serviços (sem habitantes)

Separação de classes em Quartis

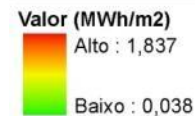
# PV in urban environment



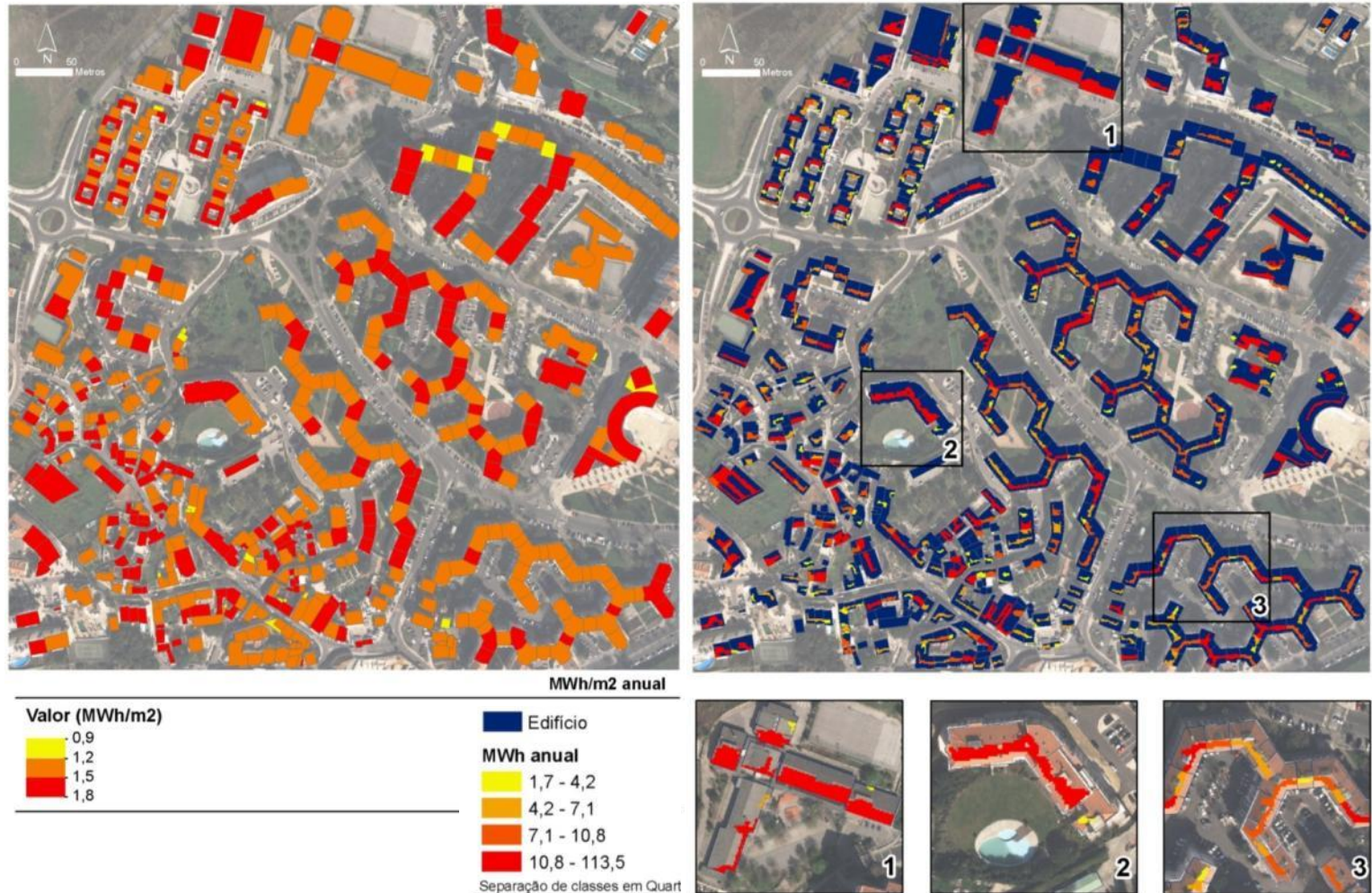
Mapa solar anual (MDT)



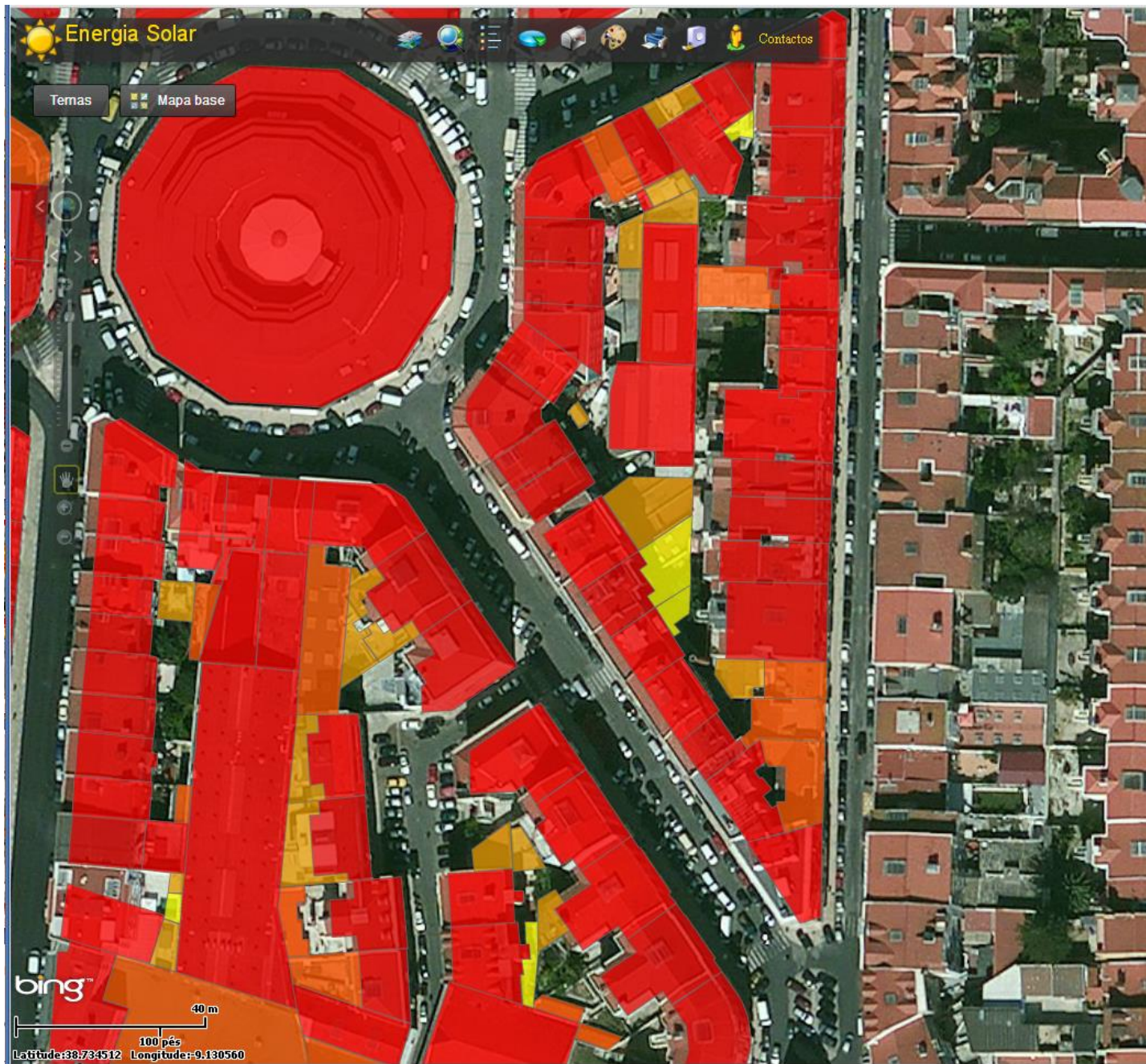
Mapa solar anual (MDS)



# PV in urban environment











# PV in urban environment

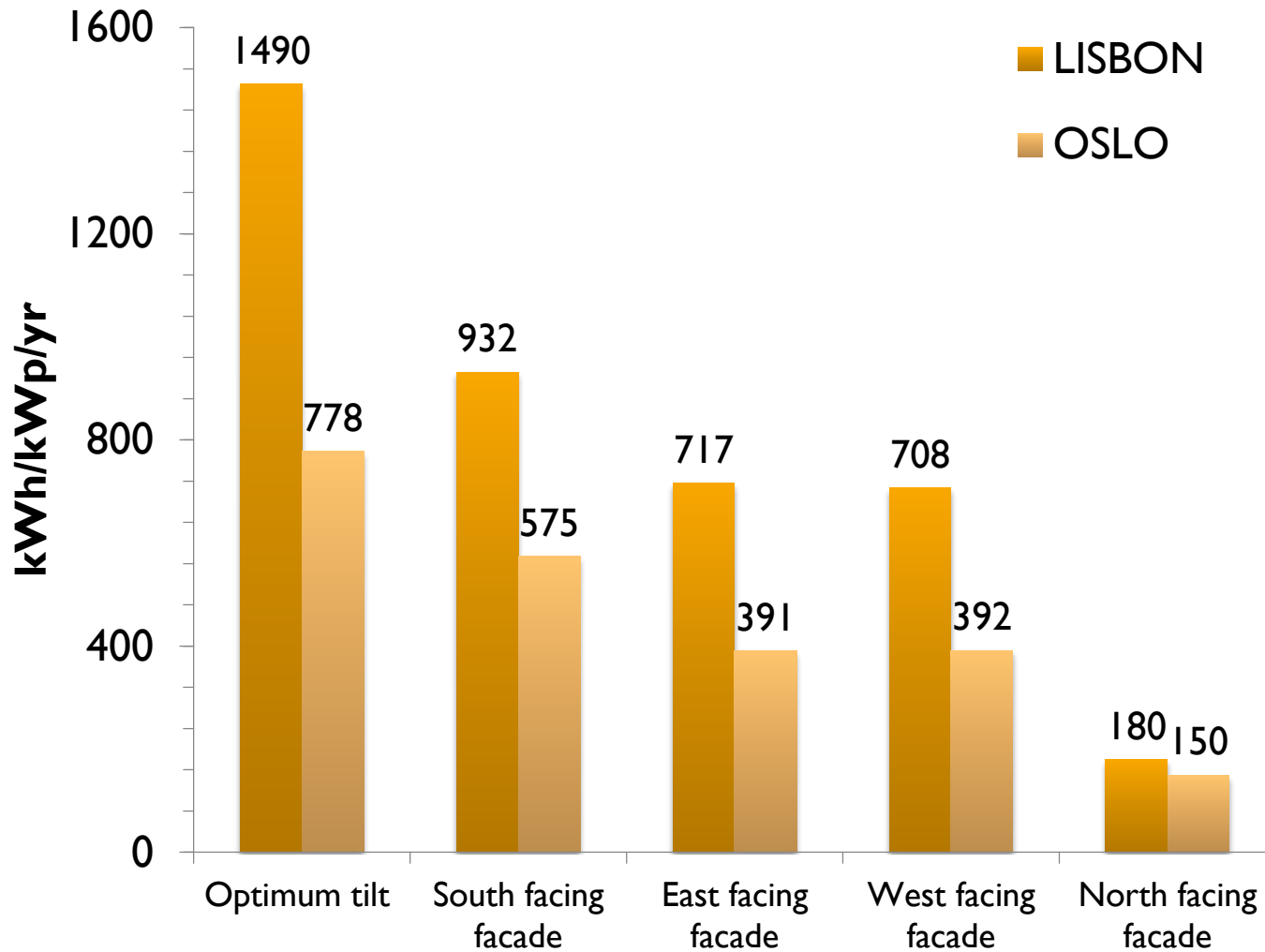
- Procedure for estimating the PV potential of an urban region using LiDAR data based on the **Solar Analyst extension for ArcGIS**.
- PV potential of the **538 buildings** to be around **11.5 GWh/year** for an installed capacity of **7MW**, which corresponds to **48 %** of the local electricity demand.
- For **low PV penetration** (about 10% of total roof area) the PV potential is well estimated by considering no shade and the local optimum inclination and orientation.
- For **high PV penetration** (i.e. covering close to all roof area) the PV potential is well estimated by considering a horizontal surface with the footprint area of the buildings.

# PV in urban environment

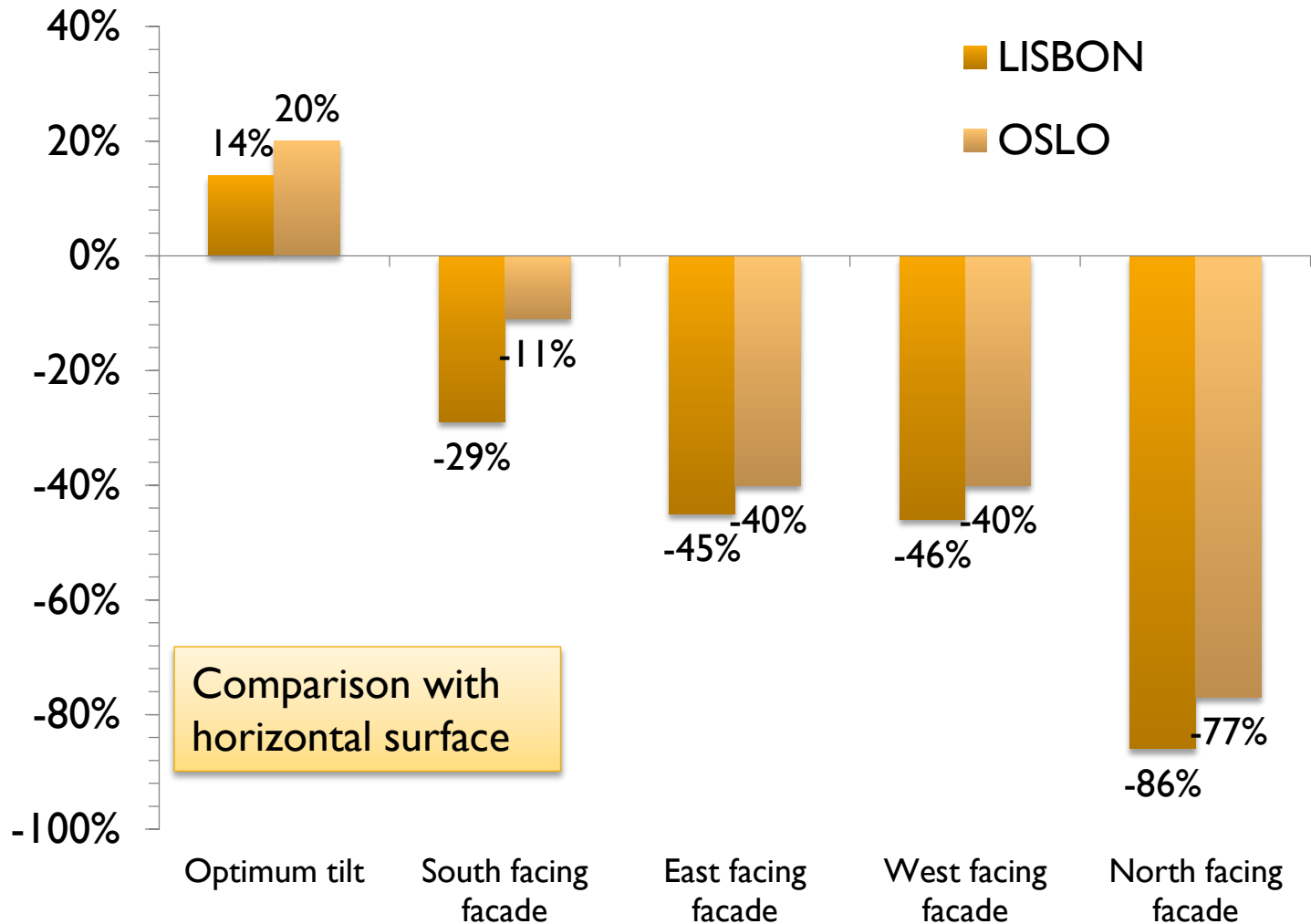


0  2100  
[kWh/m<sup>2</sup>/y]

# THE ROLE OF BUILDING FACADES

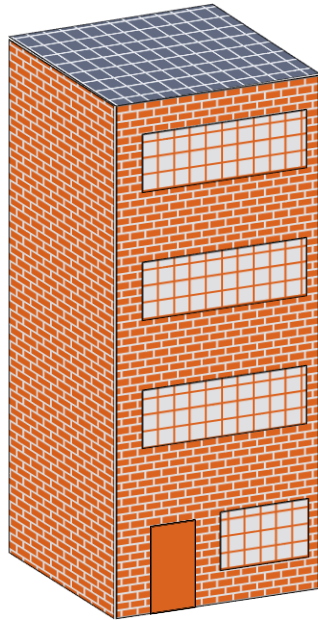


# THE ROLE OF BUILDING FACADES



# THE ROLE OF BUILDING FACADES

## Solar facades?



### Typical 4 storey building

Roof area:

$$10 \times 10 \text{m}^2 = 100 \text{m}^2$$

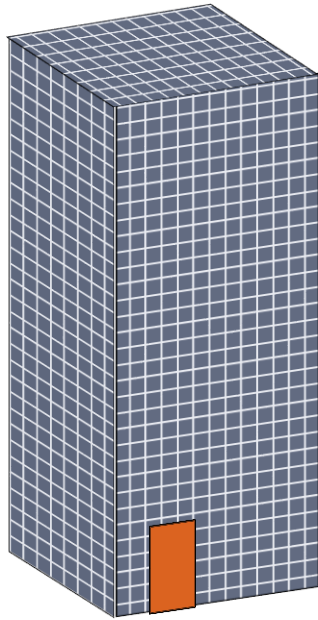
Annual solar PV production on roof:

**18.6 MWh/day**

(with optimum orientation/inclination)

# THE ROLE OF BUILDING FACADES

## Solar facades?



### Typical 4 storey building

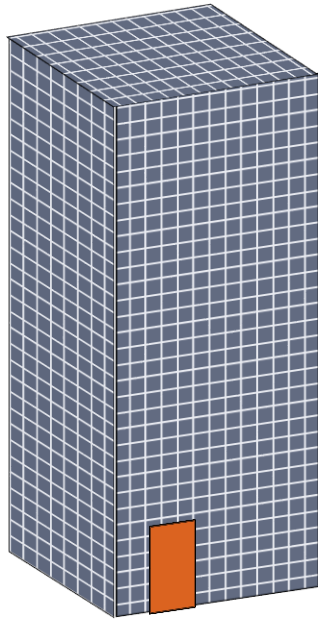
Roof area:  
 $10 \times 10 \text{m}^2 = 100 \text{m}^2$

Facades area:  
4 facades  
x 4 storeys  
x 3m  
x 10m = **480m<sup>2</sup>**

Total area:  
**580m<sup>2</sup>**

# THE ROLE OF BUILDING FACADES

## Solar facades?

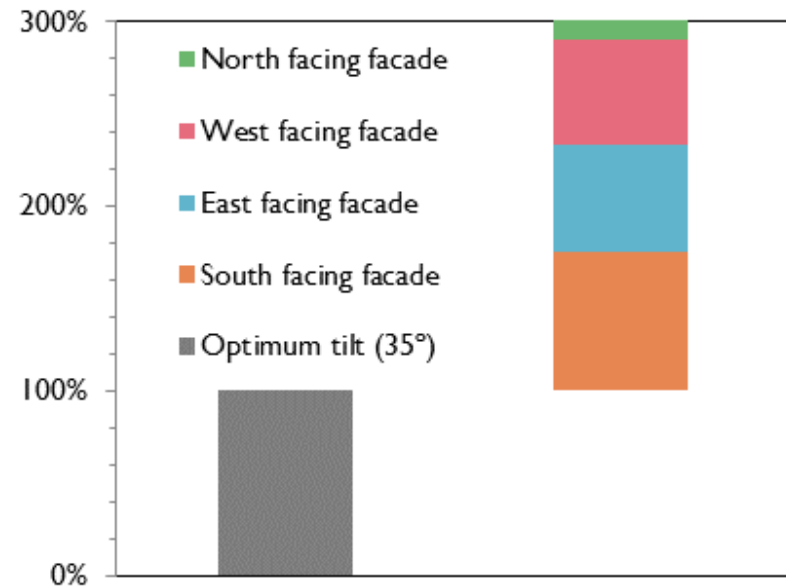


### Typical 4 storey building

Roof area:  
 $10 \times 10 \text{m}^2 = 100 \text{m}^2$

Facades area:  
4 facades  
 $\times 4$  storeys  
 $\times 3 \text{m}$   
 $\times 10 \text{m} = 480 \text{m}^2$

Total area:  
 **$580 \text{m}^2$**

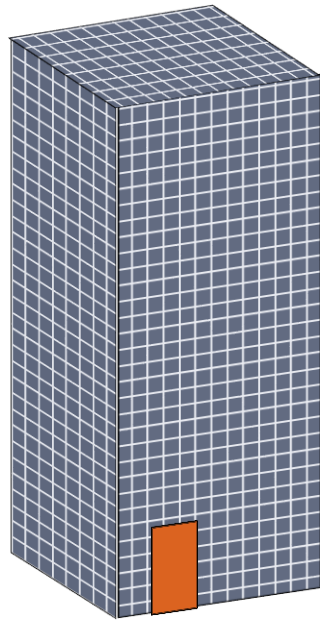


Annual solar PV production on roof and facades:  
 $18.6 + 38.1 = 56.7 \text{ MWh/day}$

# THE ROLE OF BUILDING FACADES

## Solar facades?

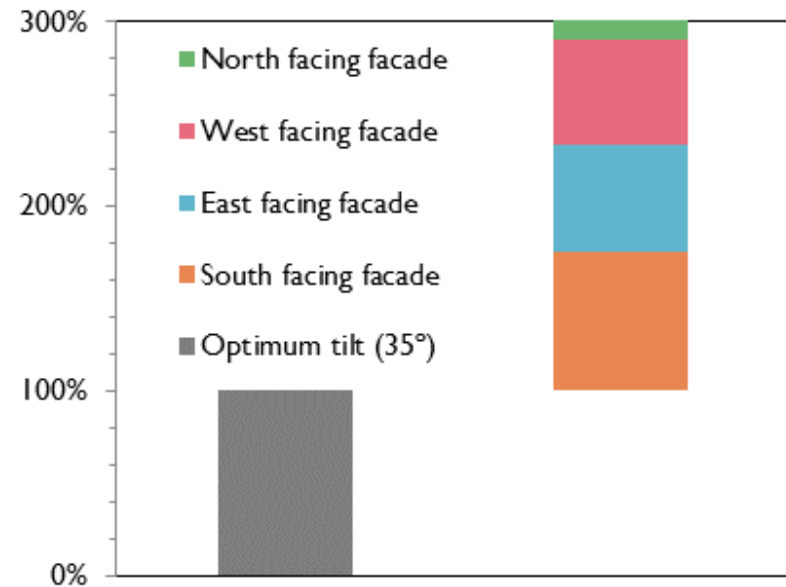
### Typical 4 storey building



Roof area:  
 $10 \times 10 \text{m}^2 = 100 \text{m}^2$

Facades area:  
4 facades  
x 4 storeys  
x 3m  
x 10m =  $480 \text{m}^2$

Total area:  
 $580 \text{m}^2$

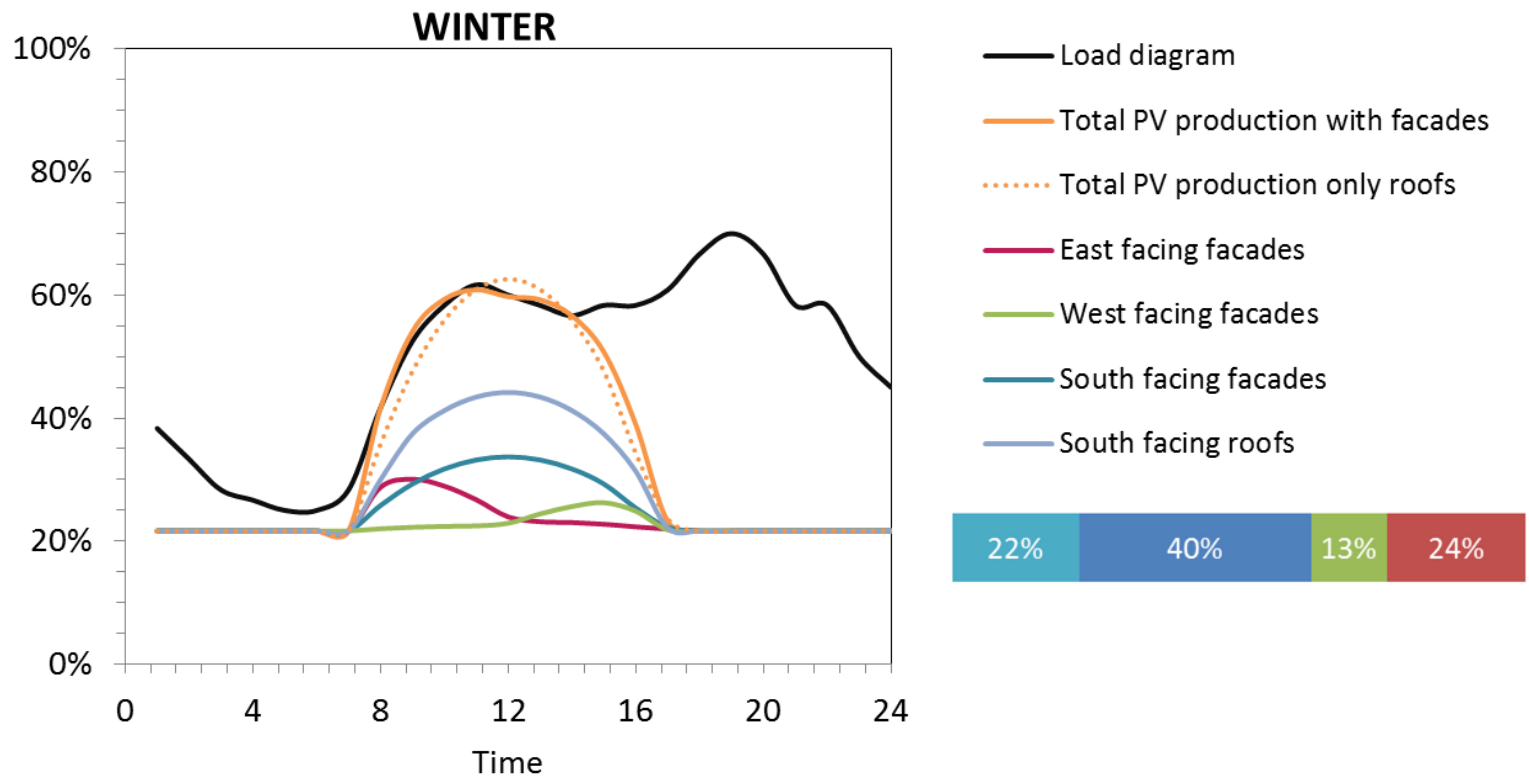


Facades can increase the PV area dramatically (x5.8) and, although with less than optimum inclination/orientation may contribute significantly to the overall production (x3).

# THE ROLE OF BUILDING FACADES

## Solar facades

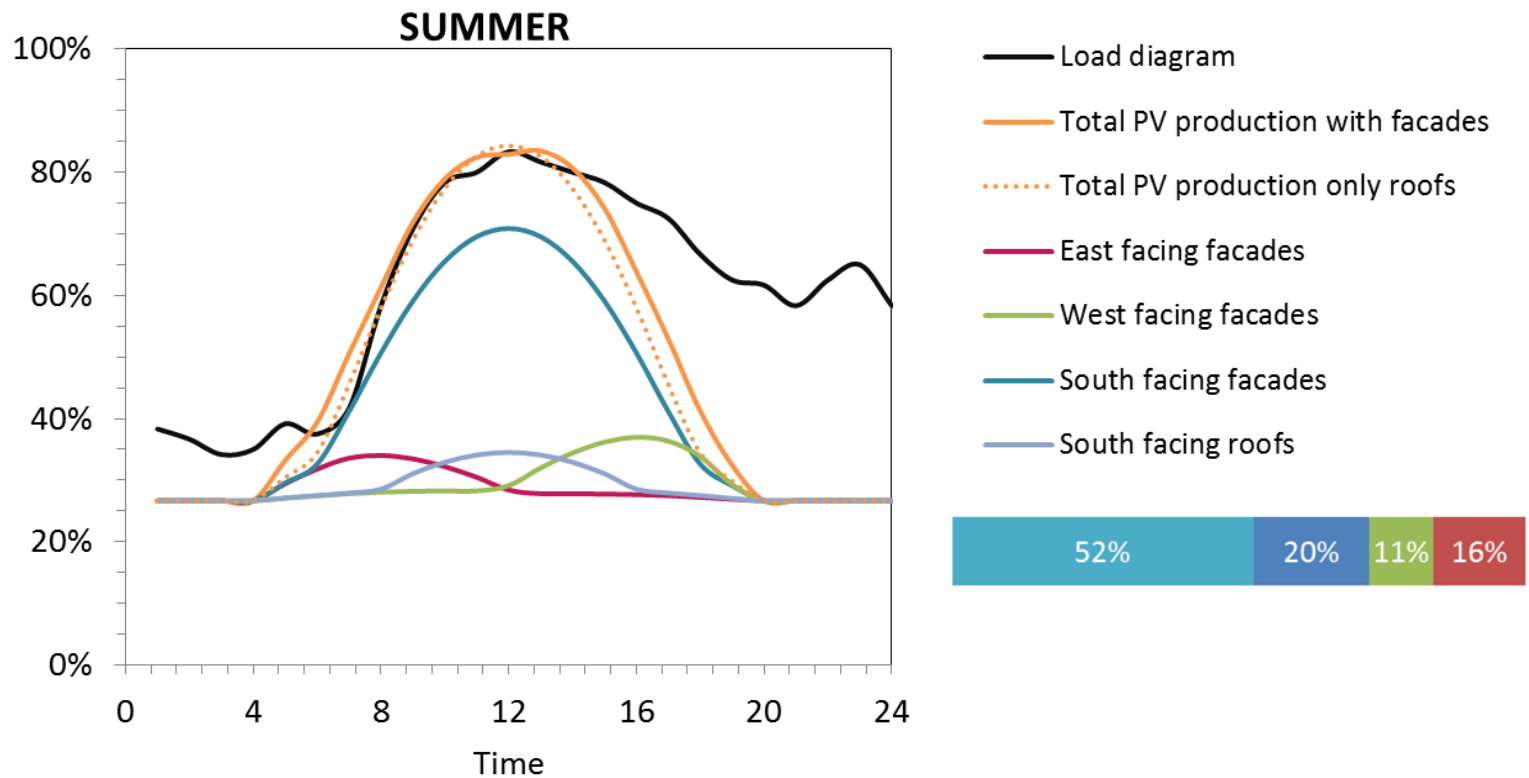
17% decrease in mismatch between supply and demand during sunlight hours (+32% covered area)



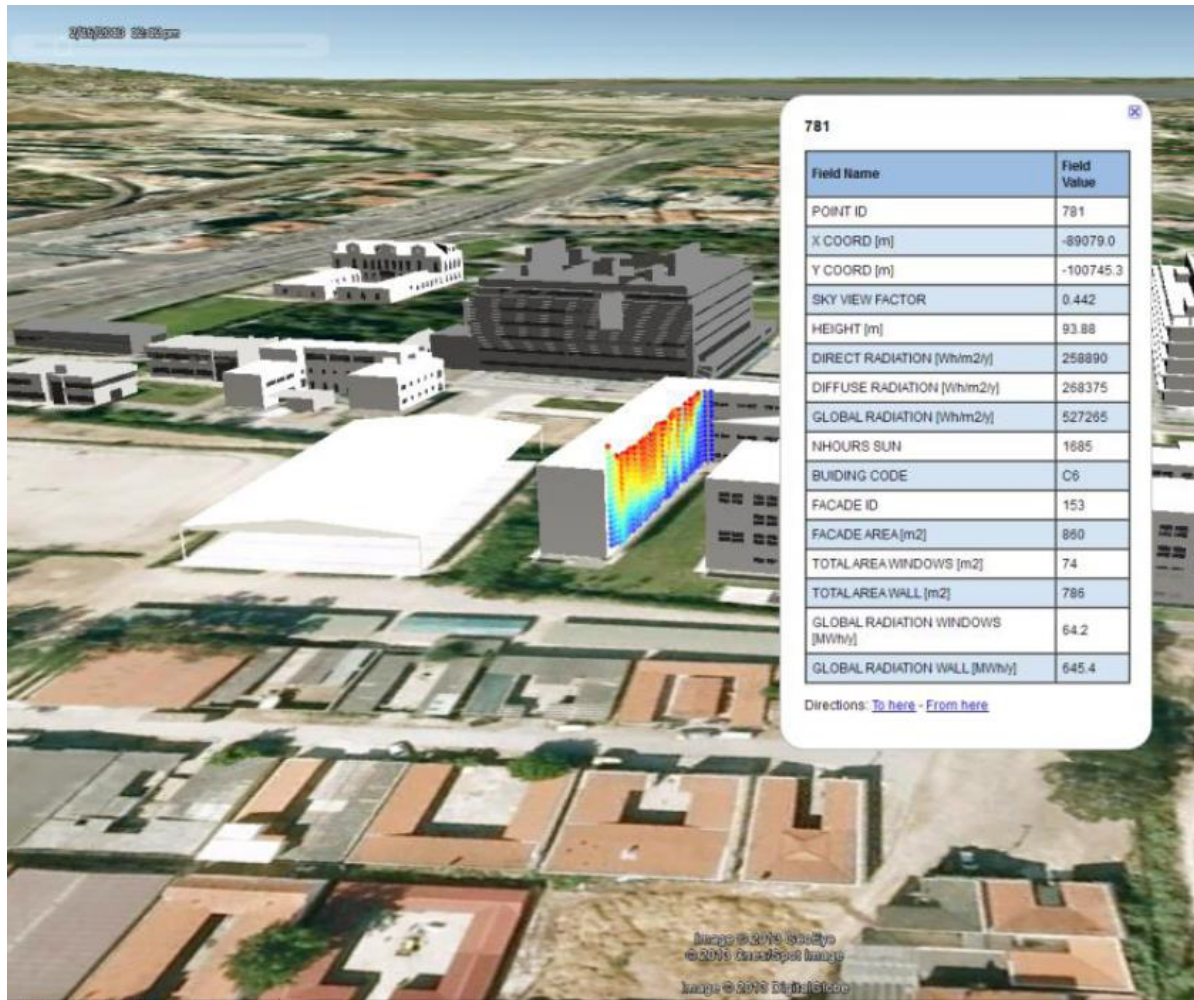
# THE ROLE OF BUILDING FACADES

## Solar facades

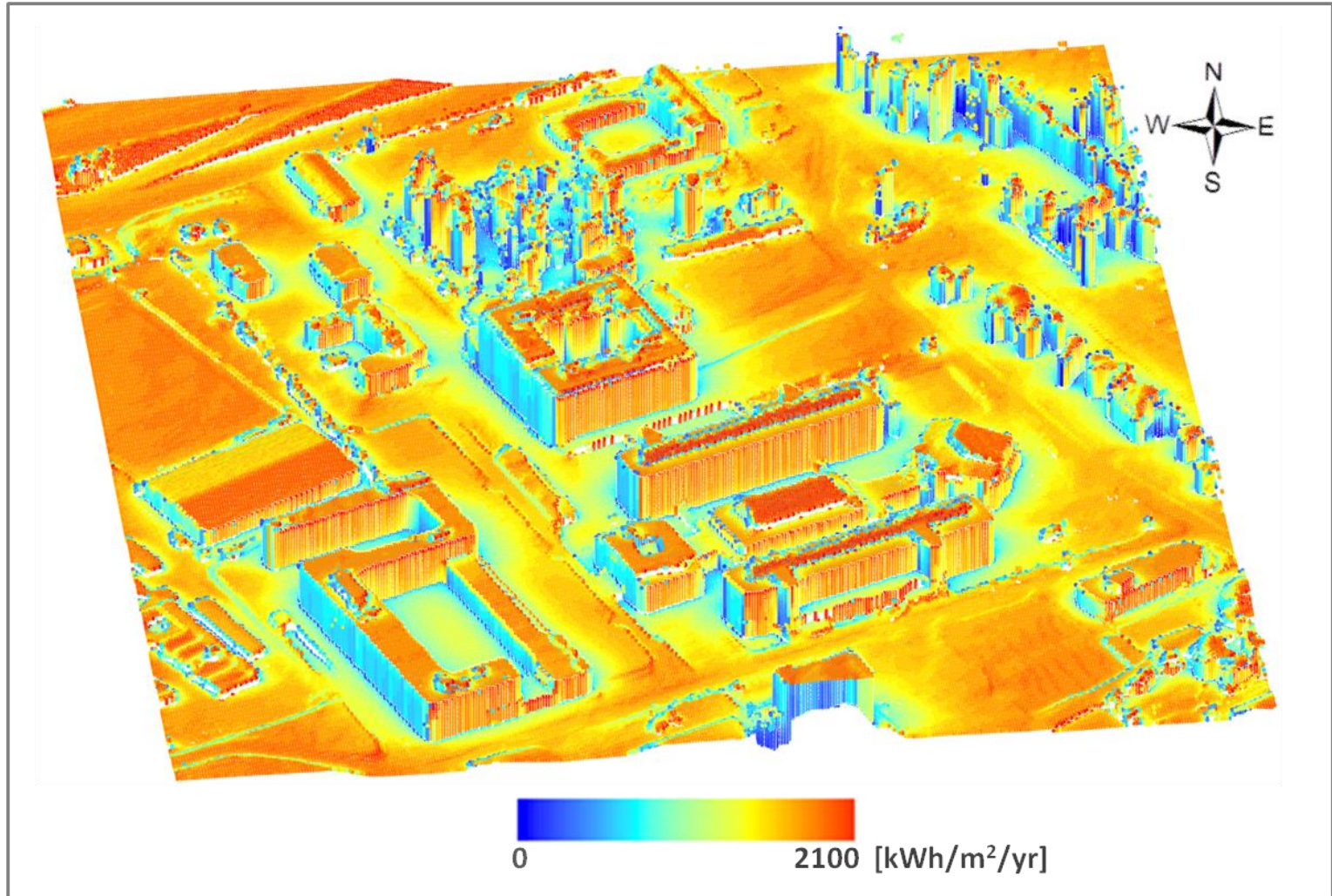
19% decrease in mismatch between supply and demand during sunlight hours (+46% covered area)



# THE ROLE OF BUILDING FACADES



# THE ROLE OF BUILDING FACADES

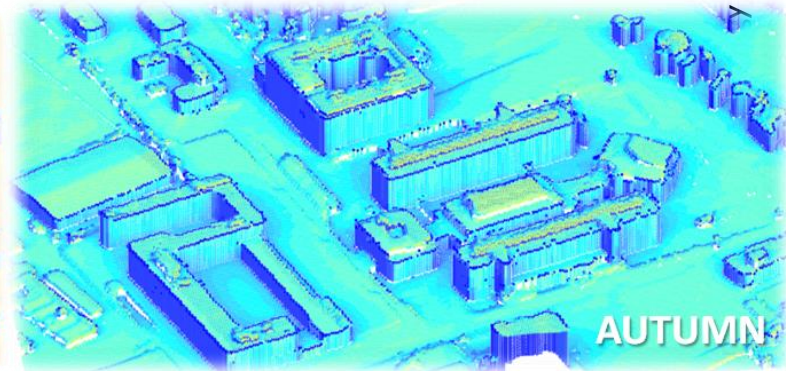
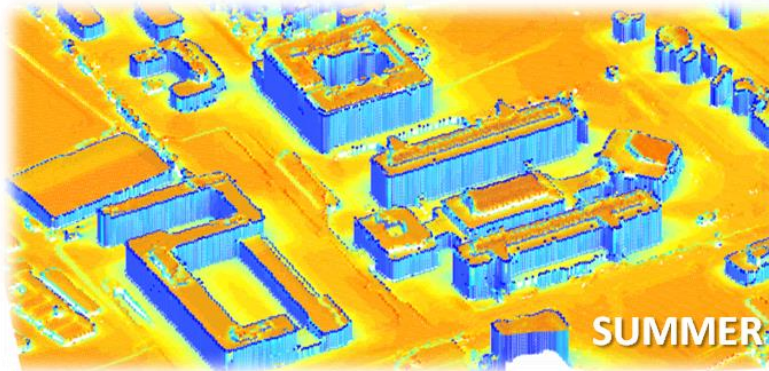
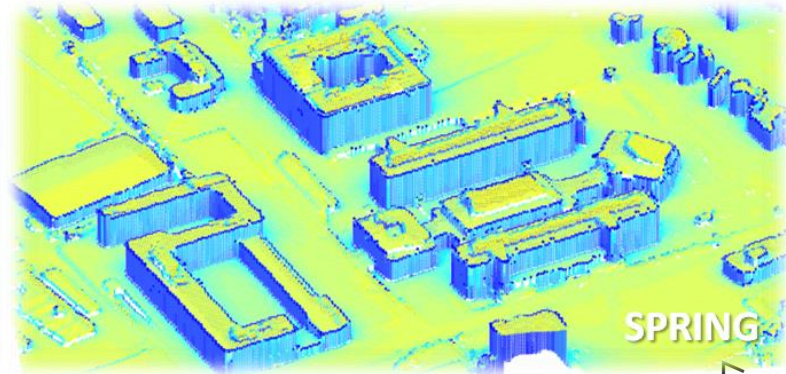
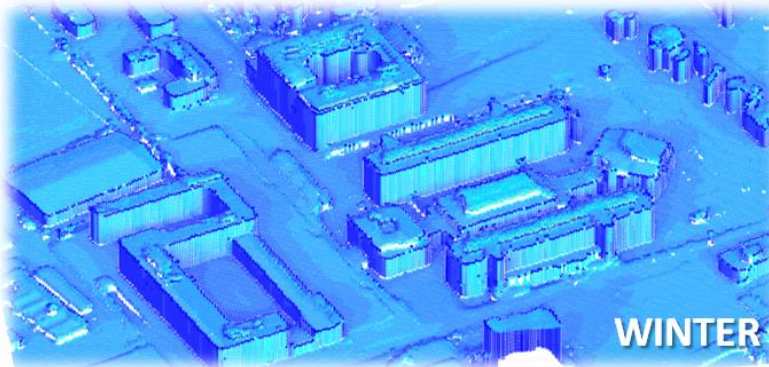


Redweik et al, Solar Energy 97 (2013) 332–341

# THE ROLE OF BUILDING FACADES

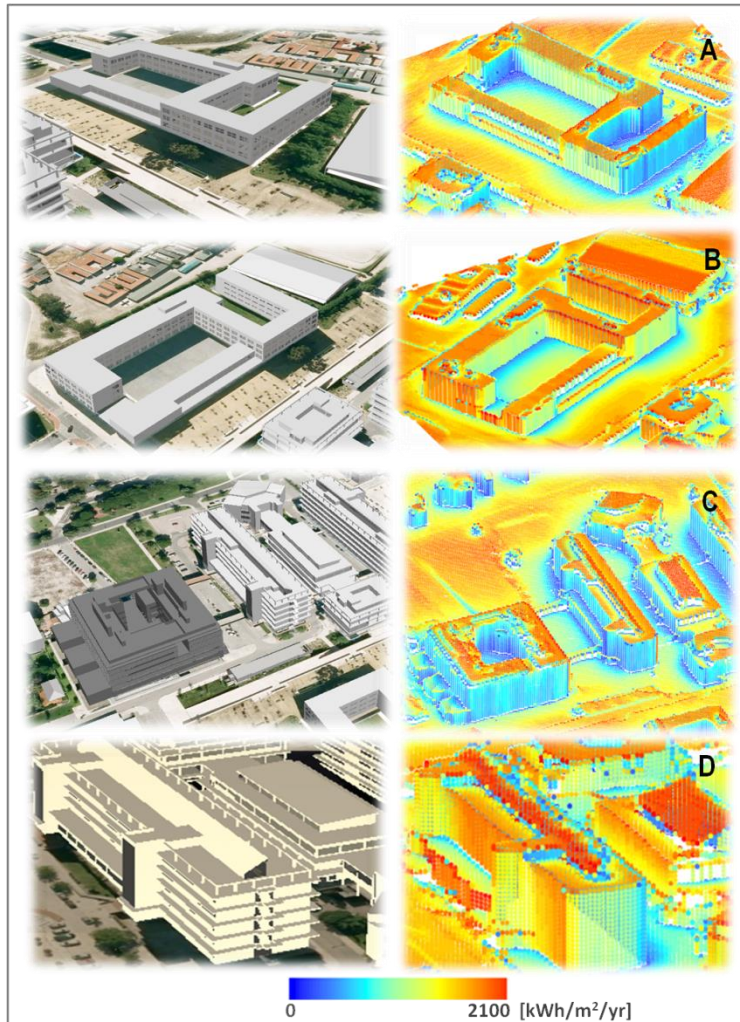


Seasonal Global Radiation

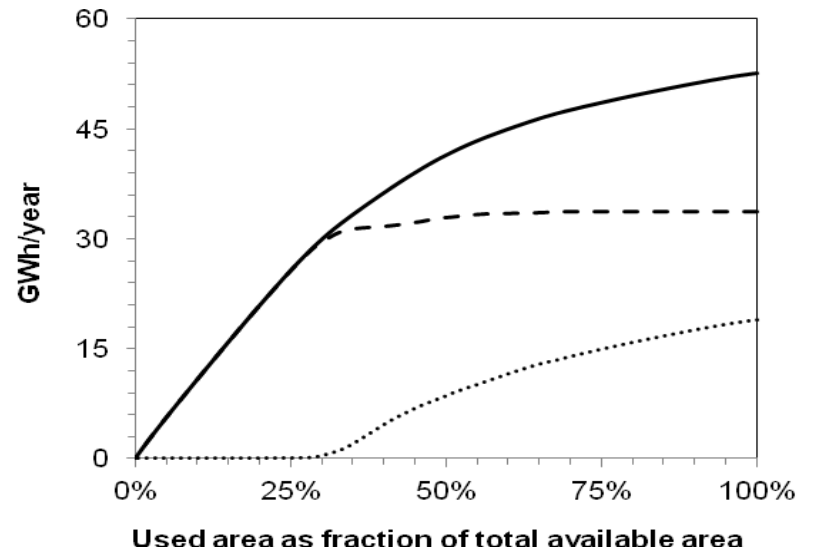
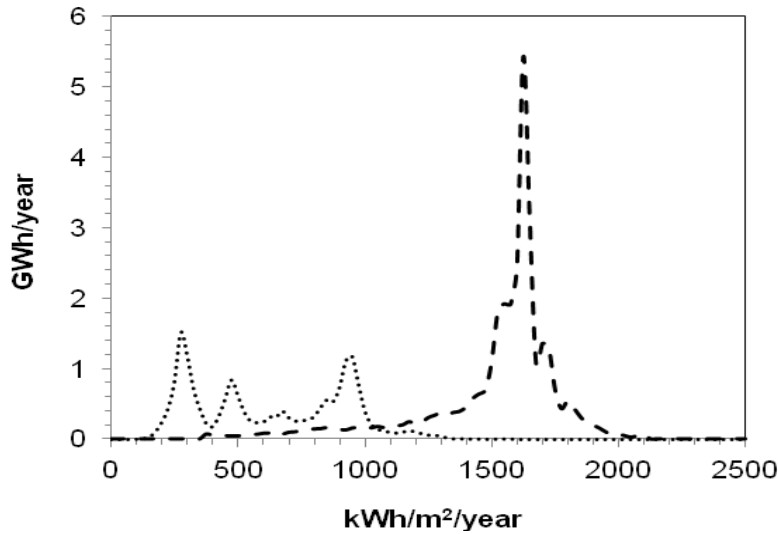
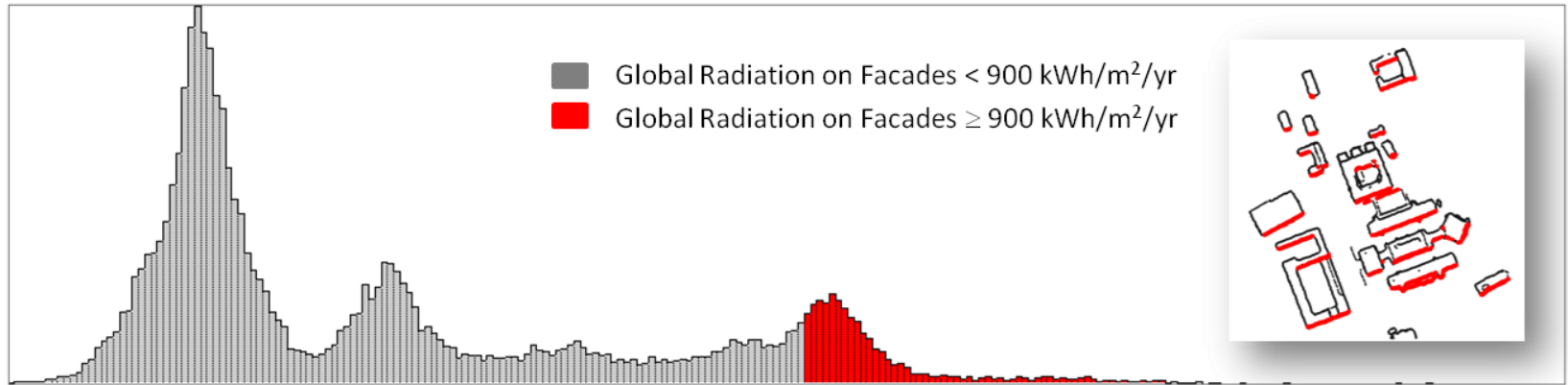


# PV in urban environment

## Solar facades



# THE ROLE OF BUILDING FACADES



SOLARIA





# PV in urban environment

## Conclusions

- Facades can play a **relevant role** for PV production in the urban environment
- **Lower production** for less than optimum orientation/inclination
- Relatively higher production in **winter**
- Relatively higher production during **earlier and later hours of the day**
- Mutual **shading** of buildings needs to be taken into account
- **GIS tools** for assessment of solar potential of facades needs further development

# Next class

- **Further reading**

M. Šúri, et al, **Potential of solar electricity generation** in the European Union member states and candidate countries. *Solar Energy*, 81 (2007) 1295–1305

M. Šúri et al, Uncertainties in photovoltaic electricity **yield prediction** from fluctuation of solar radiation. Proc. 22nd European Photovoltaic Solar Energy Conference, Milano, Italy 2007

T. Huld et al, Comparison of Potential Solar Electricity Output from **Fixed-Inclined and Two-Axis** Tracking Photovoltaic Modules in Europe, *Prog. Photovolt: Res. Appl.* 2008; 16:47–59

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