Solar energy

- measurement
- source of data
- solar maps
- practical recalculation

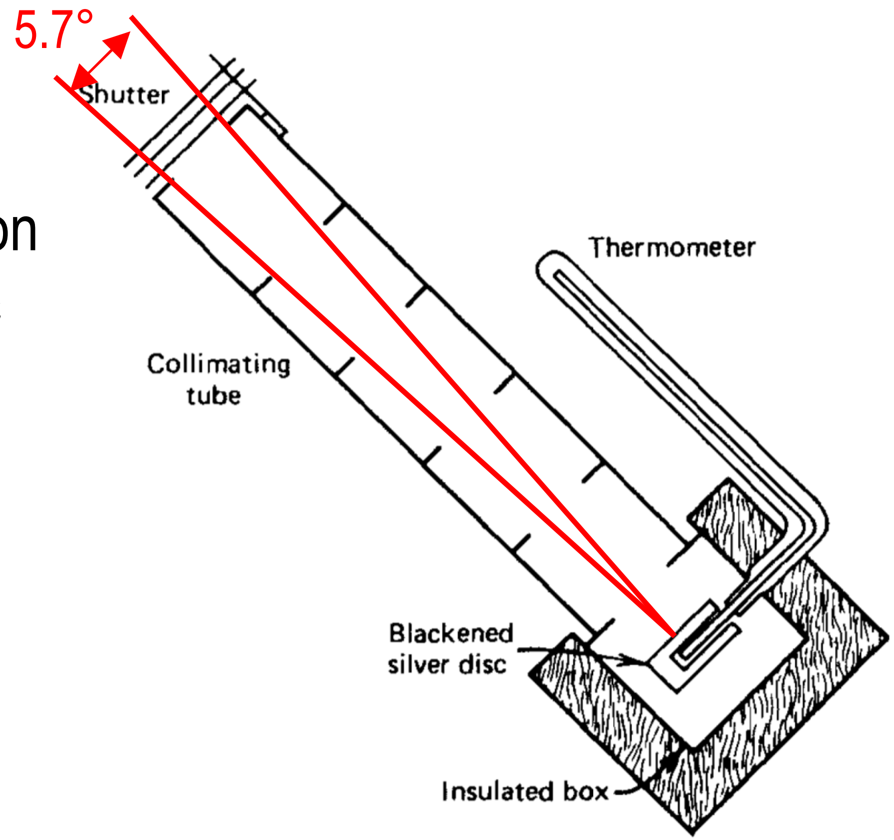
Measurement of direct solar irradiance

- **pyrheliometer** (actinometer)

  collimated sensor for measurement of solar radiation coming directly from Sun disc (and small portion of sky around)

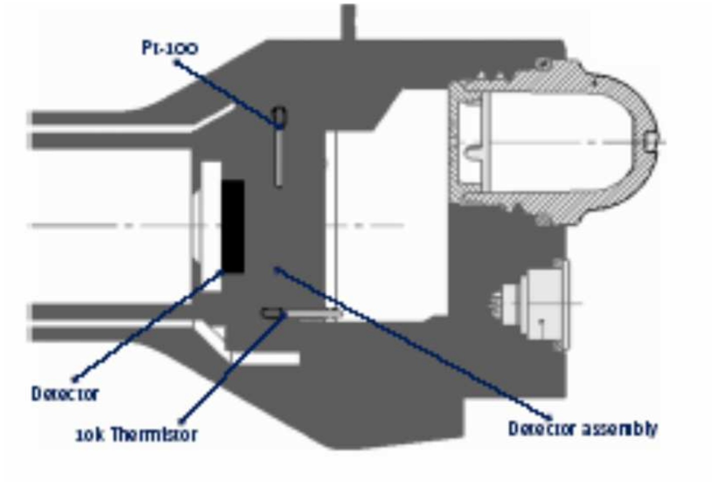
  measurement in incidence angle (tracking Sun)

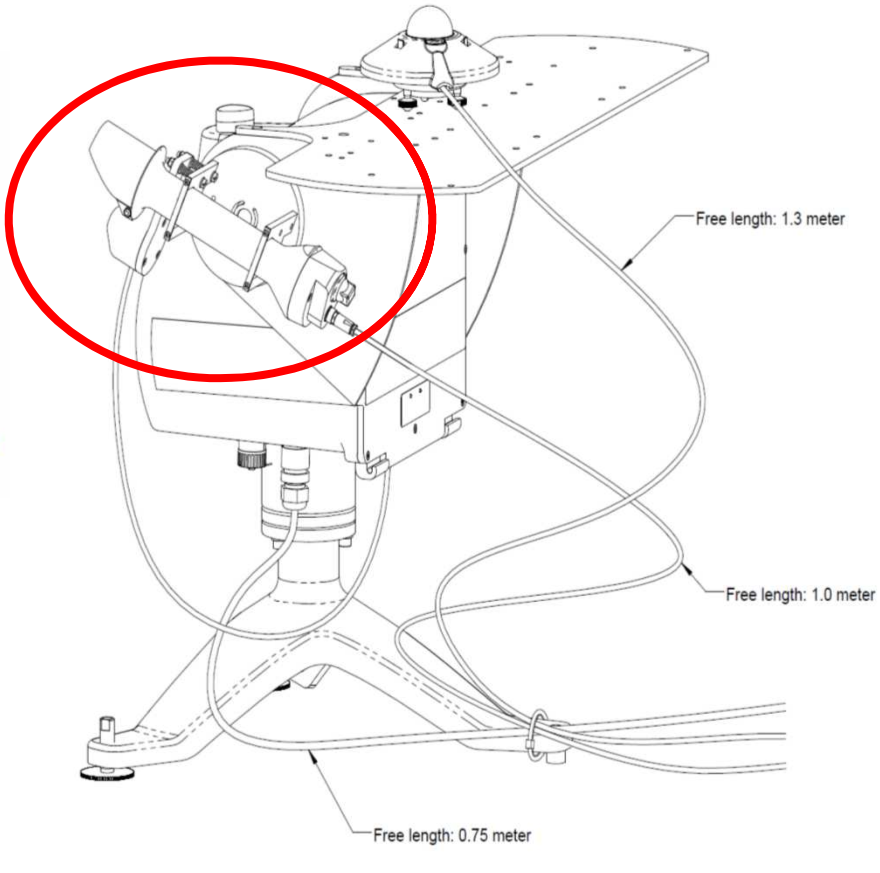
  standard for other sensors



Abbot pyrheliometer (1902)

Measurement of direct solar irradiance





Pyrheliometer CHP1 (2008)

Measurement of global solar irradiance

- **pyranometer** (solarimeter)

  measurement of hemispherical total (direct + diffuse) solar irradiance

  thermocouple sensor - measurement of temperature difference

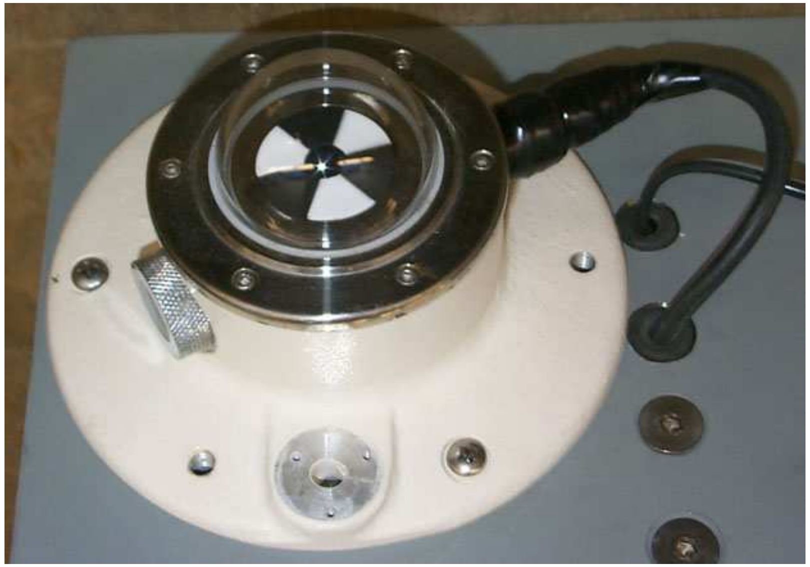
  temperature difference ~ solar irradiance

  photovoltaic sensor – measurement of produced electric output

  problems: spectral sensitivity, temperature dependence ...

Thermocouple pyranometers

- **segmented pyranometer** (star pyranometer, Stern-pyranometer)
  measurement of temp difference between two segments (black and white)
  multiple thermocouple
  USA, Canada



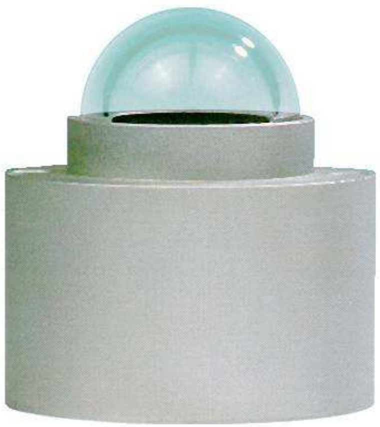
Thermocouple pyranometers

- **disc pyranometer** (Moll-Gorzynski)

  measurement of temp difference between the disc and body of pyranometer

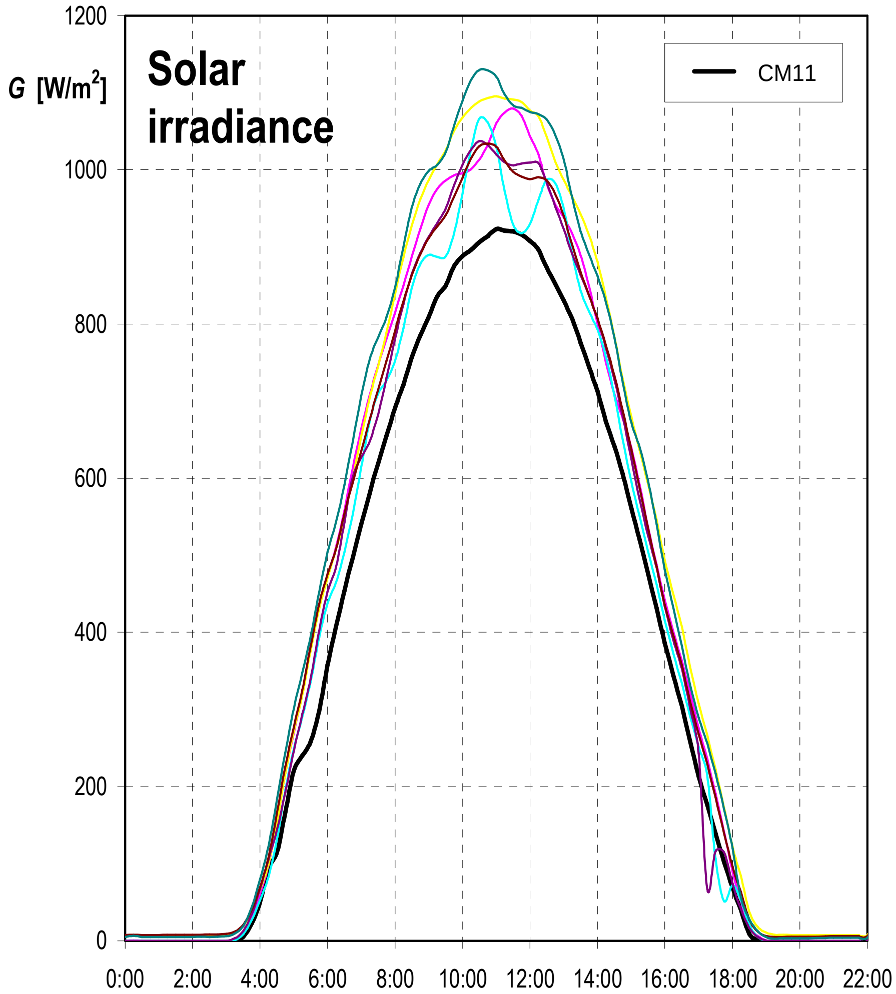
  multiple thermocouple

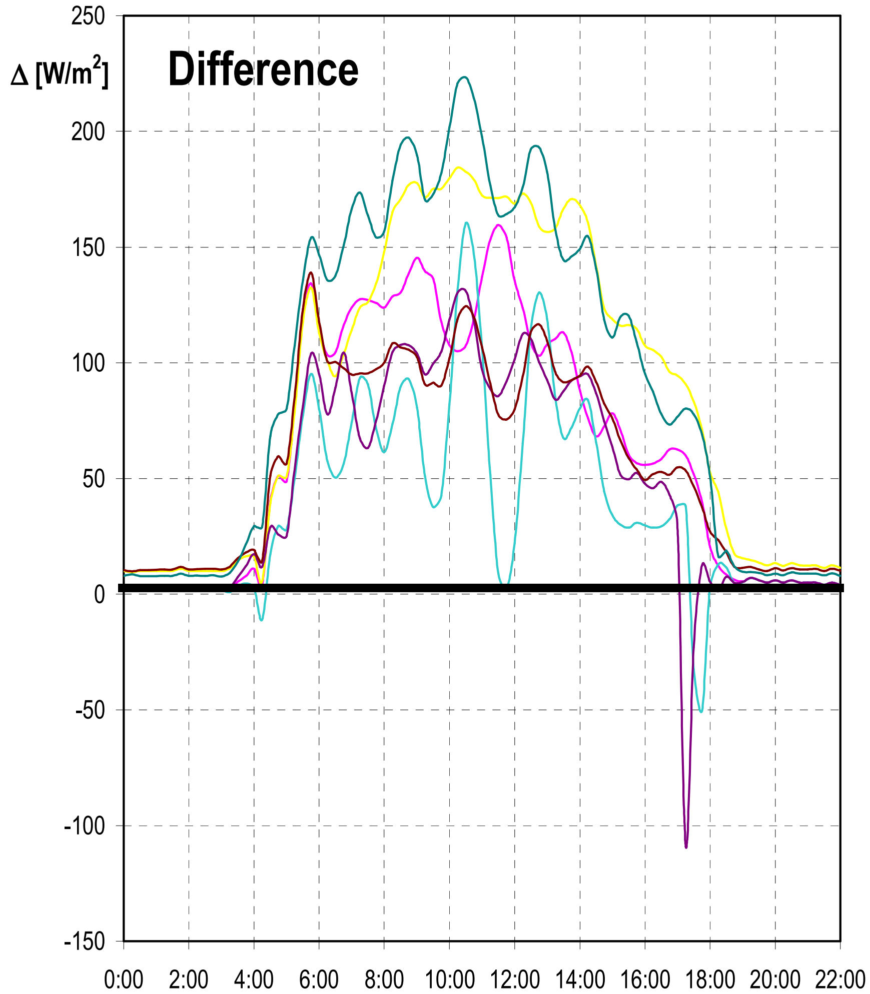
  Europe



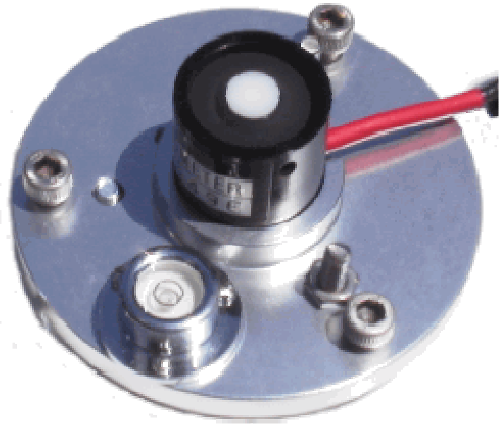
Quality?

Disc pyranometer Kipp&Zonen CM11 x noname producer (segmented pyranometer)

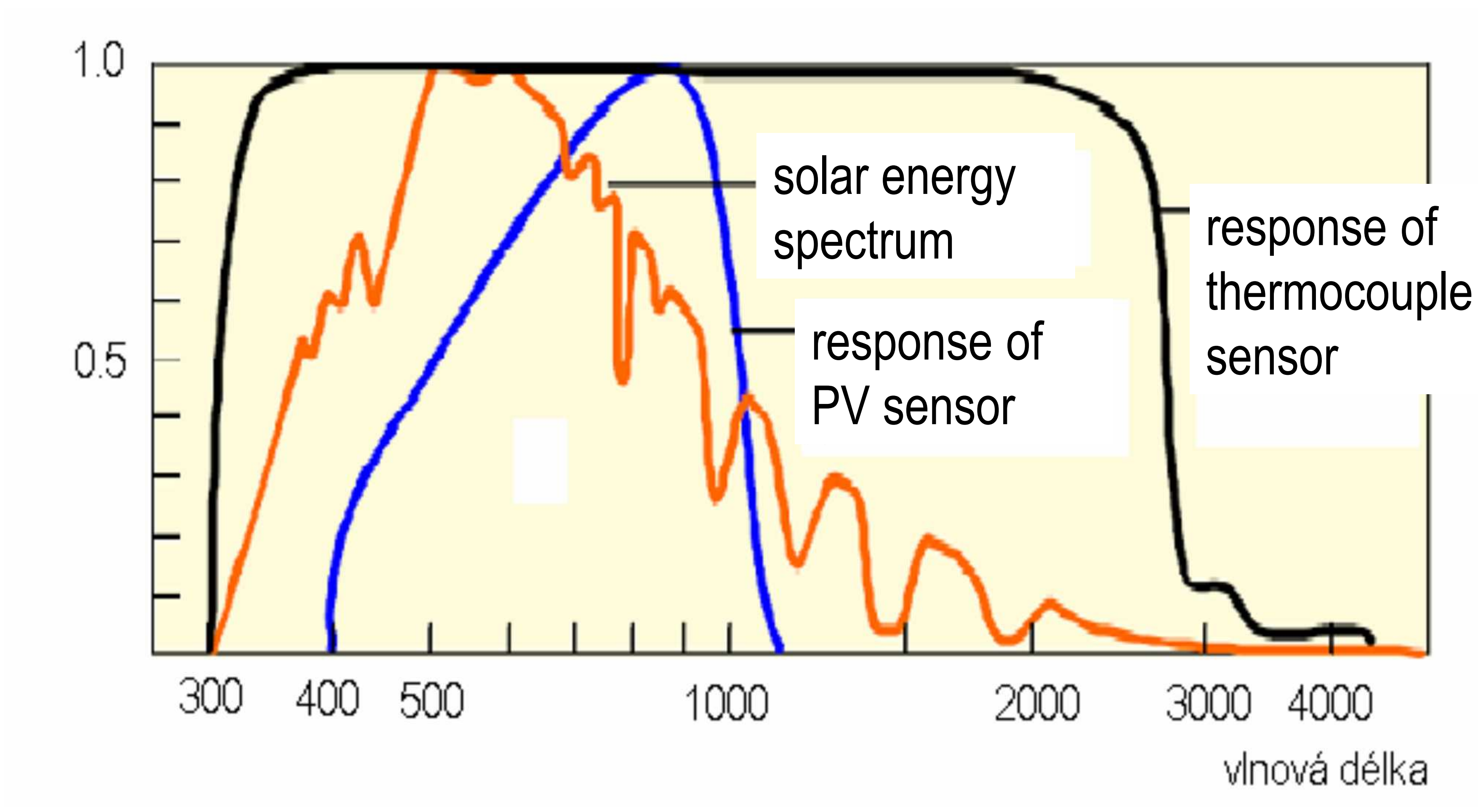




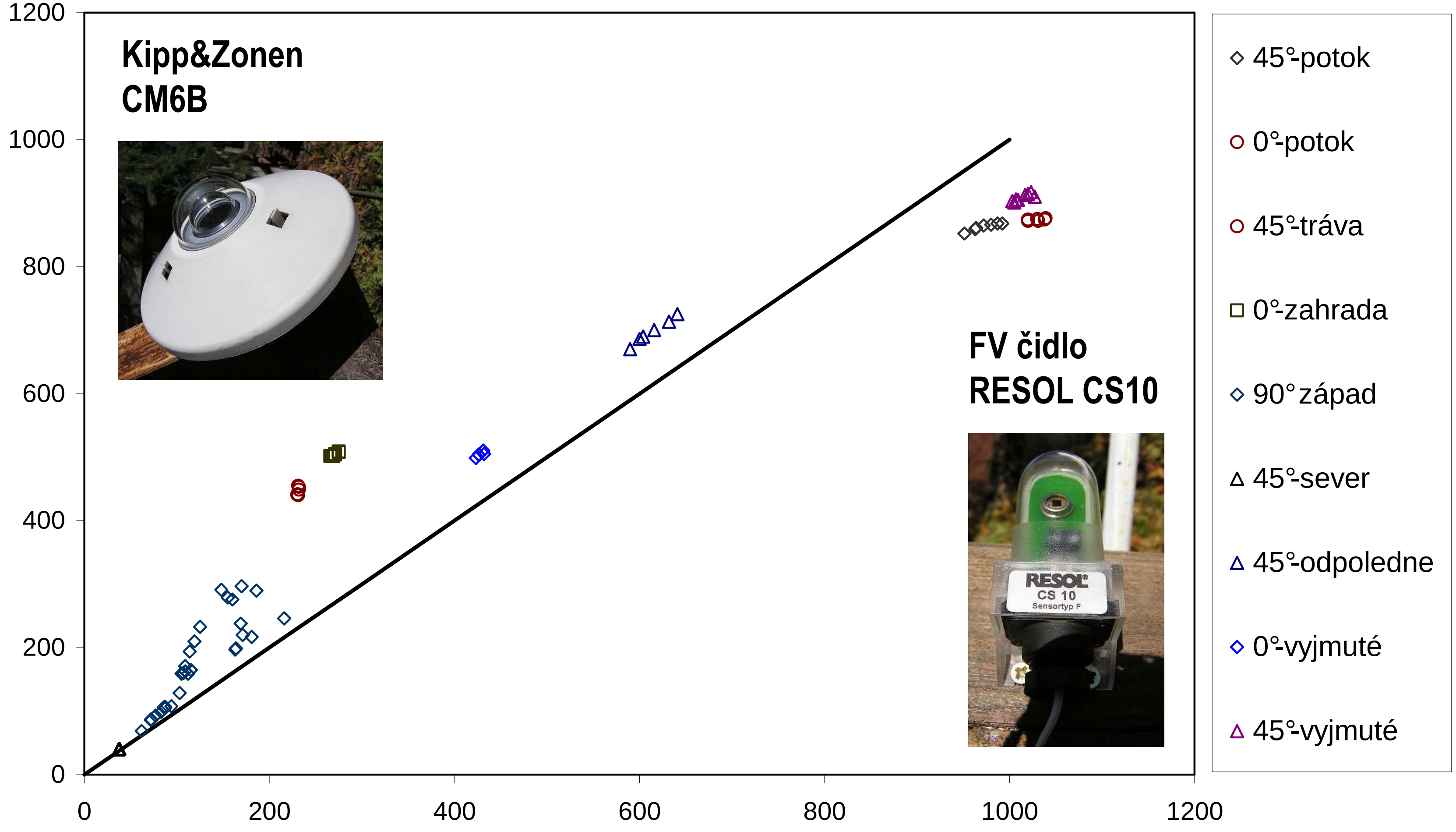
Photovoltaic sensors



Photovoltaic sensors: spectral sensitivity



Comparison of PV and TC sensor



Measurement of diffuse irradiance

- **pyranometers with a shading device** (shading of direct irr.)

  shading ring – adjustment once per 14 days with change of declination

  shading ball – tracking system

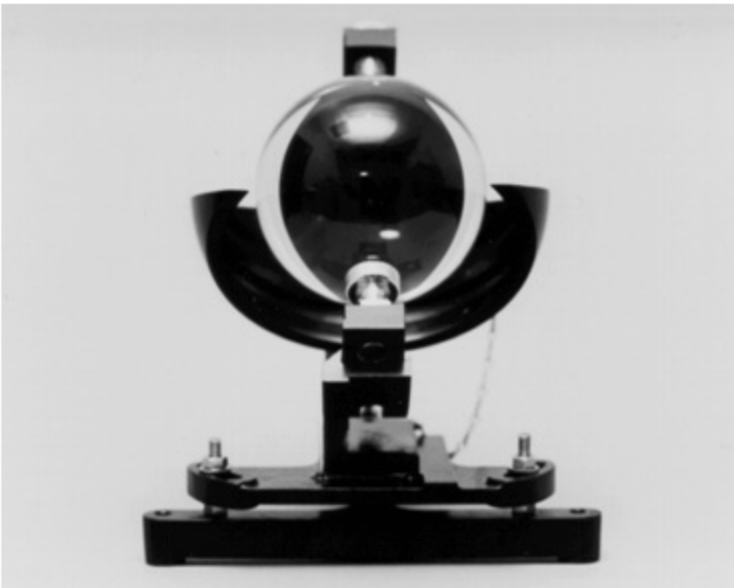


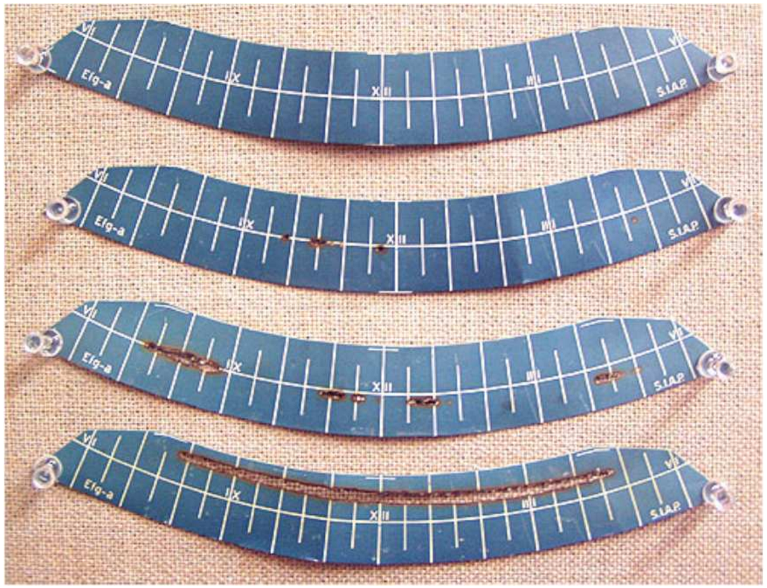
Measurement of duration of sunshine

- **heliograph** (Campbell-Stokes heliograph)

  glass ball 10 cm as lens, concentration of solar beams

  if direct component higher than critical, track is burn down on paper (heliogram), length of track = duration of sunshine

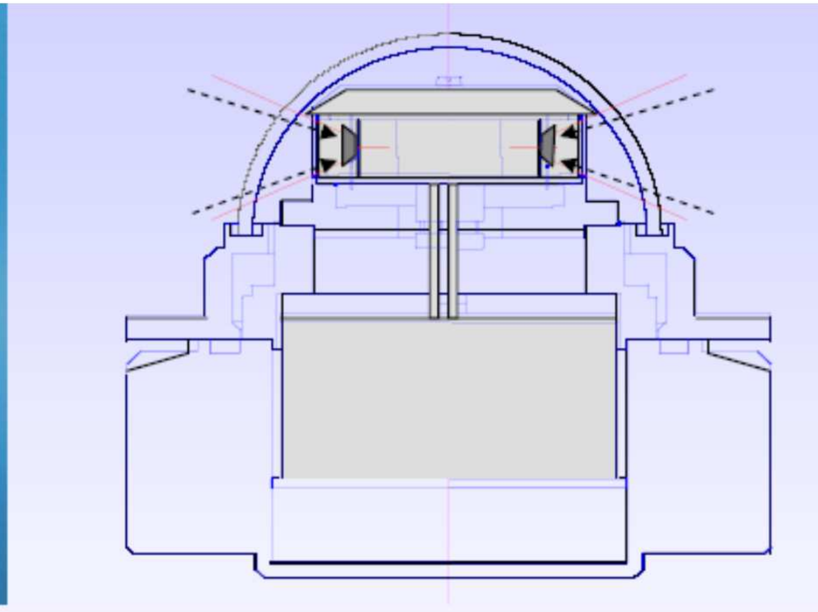




Measurement of duration of sunshine

- **electronic types**

  slots with photodiods

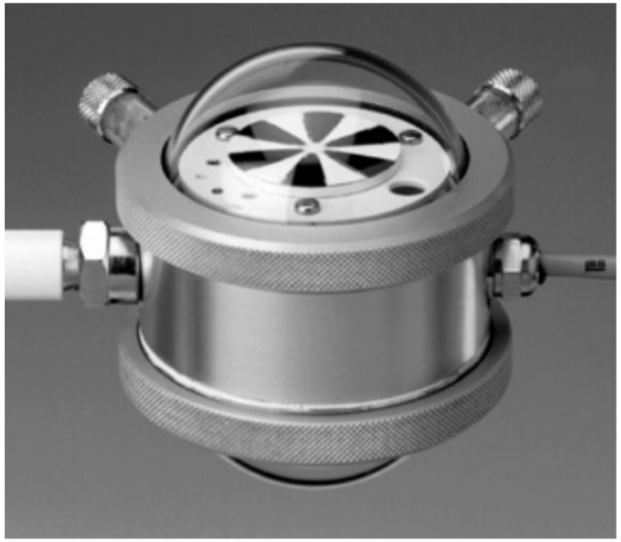


Measurement of albedo

- **albedometer** (double-pyranometr)

  upper pyranometer receives solar solar irradiance incident on given surface

  lower pyranometer faces the surface and receives only reflected solar irradiance



Sources of solar radiation data

- **PVGIS** – Photovoltaic Geographical Information System

  Joint Research Centre EC, originally for PV potential

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

- **Meteonorm** – software of Meteotest company

  complex meteorological reference with a catalogue of meteodata, http://www.meteonorm.com

- **ČHMÚ** – Czech Hydrometeo Institute, http://www.chmu.cz

  climatic data – hourly values, real measured data for sale

- **Tables** – theoretical calculation for typical locations, corrected with relative duration of sunshine (for designers)

PV GIS - inputs

- **terrain model**

  digital model U.S. Geological Survey, Shuttle Radar Topography Mission (elevation, terrain profile)

- **climatic data**

  not using satellite measurements

  566 European terrestrial meteostations

  real measured climatic data

PV GIS - inputs

- **average monthly data**

  daily solar irradiation for given surface

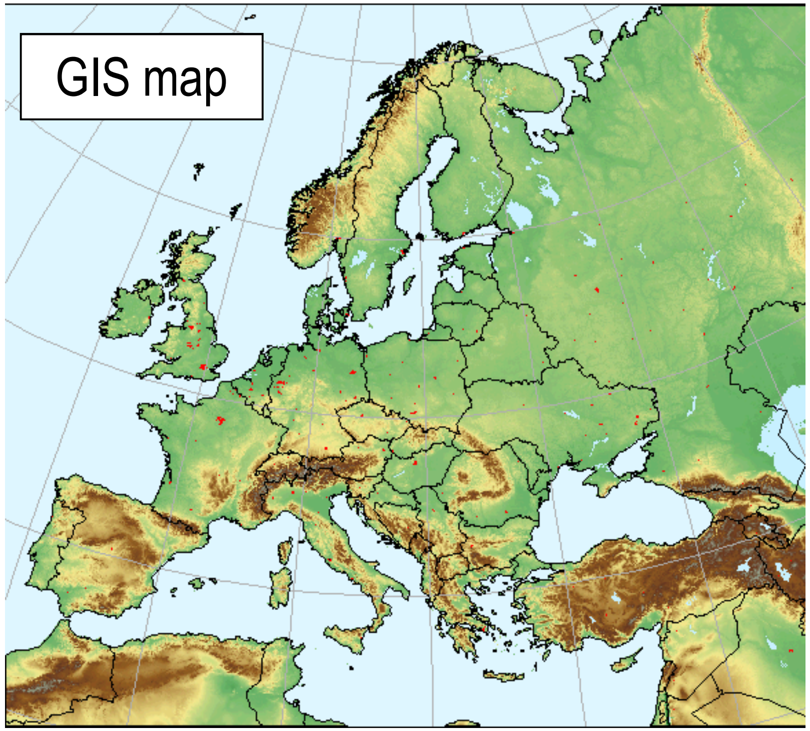
  temperature in period of sunshine

- **based on terrain properties**

  elevation

  shading by country profile

- **resolution 1 km^2**



PV GIS - method

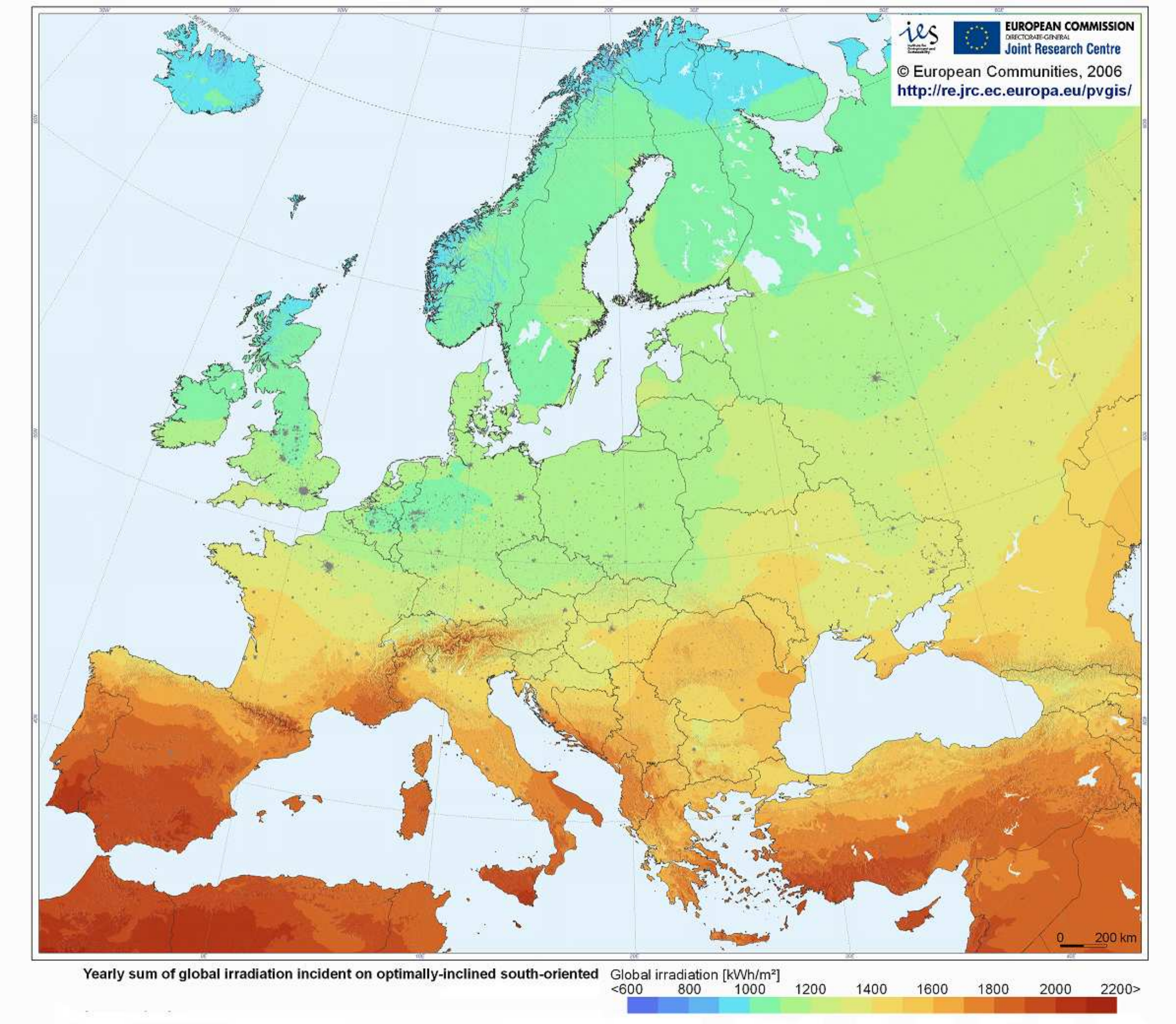
- **theoretical calculation** of solar irradiance for **clear sky** at *horizontal plane* for given elevation and given atmosphere

- **calculation** of global solar irradiance at horizontal plane for **real cloudiness** at *horizontal plane* based on **index of sky clearness** (ratio real / clear sky; monthly averages from meteostations, **interpolation to raster GIS**)

- **calculation** of global solar irradiance for **real cloudiness** at *given plane (surface)*

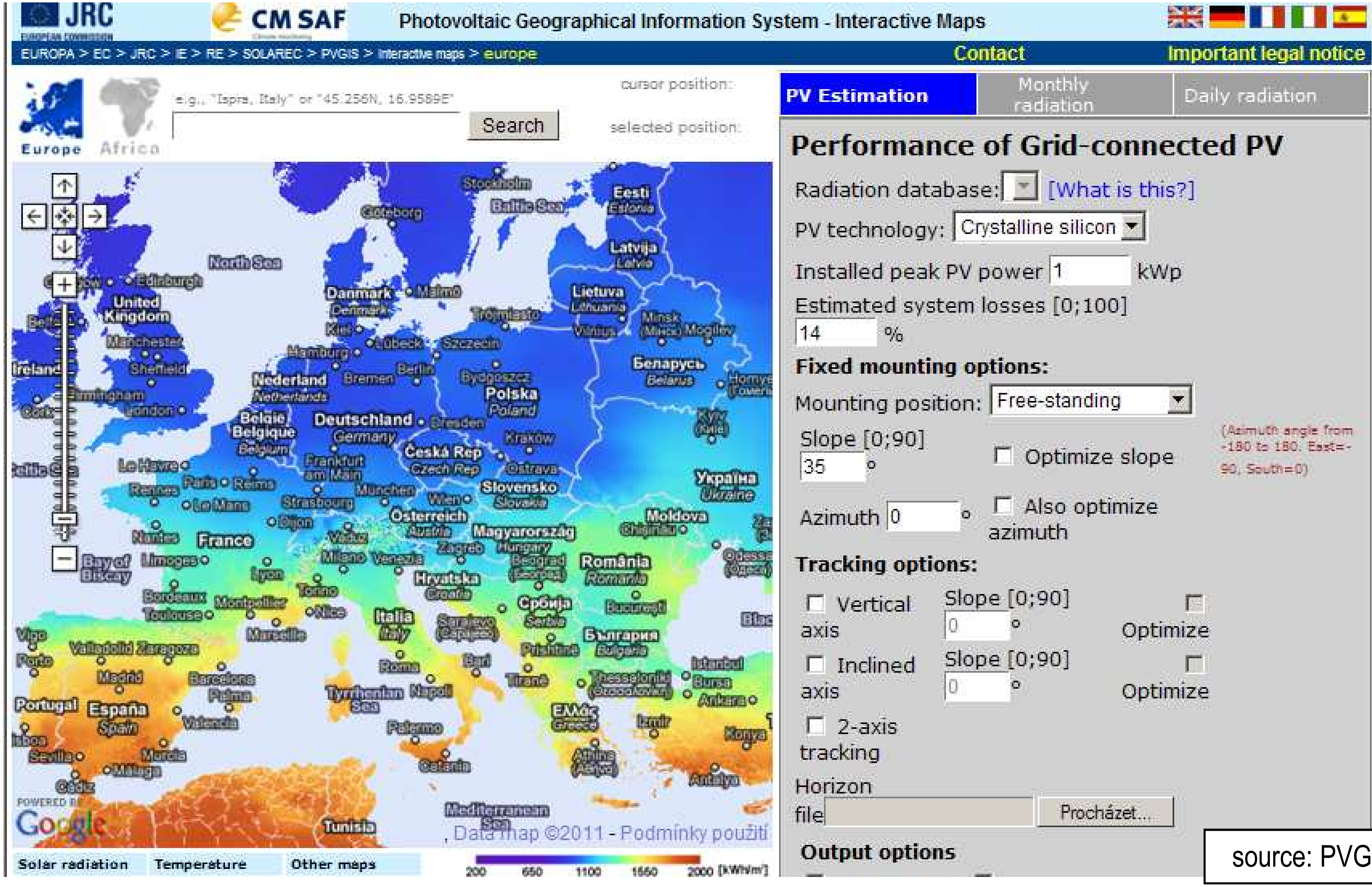
dividing of total radiation to direct and diffuse, recalculation for given surface, albedo 15 %

PV GIS



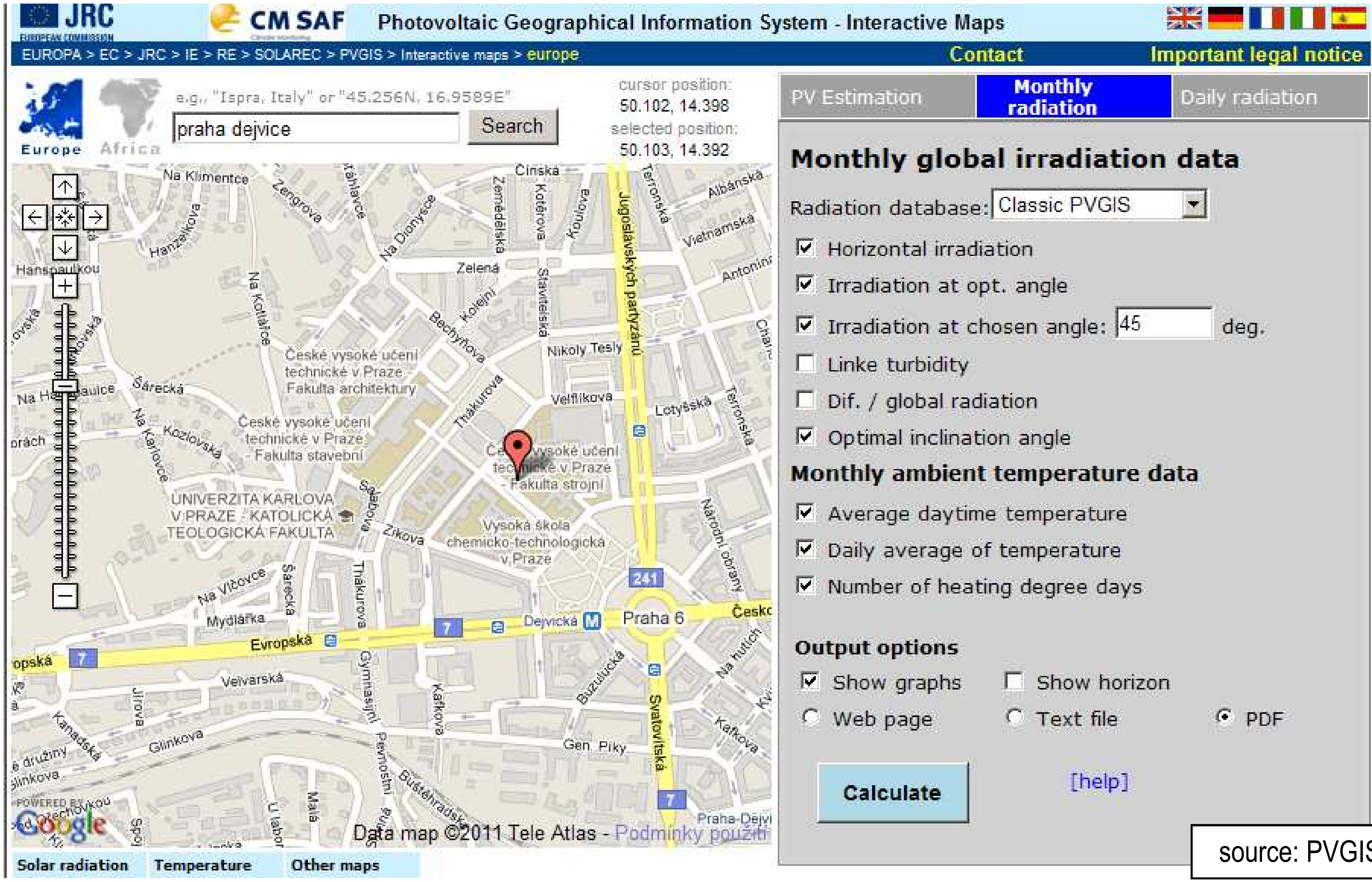
source: PVGIS

PV GIS



source: PVGIS

PV GIS

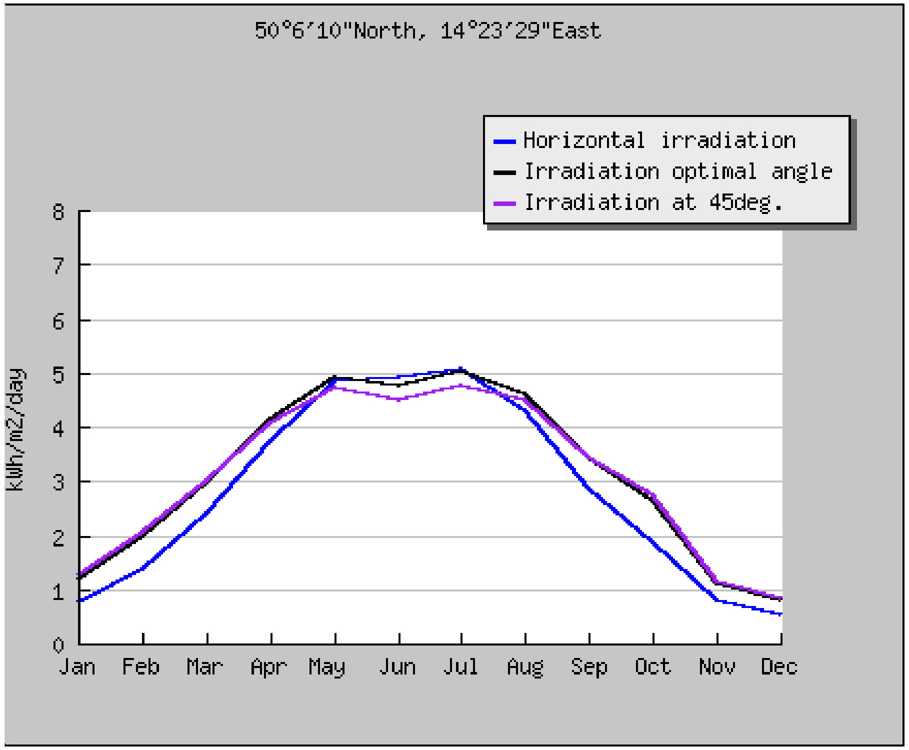


source: PVGIS

PV GIS

Annual irradiation deficit due to shadowing (horizontal): 0.0 %

Month	Hh	Hopt	H(45)	Iopt	TD	T24h	NDD
Jan	756	1170	1240	63	-1.0	-1.3	560
Feb	1390	1960	2050	57	1.7	1.1	459
Mar	2400	2980	3020	45	4.8	4.0	386
Apr	3740	4160	4080	32	10.7	9.1	184
May	4850	4930	4720	20	16.2	14.1	77
Jun	4900	4770	4500	12	19.0	16.9	34
Jul	5060	5030	4780	16	20.8	18.8	6
Aug	4290	4610	4480	27	20.7	18.7	37
Sep	2860	3430	3450	41	15.8	14.4	164
Oct	1860	2630	2740	55	10.9	10.0	332
Nov	789	1100	1150	58	4.4	4.0	500
Dec	537	795	842	62	0.2	-0.1	600
Year	2790	3140	3090	34	10.3	9.1	3339



Hh: Irradiation on horizontal plane (Wh/m2/day)

Hopt: Irradiation on optimally inclined plane (Wh/m2/day)

H(45): Irradiation on plane at angle: 45deg. (Wh/m2/day)

Iopt: Optimal inclination (deg.)

TD: Average daytime temperature (°C)

T24h: 24 hour average of temperature (°C)

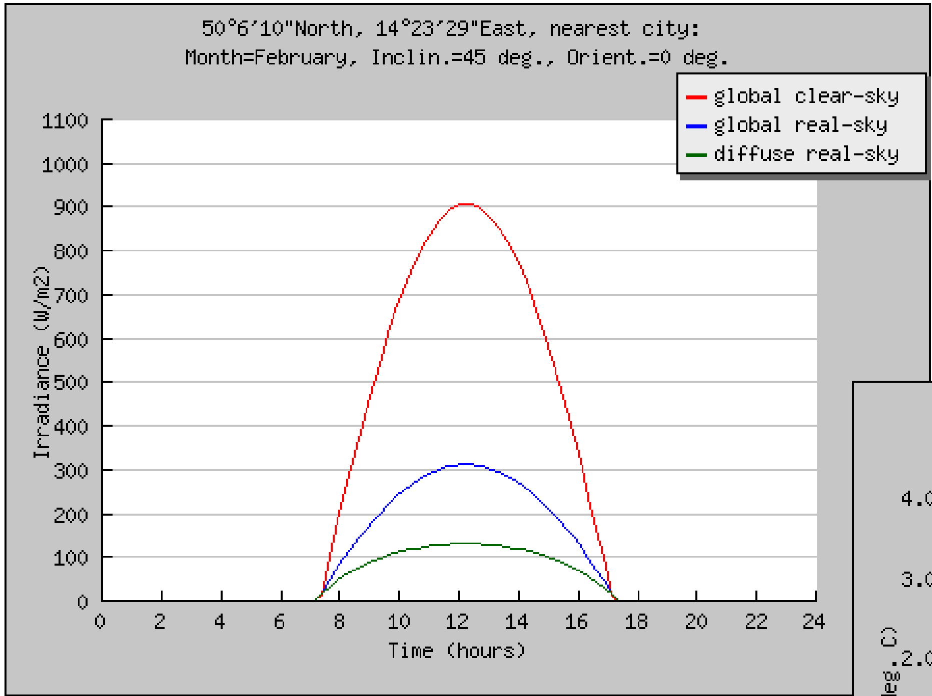
NDD: Number of heating degree-days (-)

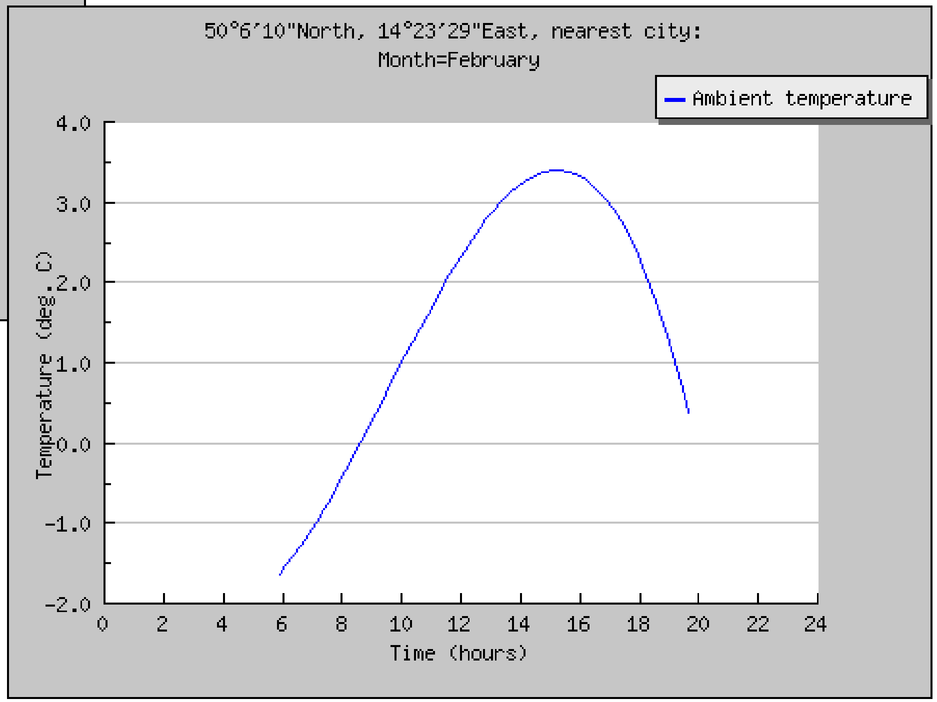
source: PVGIS

PV GIS

source: PVGIS

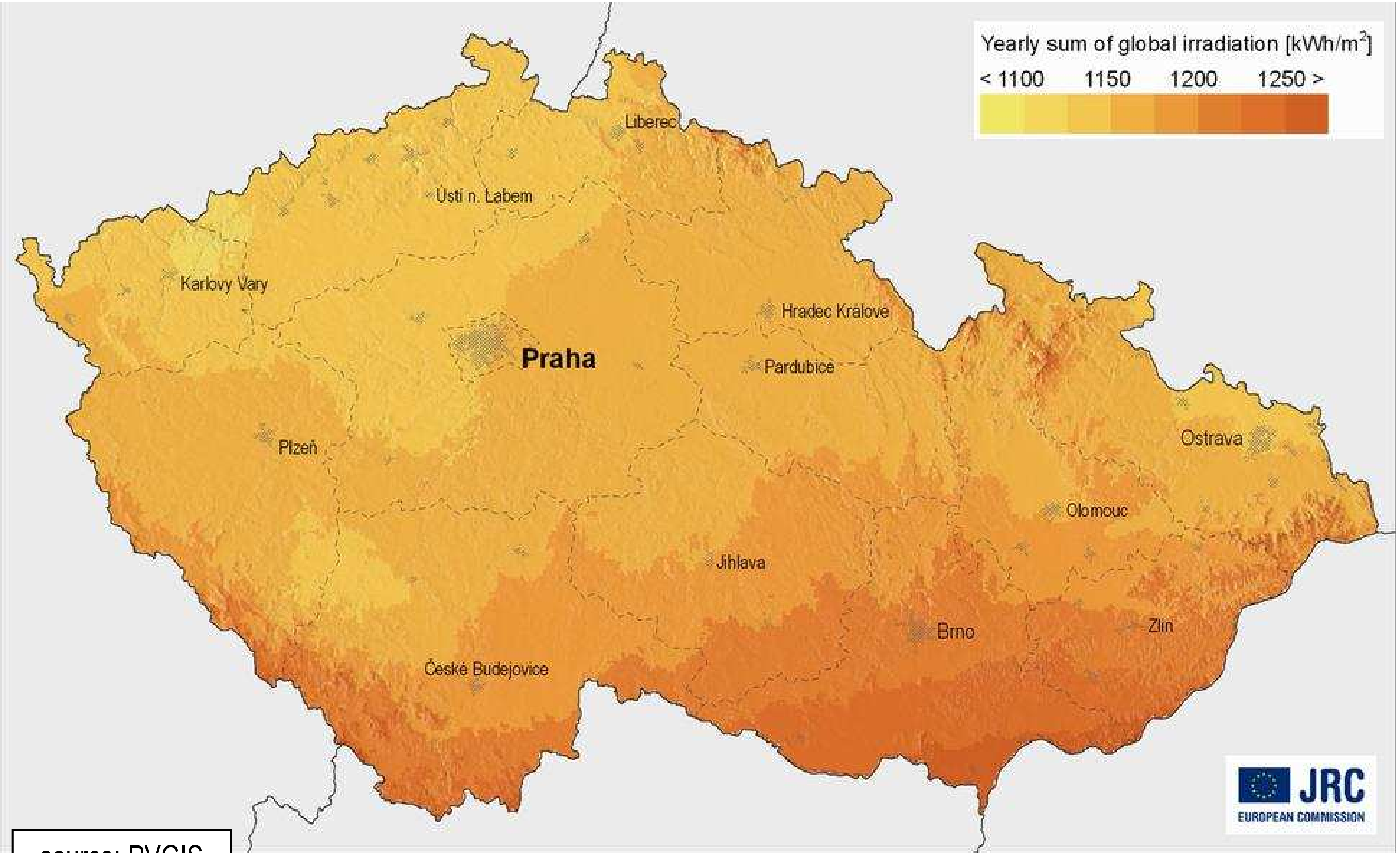
PV GIS





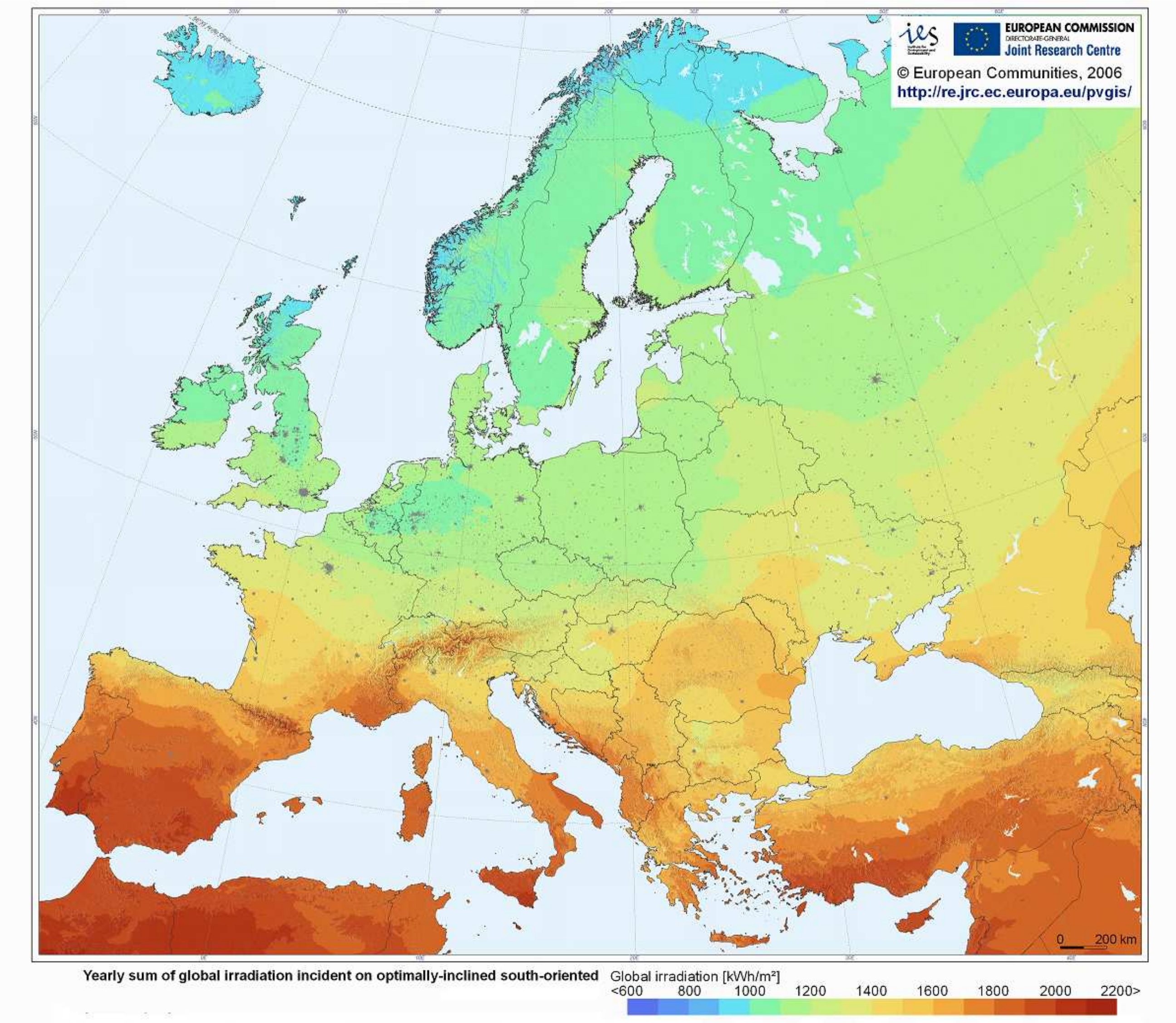
source: PVGIS

Solar energy in Czech Republic



source: PVGIS

Solar energy in Europe



source: PVGIS

Solar energy in Germany

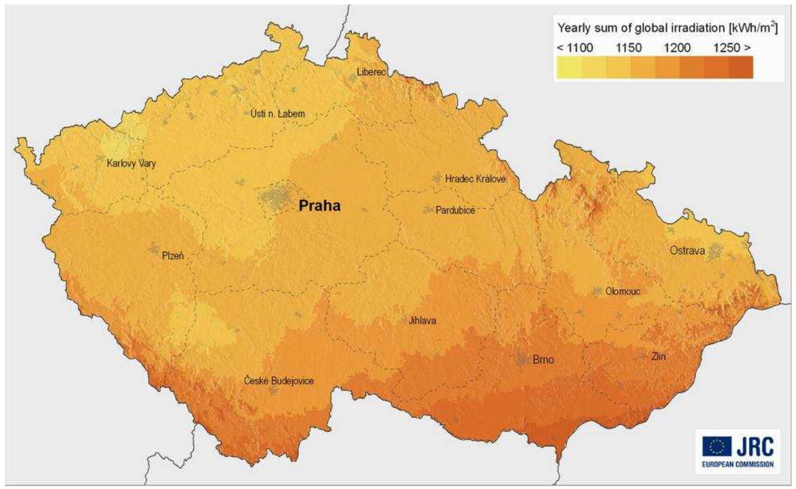
Germany and Czech Republic

similar conditions: **1000 to 1200 kWh/m²**

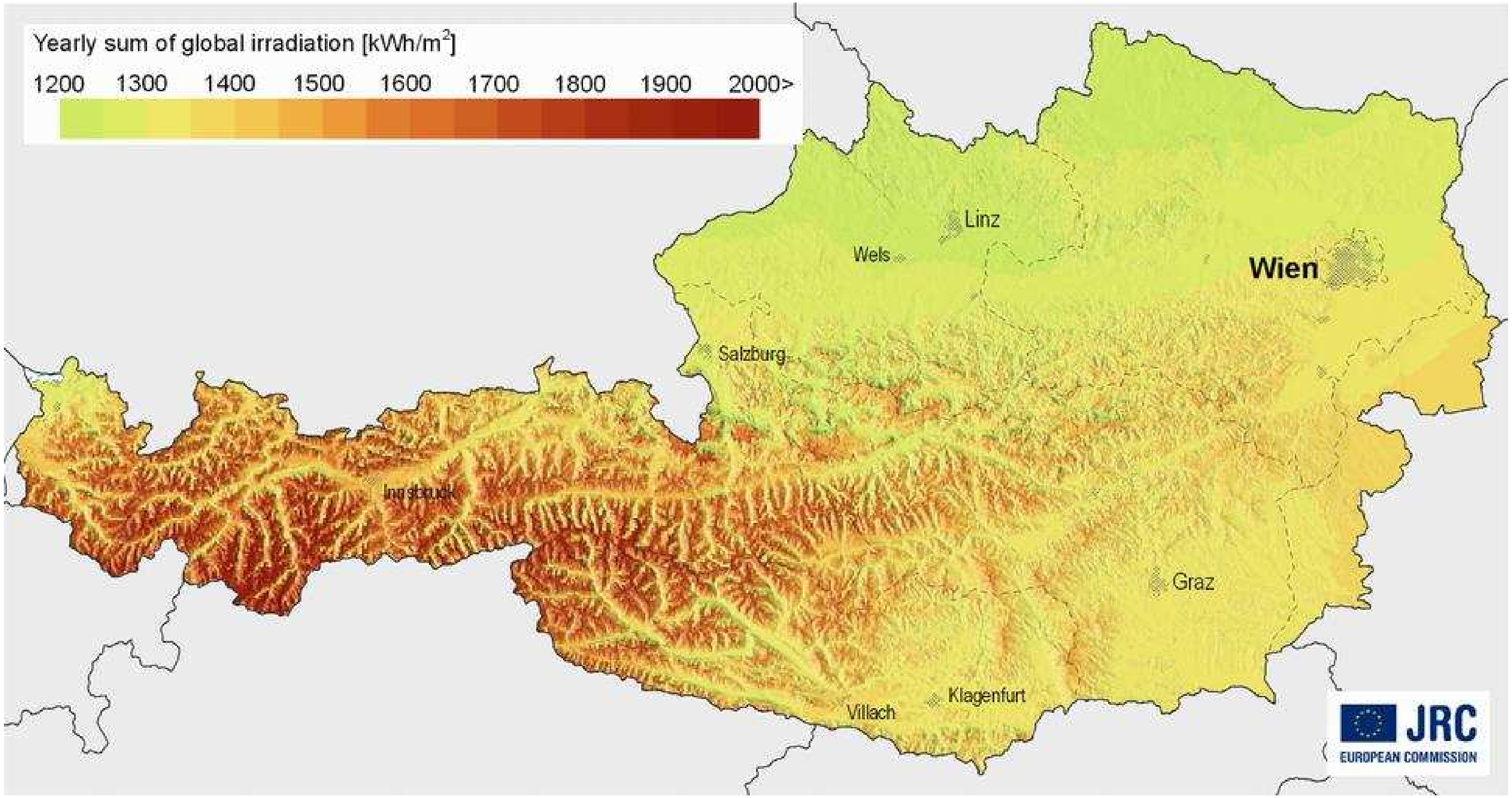
similar solar systems

similar solar collectors

similar energy yields



Solar energy in Austria



Solar potential of Austria starts where czech potential ends ...

source: PVGIS

Meteonorm

- **database of climate data**

climate data from more than **8055** meteostations

global solar irradiation

duration of sunshine

1981-2000

temperature

humidity

precipitation

wind velocity and direction

1961-1990, 1996-2005

monthly data (daily averages, monthly sums, ...)

Meteonorm

- **terrestrial meteostations**

  CZ: uses 32 meteostations, 8 stations with measurement of solar energy

  Europe: 1551 stations, from which 361 solar radiation

- **satellite data Heliosat II**

  with density of stations > 300 km: only satellite data

  with density of stations > 50 km: interpolation between terrestrial and satellite data

Meteonorm - method

- **field (space) interpolation** of monthly averages / sums of solar irradiance at *horizontal plane*

  according to location, elevation, topography, etc.

- **generator hourly climatic data**

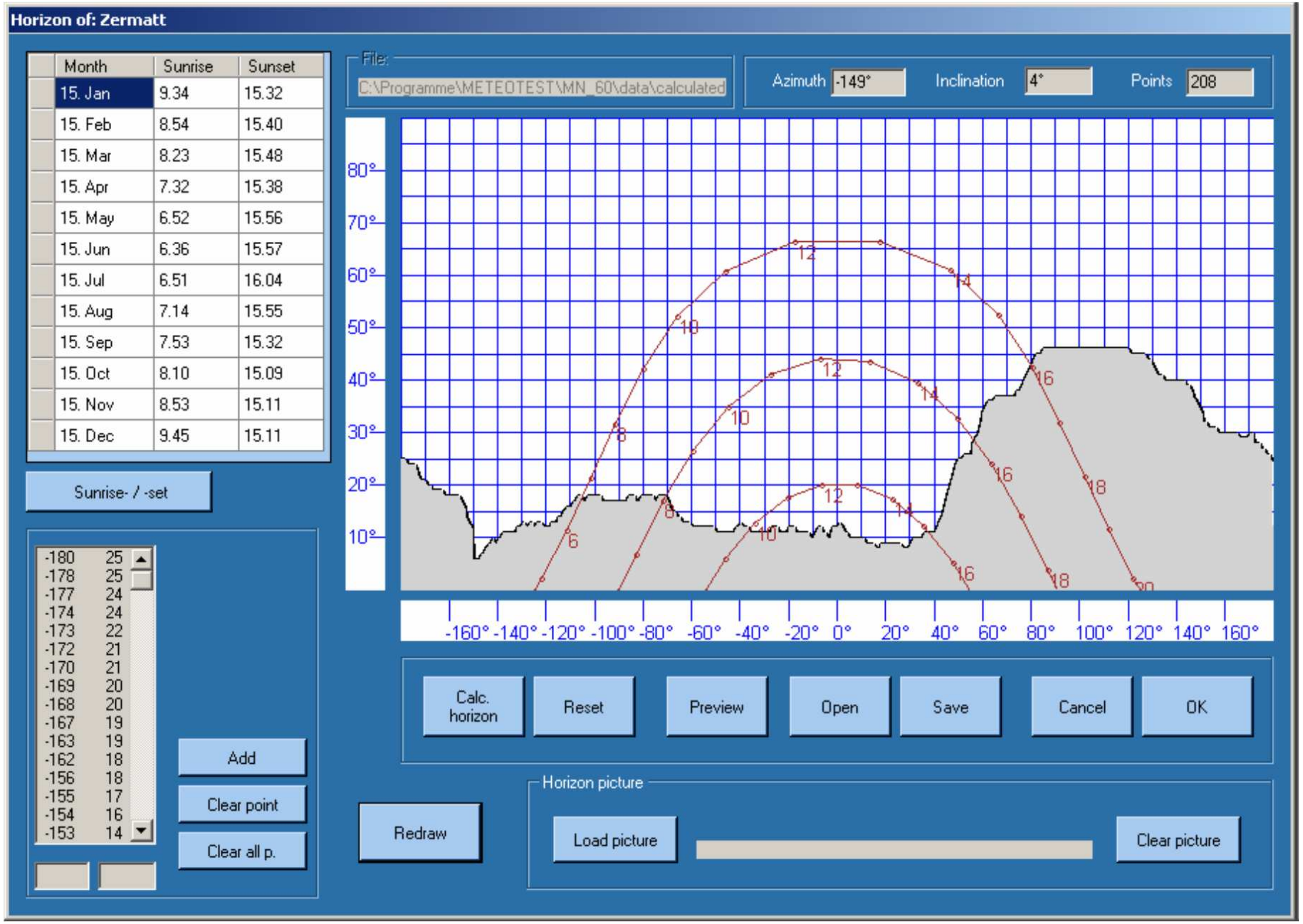
  calculation of hourly data of total solar irradiance at *horizontal plane* with monthly sums = 10 years averages

- **dividing** total solar irradiance to direct and diffuse component for *horizontal plane*

- **calculation** of total solar irradiance *at given plane (surface)*, considering given local profile of horizont

Meteonorm - outputs

Meteonorm - outputs



Meteonorm - outputs

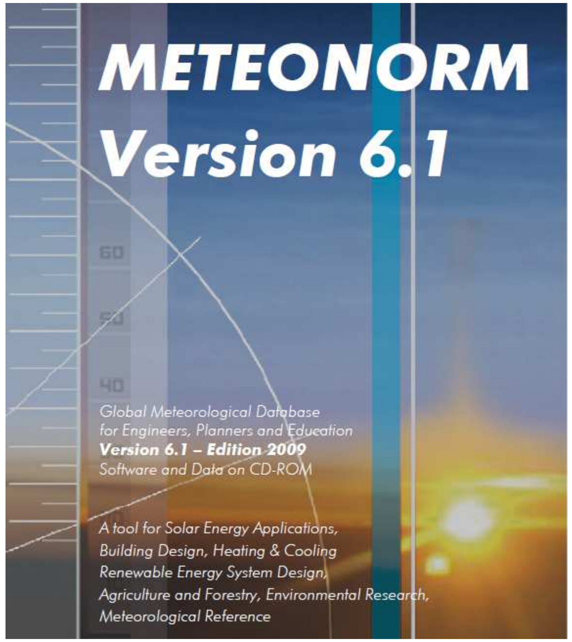
- **hourly climatic data**

  for given conditions

  30 formats for different simulation softwares

  TMY, TRY, DRY

  softwares TRNSYS, DOE, T-SOL, POLYSUN

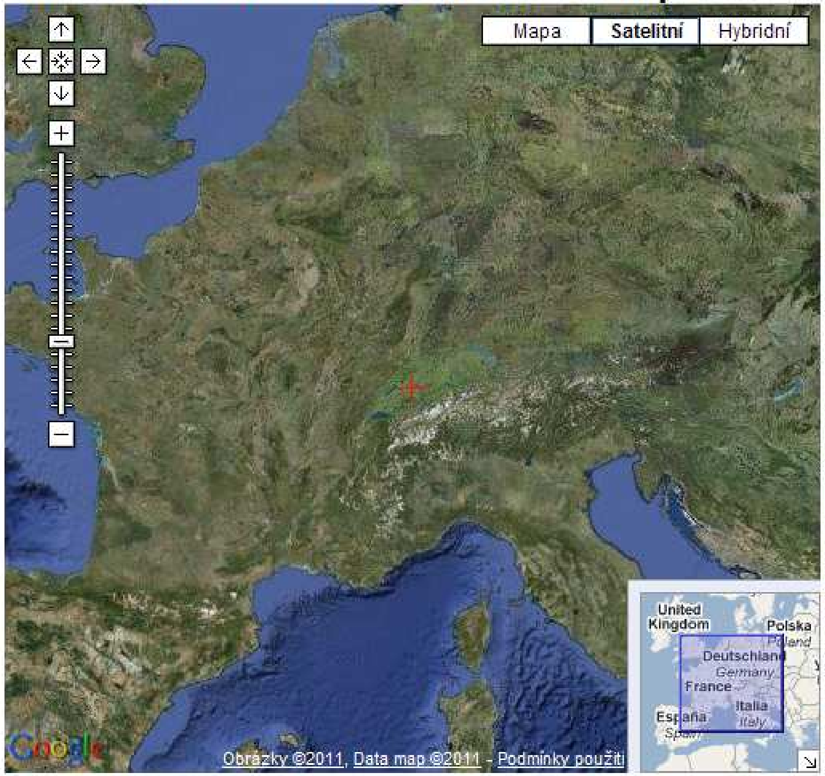


Meteonorm – web application

Climate data worldwide

Get an impression of METEONORM's capabilities! With a few clicks you can create climate diagrams for any site in the world.

Please center the desired site on the map...



... or select site

either by address, eg. "Hamburg, Germany":

Bern, Switzerland

find

or by Geographical coordinates:

N

E

search

... and get the result!

Geographical:

Lat: 46.953 N Lon: 7.423 E

UTM:

x: 380004 y: 5201148

UTM zone: 32

Swiss Grid:

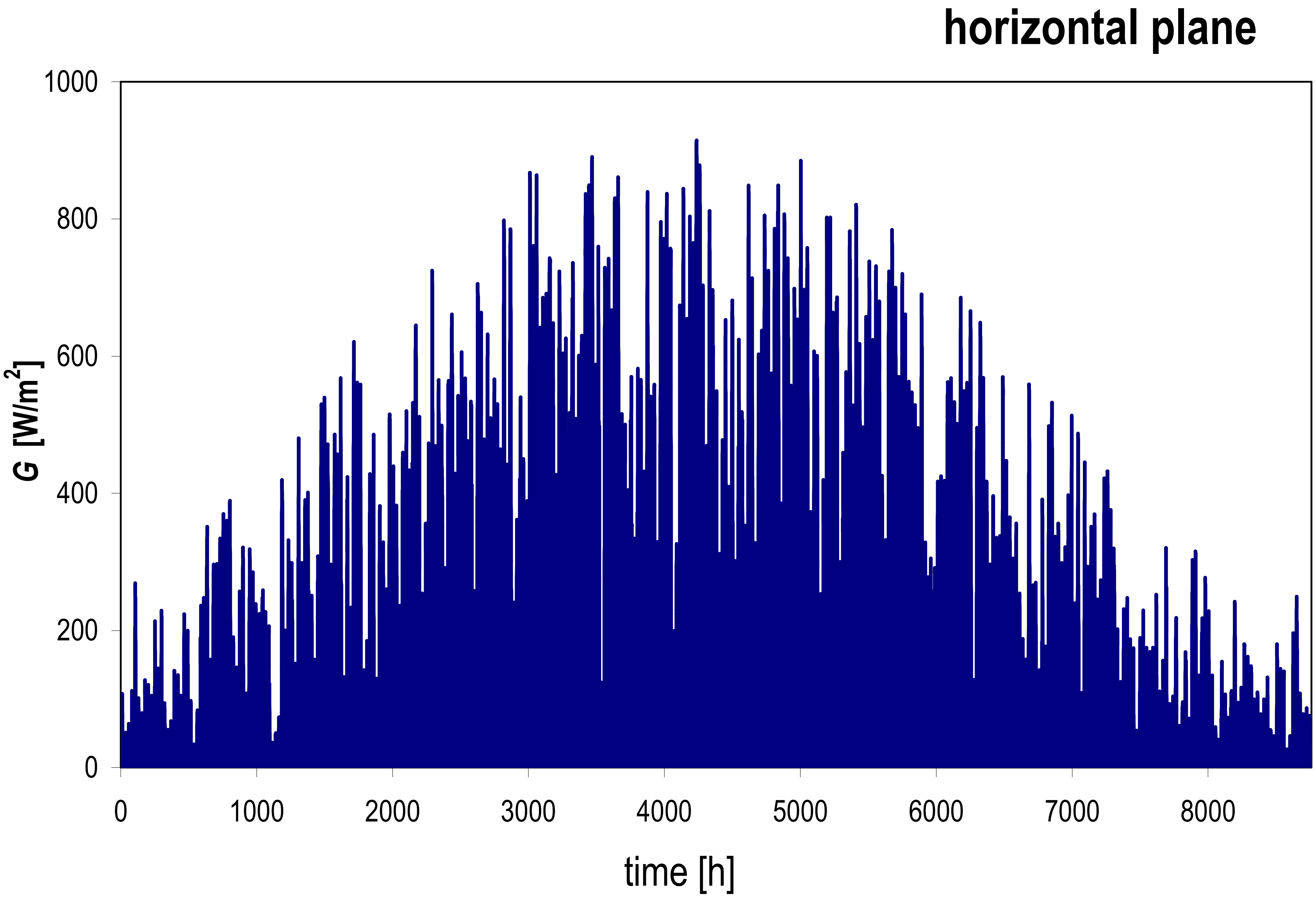
x: 598810 y: 200213

Altitude: 555 masl

» show climate data «

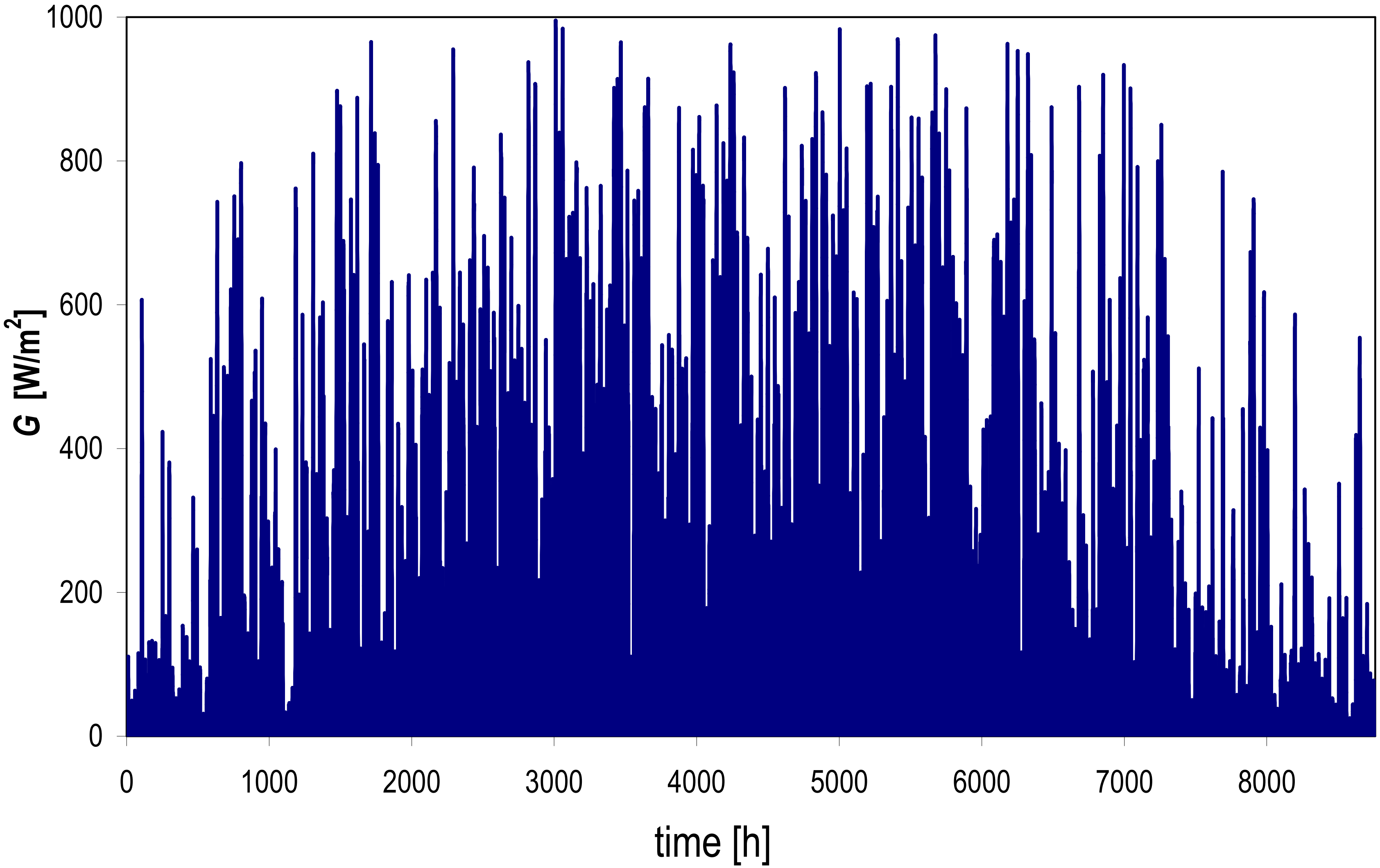
Hint: To navigate, either use the map tools, or directly use the mouse (doubleclick = center and zoom, drag = move map).

Hourly data of solar irradiance

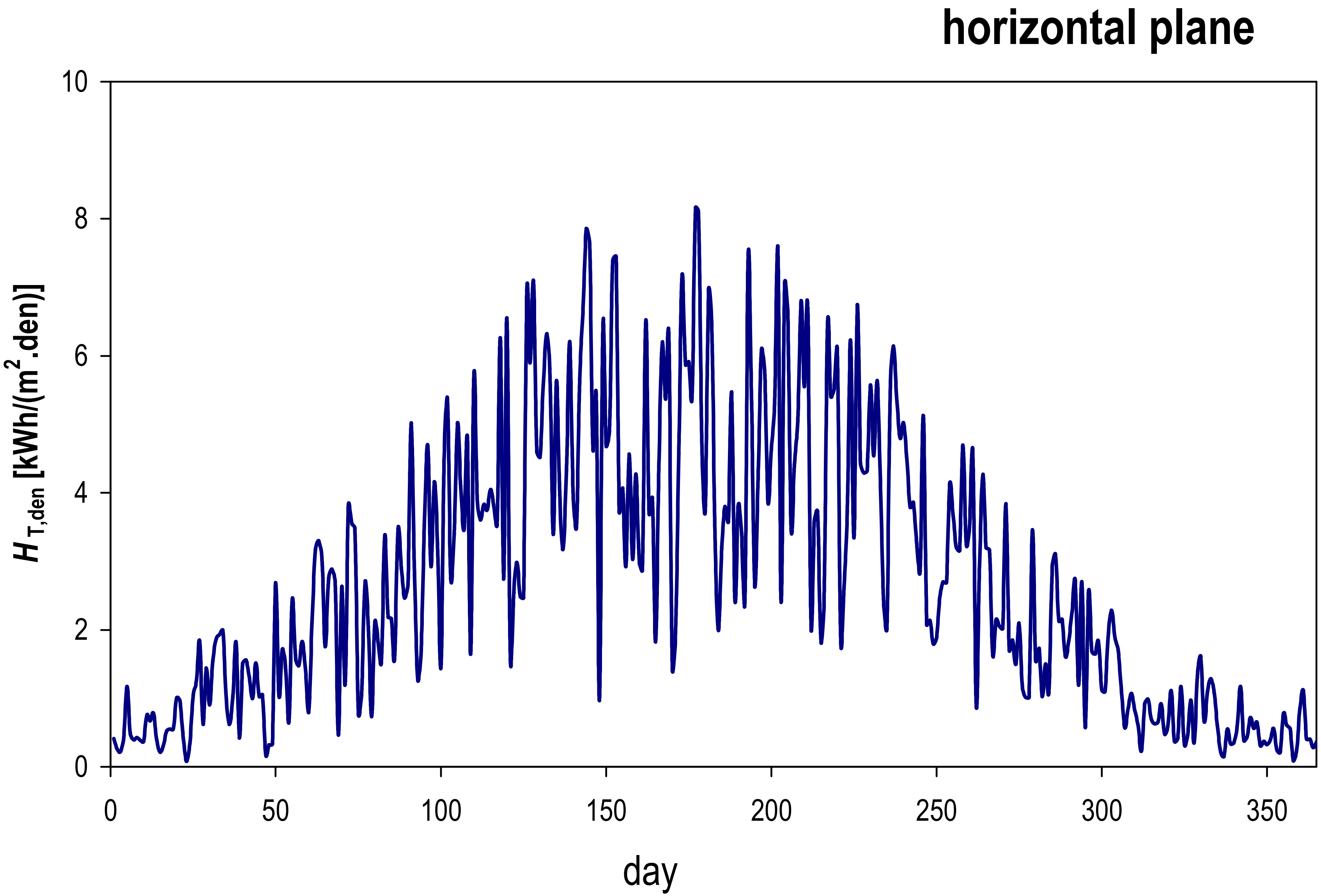


Hourly data of solar irradiance

optimum slope 45°

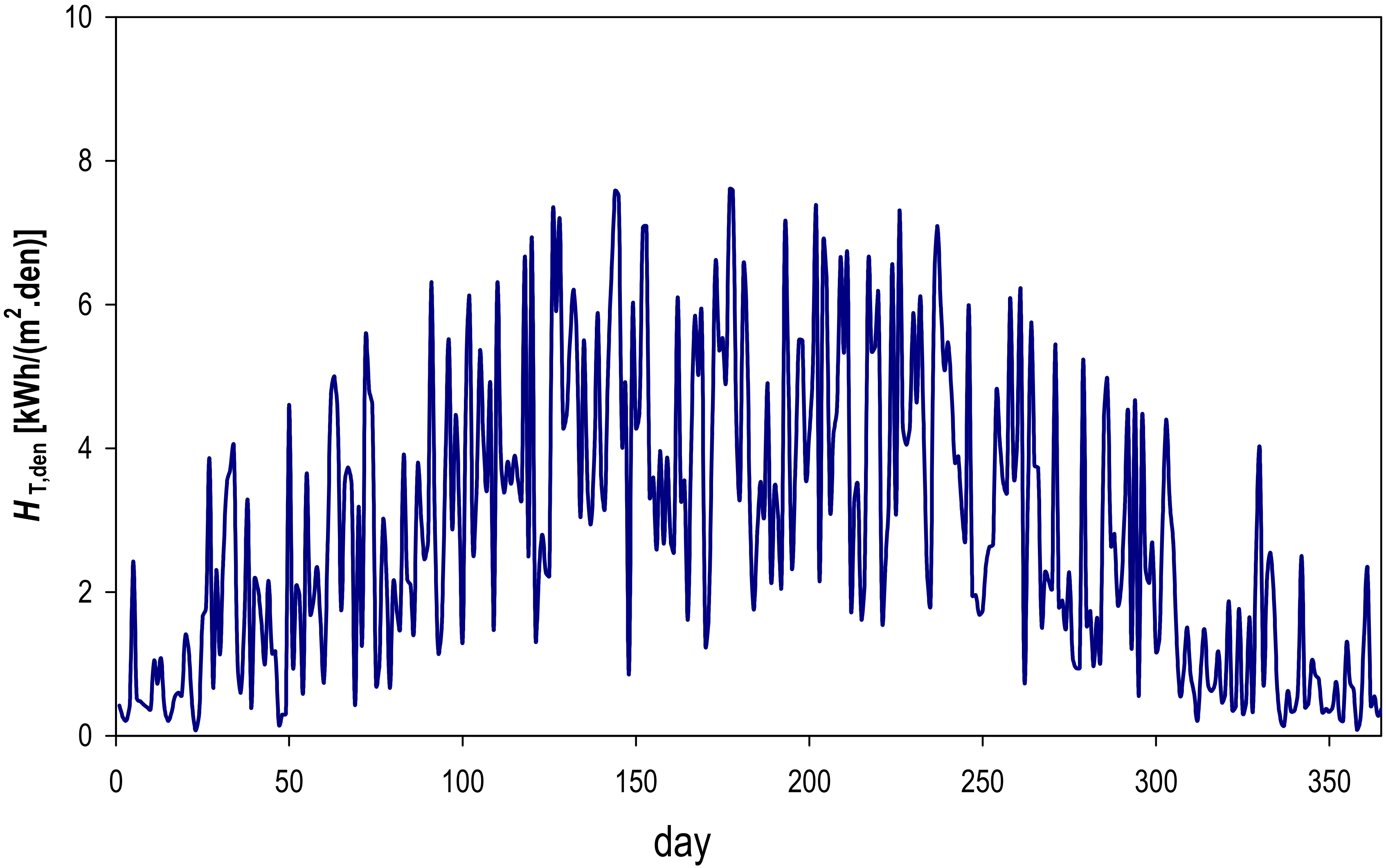


Daily solar irradiation

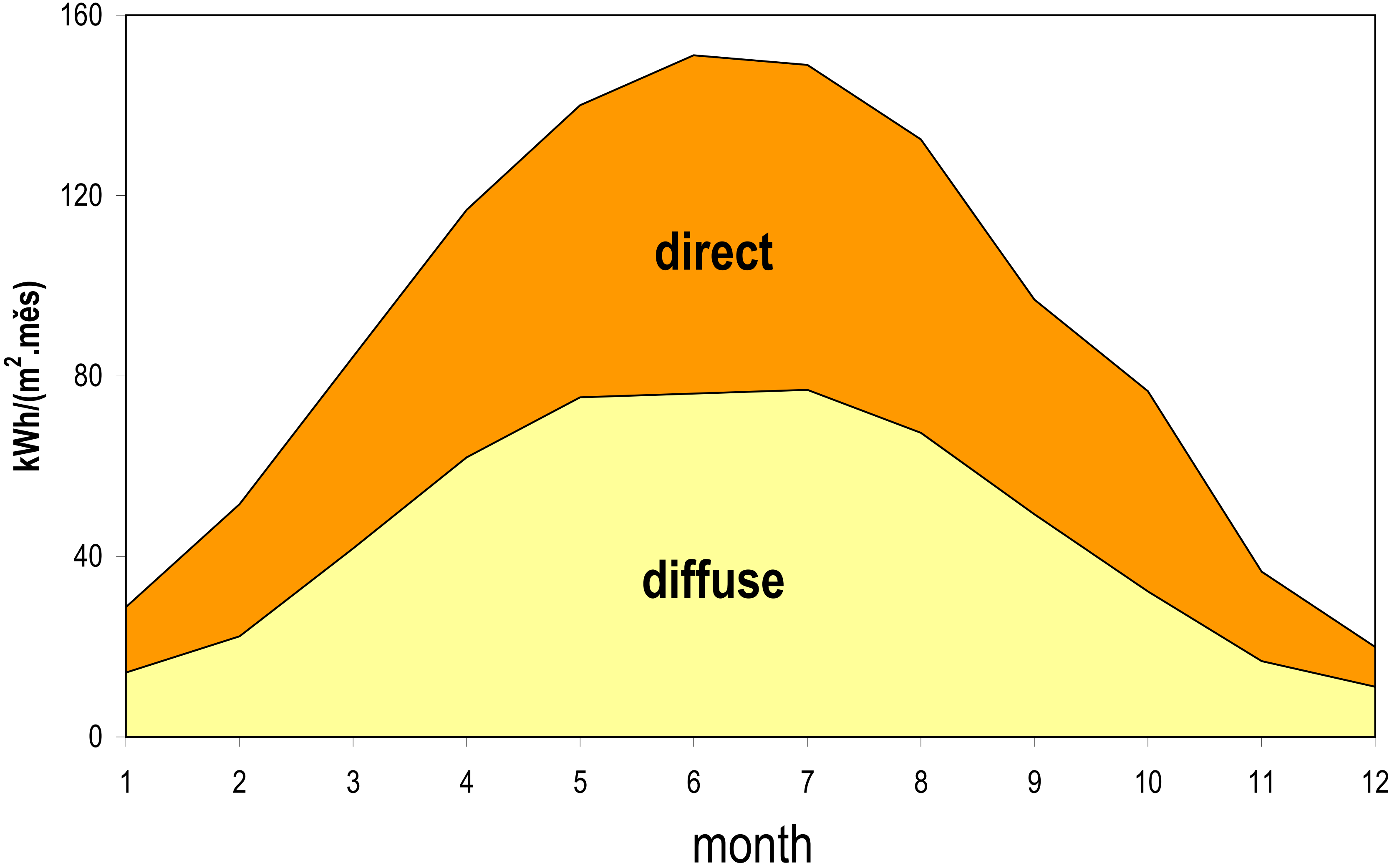


Daily solar irradiation

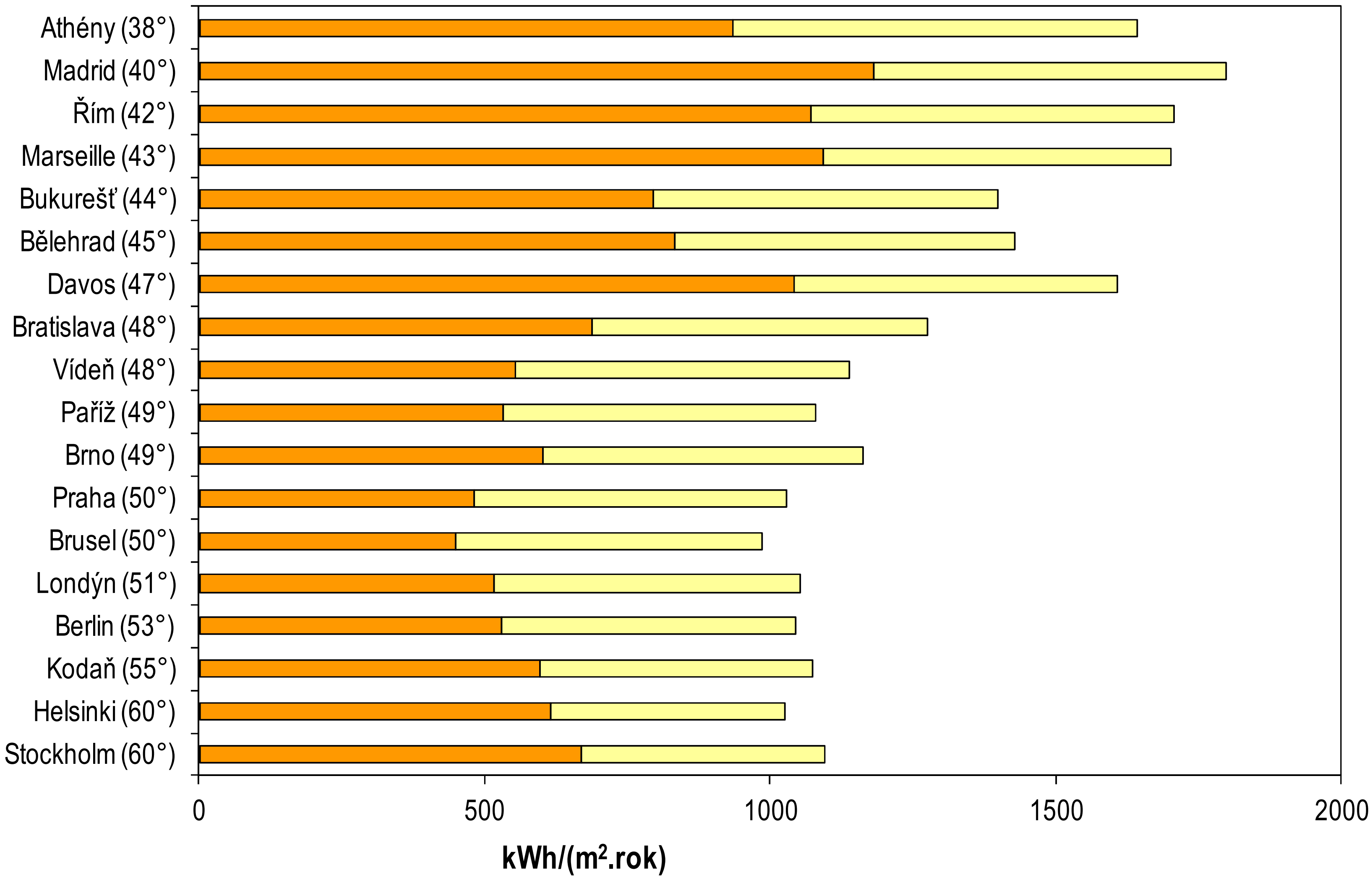
optimum slope 45°



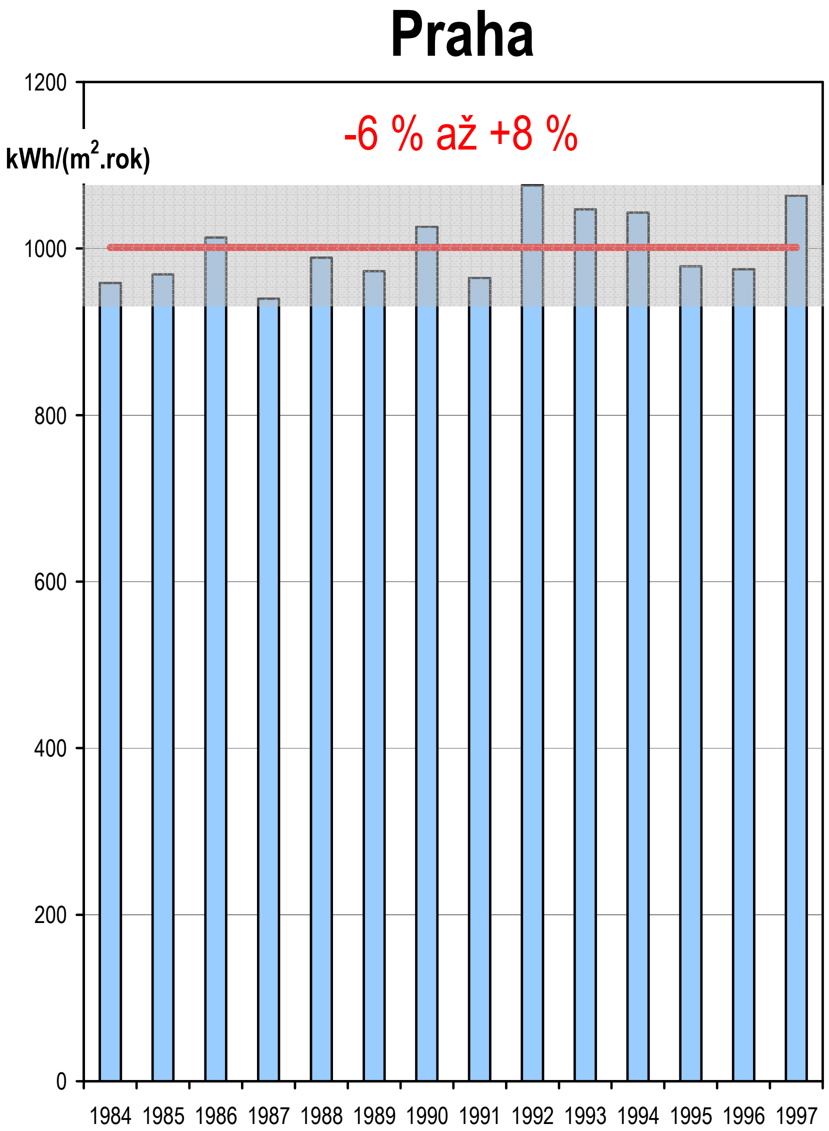
Direct : diffuse = 50 : 50 %

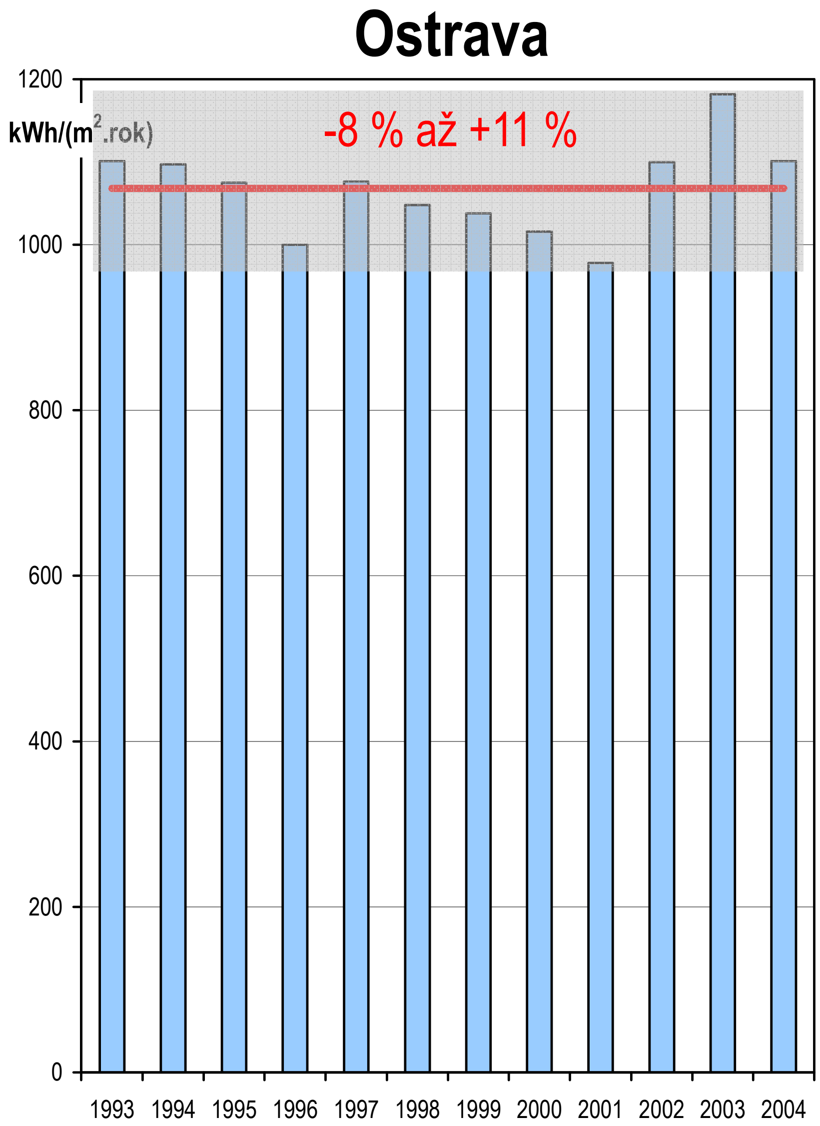


Direct : diffuse in Europe



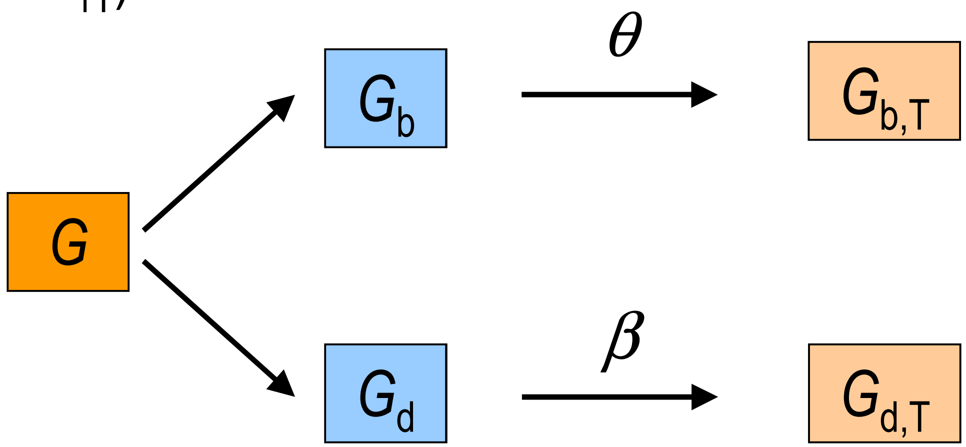
How irradiation changes?





Practical calculation

- given **measured** values of total solar irradiance on horizontal plane $G = (G_b + G_d)$
- need to recalculate it for other slope and orientation $G_T = G_{bT} + G_{dT}$ $(+\ G_{rT})$



split to components

recalculation → <u>different models:</u>

- isotropic
- anisotropic

Splitting radiation to components

- known:
  - **measured** value of total solar irradiance on horizontal plane G
  - theoretical value of total solar irradiance on horizontal plane out of atmosphere G_o

$$G_o = G_{sc}\left(1 + 0.033 \cdot \cos\frac{360 \cdot n}{365}\right)\sin h$$

clearness index
(analogy of transmittance)

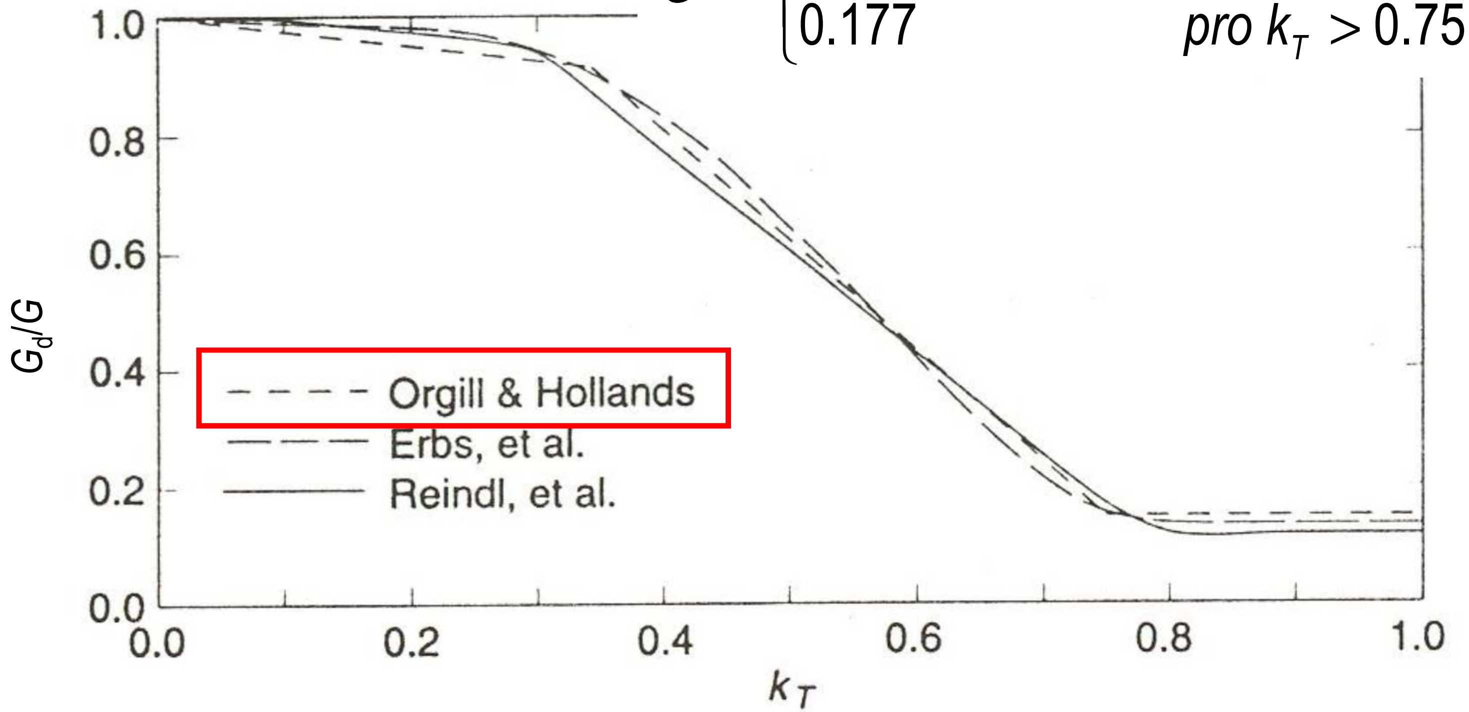
$$k_T = \frac{G}{G_o}$$

Splitting radiation to components

- **correlation** between clearness index and ratio diffuse to total on horizontal plane **exists**

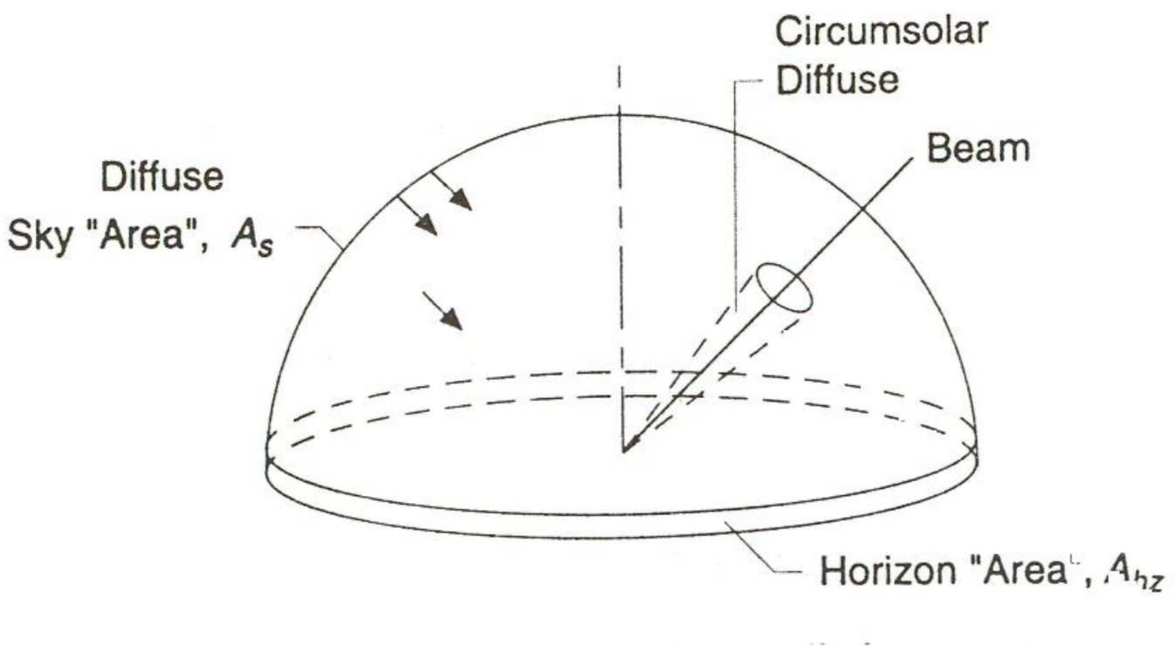
$$\frac{G_d}{G} \approx k_T$$

$$\frac{G_d}{G} = \begin{cases} 1.0 - 0.249 k_T & pro\, k_T < 0.35 \\ 1.557 - 1.84 k_T & pro\; 0.35 < k_T < 0.75 \\ 0.177 & pro\; k_T > 0.75 \end{cases}$$



Recalculation of solar irradiance

- known:
  - **splitted** values of total solar irradiance on horizontal plane $G = G_b + G_d$
  - calculation on given sloped and oriented plane



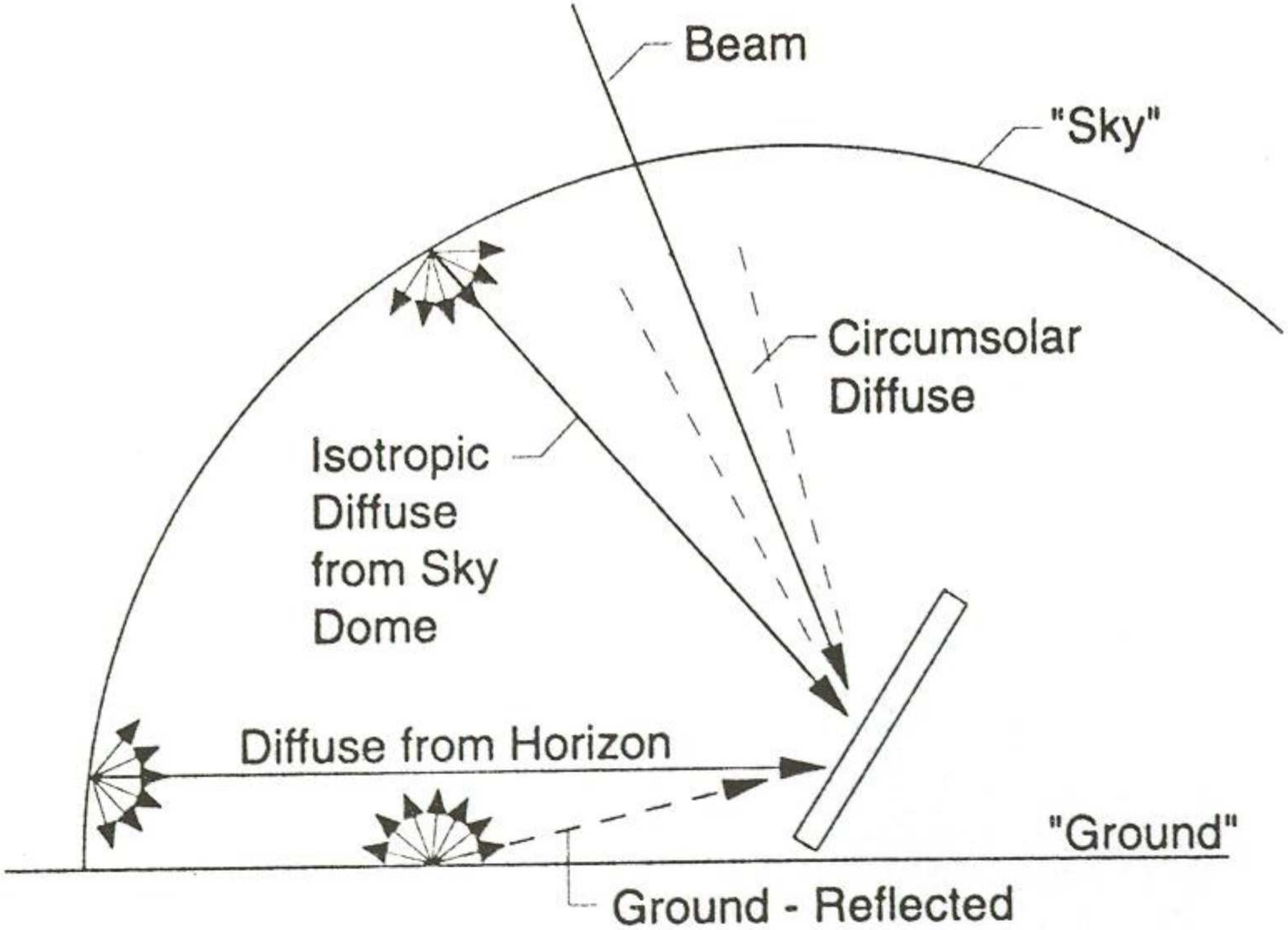
Components of solar irradiance (detail)

- **direct** – from geometry
- **diffuse** components:
  - **isotropic** – uniform from sky hemisphere
  - **circumsolar** (around Sun) – scattering of radiation around „beams“ passing the atmosphere, considered as diffuse, certain dependency on direction
  - **horizon brightening** – for clear sky – part of sky above horizon is brighter than rest of sky, thicker layer ... larger scattering

anizotropic

$$G_T = G_{bT} + G_{dT,izo} + \boxed{G_{dT,cs} + G_{dT,hz}} + G_{rT}$$

Components of solar irradiance (detail)



Direct component

$$G_{bT} = G_{bn}\cos\theta$$

$$G_b = G_{bn}\cos\theta_z$$

$$R_b = \frac{G_{bT}}{G_b} = \frac{G_{bn}\cos\theta}{G_{bn}\cos\theta_z}$$

geometry factor $$R_b = \frac{\cos\theta}{\cos\theta_z}$$

recalculation between horizontal and given plane $$G_{bT} = G_b R_b$$

Diffuse components – models

- **isotropic** sky – diffuse and reflected is only isotropic
- **anisotropic** sky – except isotropic also other diffuse components
  - ***Hay-Davies***: circumsolar (YES), horizon brightening (NO)
  - ***Hay-Davies-Klutcher-Reindl*** (HDKR): model HD + correction for horizon brightening
  - ***Perez***: most difficult, very detail analysis of all 3 components

all given models of diffuse irradiance appear in simulation programs (ESP-r, TRNSYS, aj.)

Isotropic model

- solar irradiance in 3 components : direct, isotropic diffuse (uniform from sky) and diffuse reflected from terrain

$$G_T = G_b R_b + G_d \boxed{\left(\frac{1+\cos\beta}{2}\right)} + G\rho_g \boxed{\left(\frac{1-\cos\beta}{2}\right)}$$

view factor to the sky view factor to the ground

Anizotropic model Hay-Davies

- simple extension of isotropic
- **anisotropy index A_i**: which part of diffuse is circumsolar

$$A_i = \frac{G_b}{G_o} = \frac{G_{bn}\sin h}{G_{on}\sin h} = \frac{G_{bn}}{G_{on}}$$

- circumsolar is directional dependent

$$G_T = \left(G_b + \boxed{G_d A_i}\right) R_b + G_d \boxed{\left(1 - A_i\right)} \left(\frac{1+\cos\beta}{2}\right) + G\rho_g \left(\frac{1-\cos\beta}{2}\right)$$

clear sky: $\boldsymbol{A_i}$ is high, majority of diffuse is cirkumsolar

overcast without beam radiation: $\boldsymbol{A_i}$ is low, isotropic model enough

Anizotropic model HDKR

- modification of Hay-Davies
- introduces **correction for horizon brightening**

$$G_T = G_b R_b + G_{dT} + G r_g \left(\frac{1-\cos\beta}{2} \right)$$

$$= (G_b + G_d A_i) R_b + G_d \left\{ (1 - A_i) \left(\frac{1+\cos\beta}{2} \right) \boxed{\left[1 + f \sin^3 \left(\frac{\beta}{3} \right) \right]} \right\} + G \rho_g \left(\frac{1-\cos\beta}{2} \right)$$

modulating factor $f = \sqrt{\frac{G_b}{G}}$

Perez anizotropic model

- different from others

$$G_{dT} = G_d\left[(1-F_1)\left(\frac{1+\cos\beta}{2}\right)+F_1\boxed{\frac{a}{b}}+F_2\sin\beta\right]$$

$$\frac{a}{b} = R_b$$

major part of day

F_1 circumsolar coefficient (see further)

F_2 horizon brightness coefficient (see further)

a term considering that cone of circumsolar radiation reach the given surface

$a = \max[0, \cos\theta]$

b term considering that cone of circumsolar radiation reach the horizontal plane

$b = \max[\cos 85, \cos\theta_z]$

Perez anizotropic model

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_z}{180} f_{13}\right)\right]$$

brightness $\Delta = AM \dfrac{G_d}{G_{on}}$

$$F_2 = f_{21} + f_{22}\Delta + \frac{\pi\theta_z}{180} f_{23}$$

clearness $\varepsilon = \dfrac{\dfrac{G_d + G_{bn}}{G_d} + 5{,}535\times10^{-6}\,\theta_z^3}{1 + 5{,}535\times10^{-6}\,\theta_z^3}$

Range of ε	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{23}
1.000–1.065	−0.008	0.588	−0.062	−0.060	0.072	−0.022
1.065–1.230	0.130	0.683	−0.151	−0.019	0.066	−0.029
1.230–1.500	0.330	0.487	−0.221	0.055	−0.064	−0.026
1.500–1.950	0.568	0.187	−0.295	0.109	−0.152	0.014
1.950–2.800	0.873	−0.392	−0.362	0.226	−0.462	0.001
2.800–4.500	1.132	−1.237	−0.412	0.288	−0.823	0.056
4.500–6.200	1.060	−1.600	−0.359	0.264	−1.127	0.131
6.200–∞	0.678	−0.327	−0.250	0.156	−1.377	0.251

[a] From Perez et al. (1990).